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Cost and Performance Report
(MM-0036)

Handheld Broadband Electromagnetic UXO Sensor

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COST & PERFORMANCE REPORT
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ACRONYMS AND ABBREVIATIONS

ADC	analog-to-digital converter
APG	Aberdeen Proving Ground
ATC	Aberdeen Test Center
ATV	all-terrain vehicle
DGPS	differential global positioning system
DS	discrimination stage
DSP	Digital Signal Processor
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
FAR	false alarm rate
FET	field effect transistor
GPS	global positioning system
ID	inphase difference
PACDIV	Naval Facilities Engineering Command Pacific Division
PD	probability of detection
QA/QC	quality assurance/quality control
ROC	Receiver Operator Characteristics
Rx	receiver
s/n	signal-to-noise ratio
Tx	transmitter
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
UXO	unexploded ordnance

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The staff at Geophex, Ltd. developed the GEM-3 technology under this project. Key personnel included Dr. IJ Won, president and chief technical officer; Alex Oren, chief engineer; and Dr. Bill SanFilipo, responsible for the Aberdeen Proving Grounds (APG) demonstration of the technology. Key government personnel included Dr. Jeffrey Marqusee, ESTCP director; Dr. Anne Andrews, ESTCP program manager; their staff; and the In-Progress Review technical advisors who provided advice during the course of the project. Dr. George Robitaille and the staff at APG, including Larry Overbay and Rick Fling (site manager), were responsible for the operation of the APG demonstration site.

Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Detection of unexploded ordnance (UXO) and discrimination between UXO and metallic clutter pose challenges to cost-effective remediation of UXO-contaminated land in order to reclaim it for civilian use. The need to develop sensors that can be deployed in a realistic setting and accomplish these goals motivated this project.

The broadband electromagnetic sensor improvement and demonstration undertaken in this project took the prototype GEM-3 and evolved it into an operational sensor with increased bandwidth and dynamic range, and enough memory and processing power to allow efficient data acquisition while decreasing the weight for ease of operation. Specifically, the frequency range was doubled from 24 kHz to 48 kHz; the 24-bit analog-to-digital converter (ADC) replaced the 16-bit ADC, providing 48 dB increased dynamic range; the digital signal processor (DSP) was upgraded to be fast enough to allow continuous operation at more than 10 frequencies simultaneously; and compact-flash memory was added, accommodating internal storage of a day's surveying. In addition to the original handheld configuration specified at the outset, a cart-mounted, large-coil configuration has also been developed for surveying large open areas. A more detailed description is provided in Section 2.0, Technology Description.

Other new capabilities include real-time output of data for logging into a portable computer (either laptop or palm) as an option to internal storage. Seamless integration with global positioning system (GPS) provides geo-referenced data in Universal Transverse Mercator (UTM) grid coordinates. Utility software for both the laptop and the palm computers provides an advanced user interface for configuring and controlling the GEM as well as real-time data display and processing. Mechanical construction was refined as well.

The demonstration was designed to test the technology in a wide range of operational requirements, including rugged terrain (moguls), wooded areas, large open areas, and miscellaneous obstacles and challenges (water, fences, roads, etc.). To meet these requirements, multiple configurations of the technology—handheld, manually pushed cart, and all-terrain vehicle (ATV) towed sled—were implemented and tested.

1.2 OBJECTIVES OF THE DEMONSTRATION

Through this program, the GEM-3 has evolved from prototype into a fully operational, full-scale instrument, and the objective of this demonstration was to verify its capability to perform under realistic conditions of buried UXO contamination. The goal was to combine multi-frequency inphase and quadrature data in an optimal way to identify local anomalies that are potentially UXO.

The technology demonstration scope was all-encompassing, including blind-grid testing of three configurations—handheld 40cm sensor, pushcart mounted 96cm sensor, and ATV towed 96cm sensor challenge scenarios—with woods and moguls using the handheld sensor and large open fields using the large coil with pushcart and towed configurations. The moguls area was covered with snow, the woods and parts of the open area were covered with several inches of water.

1.3 REGULATORY DRIVERS

This program was undertaken in response to the Environmental Security Technology Certification Program (ESTCP) Topic 1: Unexplored Ordnance (UXO) Detection, Discrimination, and Remediation.

1.4 DEMONSTRATION RESULTS

The new features of the GEM-3 were proven to be fully functional—lightweight, high dynamic range and sensitivity, ability to record 10 frequencies continuously and simultaneously from 90 Hz to 41 kHz, high data storage capacity, tightly integrated differential global positioning system (DGPS), and advanced user interface software for the handheld computer as well as PC-based configuration and operational software. Handheld as well as cart- or sled-mounted pushed or towed configurations were developed and tested for rough, vegetated, and open terrain missions. Discrimination software that can run real-time on the handheld computer, or in a batch post processing mode, and an automatic target-picking algorithm were developed.

The results of the demonstration indicate a need for further work. Performance in the moguls and woods was not consistent with our other experiences with detection capability of the handheld GEM-3, and we believe a problem with our target geo-referencing may have occurred. We detected a large number of targets in these areas that had the characteristics of metal objects but did not match the ground truth positioning of seeded objects (UXO or clutter), indicating a probable problem with our geo-referencing. We have since repeated the demonstration in the moguls area (April 2005) with some small improvements, mainly in the algorithms, to the system, and achieved a UXO detection of nearly 70%. Detection performance was reasonable in the other areas, but discrimination capability has yet to be realized. (The Aberdeen Proving Ground [APG] site, with its wide range of ordnance types, is particularly challenging.) Further system improvements that may help accomplish this include increased range capability for detection of deeper targets and improved detection channel algorithms and discrimination algorithms. Acquisition methodologies also must be improved; we must ensure that the geo-referencing is correct, and improve the cart and towing platforms and ATV navigation.

Detailed performance results are provided in Section 4.0, Performance Assessment.

1.5 STAKEHOLDER/END-USER ISSUES

This demonstration addressed decision-making issues concerning end users associated with the applicability of the GEM-3 technology for their specific UXO detection and discrimination mission needs. Operational performance under a variety of conditions was assessed, including production capabilities, field usability, and logistical requirements. Both handheld (with small sensor disk) and cart- or sled-mounted (large sensor disk) configurations were evaluated, providing end-user assessment of the performance and operational usability of each.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

2.1.1 Hardware

The GEM-3 electromagnetic induction (EMI) system consists of three basic components: the monostatic coil sensor, the electronics console, and the user interface (control and display) module (Figure 1). The functional architecture is described by Won *et al*, 1997, and the design details of the improved system are given in the Final Report for this project.

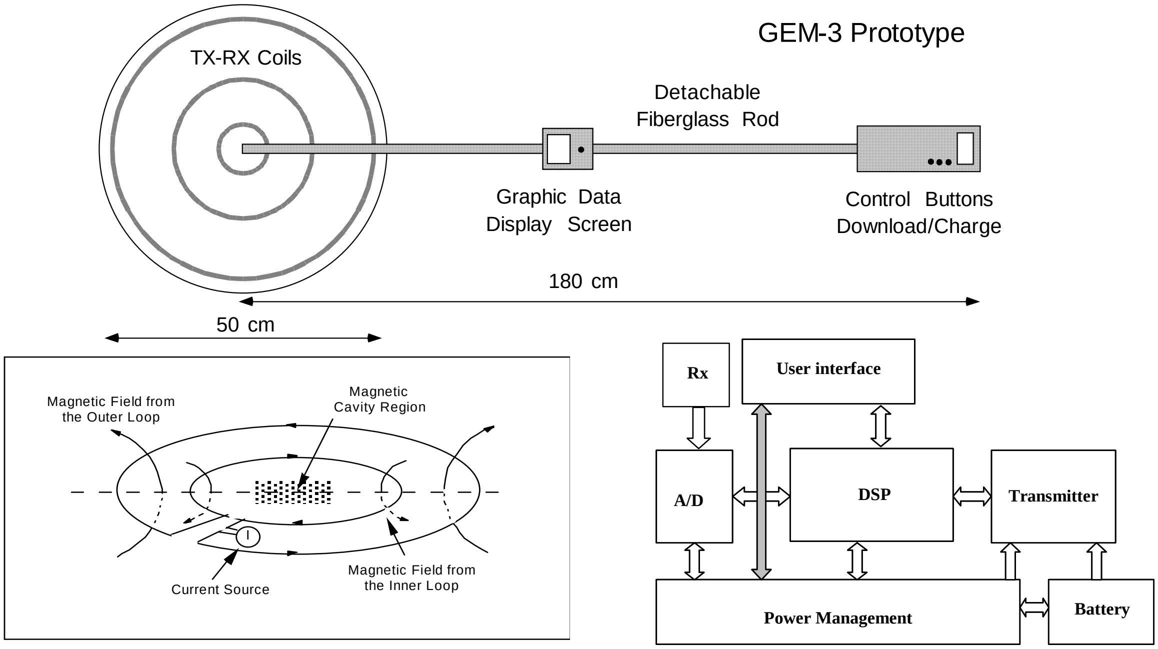

Figure 1. Schematic of the GEM-3 *(top)*, Conceptual Representation of the GEM-3 Coils *(bottom left)***, and Console Block Diagram Showing Functional Modules** *(bottom right)***.** *(The GEM-3 coils create a central magnetic cavity region using two concentric circular loops that are electrically connected in an opposing polarity.)*

Although a new custom user interface was designed and built for the prototype, the full-scale system utilizes a palmtop type computer such as the iPAQ™, with custom software for configuring the GEM, and for real-time control and display. The new hardware will also allow the use of a 12V standard off-the-shelf NI-mH battery. The improved electronics is more compact and lighter than earlier designs, provides increased dynamic range and bandwidth via 24-bit ADC with 96 kHz sampling, incorporates a preamp built into the receiver (Rx) coil to reduce cable-noise pickup, and uses more efficient and faster switching transmitter (Tx) field effect transistors (FET) for less heat and greater waveform fidelity. Photographs of the electronics are shown in Figure 2.

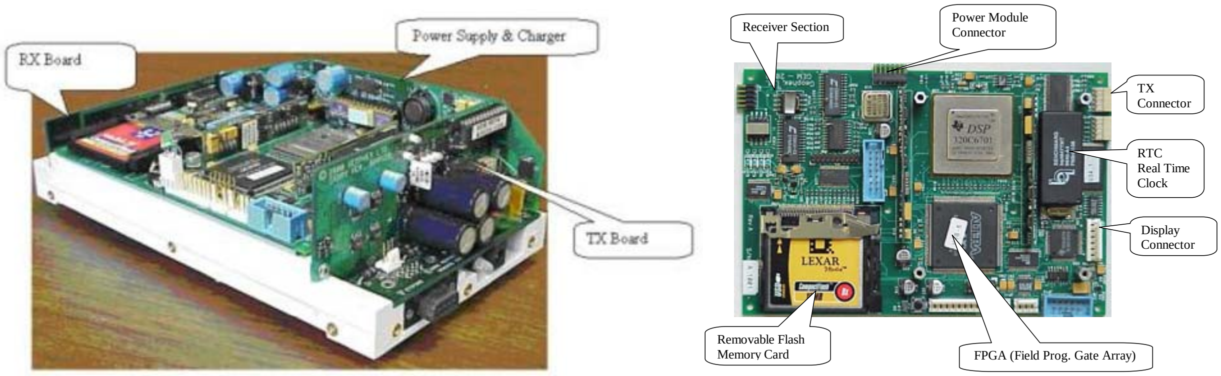

Figure 2. Photographs of the Electronics Console of the Enhanced GEM-3 *(left)* **and the DSP** *(right)***.** *(With cover removed from console, the memory card and support electronics on the interior horizontal board are viewable.)*

Through this program, the GEM-3 has evolved from prototype into a fully operational (full-scale) instrument, and the objective of this demonstration was to verify its capability to perform under realistic conditions of buried UXO contamination. The goal was to combine multi-frequency inphase and quadrature data in an optimal way to identify local anomalies that are potentially UXO.

The GEM-3 may be used in two versions—handheld with either 40cm or 64cm diameter sensor (40cm for this demonstration) or cart- or sled-mounted with 96cm sensor, as shown in Figure 3. The large-disk configuration can be mounted on a PVC sled and towed with an ATV, or mounted on wheels and hand-pushed when greater maneuverability is required.

Figure 3. The GEM-3 Can Be Handheld, Cart- or Sled-Mounted, and Pushed or Towed.

The GEM-3 electronics has integrated DGPS navigation capabilities, although, for the hand-held scenarios of this demonstration, we flagged anomalies and located them with a stand-alone DGPS afterwards.

The gain in signal–to-noise ratio (s/n) from the increase in maximum Tx current depends on several factors. Although the maximum current sustainable by the electronics is doubled, the actual realized increase depends on the set of frequencies chosen – high frequencies are inductively loaded and demand a greater share of the available voltage (12v) and, using more frequencies, shares the voltage and decreases the peak current. With a 10 frequency hybrid waveform spread roughly logarithmically over the sensor 48 kHz band (typical), the current will not reach 12 A, but if the selection is restricted to a few frequencies at the low end, the maximum current will be attained and the benefit will be more clear cut.

The GEM-3 transmitter current is produced by computer controlled rapid switching of the full battery voltage into the Tx coils, with a current response characterized by the natural self-inductance and resistance of the coil. The pulse-train pattern is customized to deliver current at the user-selected frequencies. The higher Tx waveform speed offers a more power efficient Tx system because a lower speed (also implies longer duration pulses) results in more current overshoots that must be countered with current pulses of opposite polarity, and thus more power expended at (nonoperational) switching frequency. Also, a slower waveform pulse train with longer pulses results in higher primary field spikes, which consumes much of the receiver dynamic range with residual (bucking error) primary field induced voltage.

The increase in sampling rate to 30 Hz (with an option to average internally, reducing the output rate but narrowing the noise bandwidth around each operational frequency) provides a clear-cut increase in spatial resolution during survey mode operation and greater stacking rate for s/n improvement during static logging over a target.

The 24-bit ADC provided much needed dynamic range without sacrificing sensitivity. In our early systems using a 16-bit ADC, we had experienced problems with sensor saturation in magnetic terrain, notably Kaho'olawe, Hawaii, as well as the road lanes at the landmine test site at Aberdeen Proving Grounds. In an early test at Kaho'olawe, it was necessary to reduce the electronics gain, thereby reducing sensitivity, in order to operate. At the APG mine lanes, we abandoned testing on the road lanes and could operate only over the off-road (grass) lanes. Large shallow metal targets can also saturate the ADC, and the 16-bit version had a much lower threshold before this limitation was reached. The doubling of the ADC speed to 96 kHz doubled the operational bandwidth to 48 kHz (we are now moving to 182 kHz sampling for 96 kHz bandwidth). Many targets have not reached the inductive limit at 24 kHz; i.e., the spectral character is not completely defined below 24 kHz, and so the added bandwidth should enhance spectral-based discrimination.

The advanced display has been replaced by integration with a palm-held computer (e.g., iPAQ™).

The data logging function allows tight integration of auxiliary data with the GEM data; the primary application thus far has been DGPS, but it could include magnetometer data or other sensors that utilize an RS-232 output.

The maximum number of frequencies goes hand-in-hand with the increased bandwidth; in order to take advantage of the bandwidth without sacrificing spectral resolution, more frequencies are needed. Also, increasing spectral resolution should enhance target discrimination based on spectral character, particularly when several different types of targets are of interest.

Integration of real-time detection (audio enunciated) and discrimination provides an operational prototype of an advanced system for locating targets and prioritizing a dig decision on the spot. We have implemented a simple single-point spectral matching based algorithm (best-fitting linear combination of axial and transverse target orientation frequency responses). More advanced schemes using multiple spatial samples could be added.

2.1.2 Software

The objective of the demonstration was to evaluate both the GEM-3 hardware as well as the data processing, including detection and discrimination algorithms.

2.1.2.1 Response Stage Algorithms

These target-detection algorithms provide a means to combine multifrequency data into a single output measurement that is used as the response stage of the demonstration submittals (dig lists). They are designed to suppress geologic noise, particularly soil susceptibility, and to emphasize metallic objects, and increase system s/n by combining many independent signals. They also drive sound and graphical display signals to the operator for real-time detection (hand-held configuration) of EMI anomalies that may indicate buried UXO, or anomaly-picking criteria in the automated target-picking software (towed survey configuration) used in survey data postprocessing.

Soil magnetic susceptibility is the predominate source of geologic noise (i.e., EMI anomalies caused by soil), which can result from soil variability or from sensor height and orientation changes. The response stage is designed to suppress geologic noise. In general, the multi-frequency EMI response of magnetic soil is characterized by zero quadrature and frequency-independent inphase variations (i.e., flat, zero phase spectra). A weak quadrature response increasing with frequency results from soil conductivity. Metal objects produce relatively strong quadrature responses, usually extending to low frequencies, and frequency-dependent inphase responses (Figure 4). The response stage algorithms are designed to ignore variations in the absolute level of the inphase (frequency-independent-level shifts).

Spectra from geologic anomalies have a very flat (frequency-independent) inphase character from soil susceptibility and a weak quadrature response, increasing monotonically with frequency from soil conductivity. Our response stage algorithms more easily mitigate the former, while the latter is mitigated simply by its relative weakness.

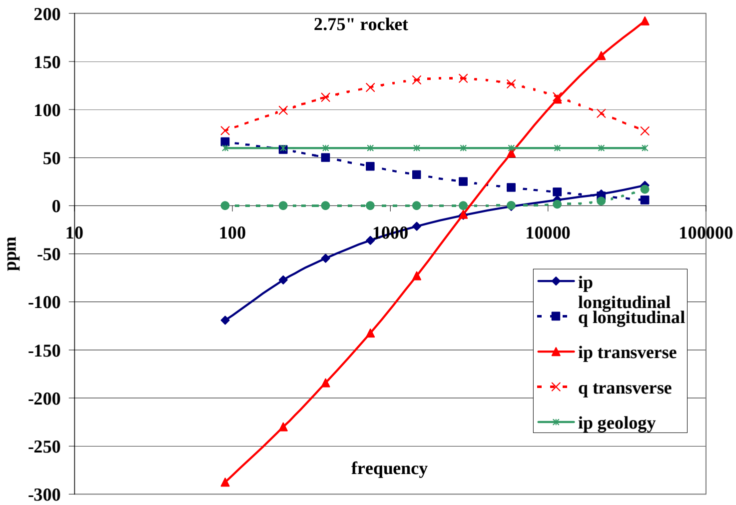

Figure 4. Example of Metallic Target Spectra for Sensor Axis. *(The target cylindrical symmetry axis [blue is longitudinal and red is transverse] shows the strong quadrature and frequency dependent inphase character. The green shows characteristic idealized geologic response.)*

We have available the following detection (response stage) algorithms:

- **Quadrature Sum**: Sum of multifrequency quadrature responses, which are insensitive to geologic magnetic susceptibility, weakly sensitive to geologic conductivity

- **Inphase Difference:** Difference between high and low frequency inphase desensitizes to geologic magnetic susceptibility, can choose frequencies with less noise as long as they are not too close

- **Spread Functions (Quadrature or Inphase):** Sum of absolute differences among all chosen frequencies, best at suppressing geologic noise, but random (high spatial frequency) noise increases

- **Total Apparent Conductivity (I-Q and Q-Q):** Nonlinear transformations tend to bring out weaker anomalies (small or deep UXO), weighted average over all frequencies, 1/log(f) weighting, which favors metal over geology.

These response stage measurements do not provide a means to identify or classify the target unless spatial data are used to extract shape features such as aspect ratio. Our discrimination schemes, described below, utilize target spectral character rather than multispatial samples.

In all these algorithms, previewing the individual spectral components or comparing results (i.e., resultant map clarity, which is somewhat subjective), allows exclusion of problem frequencies. For the survey mode data (cart or towed), maps from various choices can be compared since the algorithms are performed in postprocessing. In practice, frequencies below 270 Hz are often degraded by platform motion for a cart mounted system, and the highest frequency, near the system band limit, is often noisier than the others and more sensitive to conductive soil. The 90 Hz and 150 Hz and 47,970 Hz were excluded in the detection channel (Qspread) at Kaho'olawe and the lowest (90 Hz) and highest (41,010 Hz) at APG for the total apparent conductivity. In handheld operation, the benign platform dynamics allowed use of all frequencies at APG.

The total apparent Q-Q conductivity is considered the overall optimum response stage and was used for the open field at APG, in which the survey data were postprocessed in batch mode. Real-time implementation at that time required the use of the simpler quadrature sum in the handheld configuration in which the operator picked targets during the survey; recently, we have combined the quadrature sum with the inphase difference. When we have compared results from these three algorithms, the performance difference is usually insignificant. At Kaho'olawe, we used the quadrature spread, which showed somewhat less broad background variation than the quadrature sum, at the price of greater short spatial wavelength noise.

The response stage magnitude correlates to target metal content (size) and sensor-target range (depth); the spatial extent of the anomaly correlates to target depth.

2.1.2.2 Discrimination Stage Algorithms

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*, 2001b). Sensor-target geometry is not modeled, so data sample positions are not needed, nor are target position and orientation. The weighting factors were unconstrained (we have more recently constrained them to be positive) and incorporate response amplitude scaling associated with target range; the relative values are determined by target 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 spectral fitting error to generate the discrimination stage (DS). The DS does not correlate with sensor output amplitude as does the response stage because amplitude depends primarily on target size and depth, and both UXO and clutter occur over a broad range of sizes and depths. Our DS is based on characteristic multi-frequency spectra correlated to UXO training (library) spectra—the "shape" of the spectra (relative response between frequencies) determines which library ordnance best matches the target and how well it fits.

In addition to the weighting factors, the algorithm allows a frequency-dependent inphase offset (vertical shift in the inphase spectrum) to desensitize the fit to superimposed geologic noise from magnetic terrain. An option to add a contribution to the misfit from the offset allows some recovery of the absolute inphase level (which depends on the ferrous response of the target) target information if the soil susceptibility is not too high. The misfit is normalized by the sum of the target amplitude plus a constant adjusted so that weak targets (small or deep) allow for greater relative (%) noise.

The DS for the APG data was computed in a batch mode from single points identified with the response stage.

At APG, the DS was computed from the matching misfit, where we mapped zero fitting error to a maximum value of 10 and infinite fitting error to zero via the form:

DS = C/(0.1*C + Error), with C chosen to obtain the desired DS distribution.

The value for C ideally maps the UXO/clutter threshold to a confidence (discrimination stage) value of 5, which gives the misfit error a value of 0.1*C.

Since APG, we have modified this expression by normalizing and squaring the error:

DS = 10/(1 + (Error/C)^2), with C chosen to obtain the desired DS distribution.

This shifts the value of C to be equal to the UXO/clutter error threshold (DS=5 when error=C), and it flattens the DS distribution so that fewer targets give a DS near 5, and more targets give values near the extremes (0 and 10). The objective is to have a better separation of UXO and clutter and ideally to give a bimodal DS distribution for the two classes.

At Kaho’olawe, the total misfit was computed from a weighted sum at multiple positions, where the weighting was inversely proportional to the distance from the peak response. Data points included were manually selected for each target using a cursor selection function built into custom contour mapping software. At the time, we had not yet developed batch-mode software and were evolving our analysis methodology; the manual target-by-target processing was extremely laborious, and the benefit in results not clear; and we found it difficult to treat data consistently over the many days of processing required. That motivated the development of an algorithm that could pick target anomalies and perform the inphase difference (ID) algorithm and output a dig list with target coordinates, response stage and DS values, and target ID in a batch mode. The DS for the APG data was computed using this software, with target IDs computed from single points identified with the response stage. Use of a single point is much more straightforward for an automated algorithm, and we have not found any benefit from processing multiple samples for the same target in our testing to date, though with more research an optimal method of combining spatial samples without explicit modeling may provide improved classification performance.

Figure 5 shows examples of a good fitting and a poorly fitting target spectra to library UXO, the former likely UXO and the latter likely clutter; note that the amplitude (and correspondingly, the response stage) is greater for the likely clutter item.

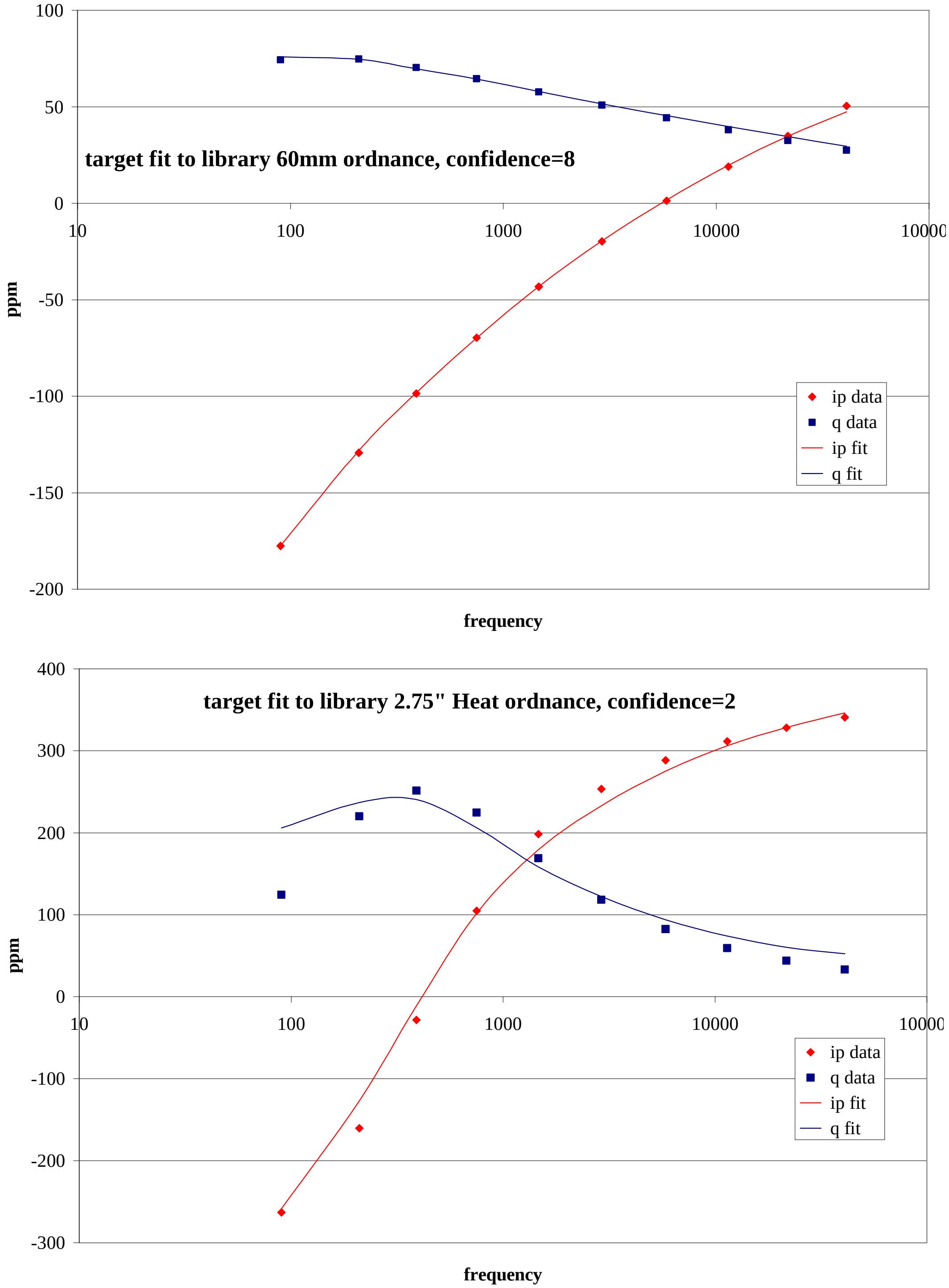

Figure 5. Examples of Blind Grid Target Spectral Fits to Library Training Spectra. *(The top graph indicates a good fit with a high [8] discrimination stage [confidence], and the bottom graph indicates likely clutter with a low [2] discrimination stage.)*

2.2 PREVIOUS TESTING OF THE TECHNOLOGY

Initial testing of GEM-3 technology was first performed at the Geophex facility in Raleigh, North Carolina. Geophex has a 10m x 10m test bed in which 21 metal pipes of various sizes, some ferrous (steel) and some nonferrous (3 aluminum, 2 copper), have been buried at depths ranging from 10 to 110cm.

The prototype of the full-scale GEM-3 technology was first demonstrated at the Kaho'olawe demonstration in October 2001 for the Naval Facilities Engineering Command's Pacific Division (PACDIV). The hardware tested incorporated all of the full-scale components except the integrated iPAQ™ user interface that has replaced the prototype control and display unit. Minor hardware changes and DSP firmware changes have been made, and changes have been made to the system configuration and user-interface (WinGEM) software. The Kaho'olawe site included several 30m x 30m calibration grids and 22 blind grids, also 30m x 30m each, of varying (moderate–high) geologically magnetic terrain. The demonstration phase at that site was performed in October 2001.

We used the cart-mounted 96cm disk exclusively, with integrated DGPS positioning of survey data recorded by the GEM-3 electronics.

2.3 PROCESS DESCRIPTION

Mobilization requires transport of the GEM sensors (and for large open areas, the ATV and towed sensor platform (pvc sled) and/or wheeled pushcart) and auxiliary equipment, including battery chargers, laptop computer, DGPS with base station, lane markers (cord, traffic cones, plastic flags, etc.).

Design criteria include determining configuration choices—handheld for areas not easily surveyed with a cart or towed system, cart for small open areas where maneuverability is required, and ATV towed system for large open areas. Line spacing, typically a half meter, may be increased if only larger ordnance is of interest, or tightened if small shallow items are important. The detection channel and discrimination algorithm settings may depend on soil characteristics (susceptibility and conductivity).

Performance metrics are based on probability of detection (PD) of UXO, false alarm rate (FAR), and survey area production rate.

Personnel training requirements are typical of commercial geophysical equipment, with familiarity of equipment setup (i.e., assembly of cart, cable connections, battery and power needs) and operation (iPAQ™ and PC software, data file management).

Health and safety issues pertain to the UXO sites, but no special hazards are associated with the GEM hardware.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The chief advantage of this technology is the potential for discrimination between ordnance and clutter, and/or identification of the ordnance. The broadband multifrequency data provides maximum EMI information that can be used to identify or classify metal objects. The high sampling rate provides dense coverage when conducting a production survey, and the dynamic range allows detection of small or relatively deep targets while remaining below saturation even when large targets are shallow, or when operating over highly magnetic soil. The various configurations and coil sizes available make the system adaptive to differing conditions (hand-held in trees or over rough terrain, large cart-mounted disk providing increased footprint and depth of exploration for flat open areas). Major improvements under this project include the following:

- Higher maximum transmitter moment (from 6 A to 12 A, 40 A with high-power option)
- Higher transmitter waveform resolution (from 96 kHz to 1,536 kHz)
- Improved receiver—ADC from 48 kHz @ 16 bits to 96 kHz @ 24 bits
- Increased computing power and faster data collection—fully 30 times a second up to 15 frequencies
- Advanced display (visual and audio)—a bigger screen
- Data-logging function—other data including GPS navigation data
- Increased number of frequencies for detection survey
- Integration of a real-time detection/discrimination algorithm (for handheld operation).

Other EMI technologies that are suitable for the UXO problem are all time-domain systems. There are only a few candidates, the most common of which provide a single or two time gates. The single time-gate systems provide little information for discrimination. The newer, more advanced time-domain EMI systems provide a number of time gates that in principle provide information similar to a frequency-domain system, but in order to match the bandwidth of the GEM-3, the decaying transient signal from eddy currents induced in a target must be observed over several decades of decay. Non-EMI technology applicable to UXO detection consists of various forms of magnetometers. Magnetic data provides limited discrimination capability (some capability to estimate size, depth, and possibly aspect ratio, but cannot detect nonferrous UXO) and is quite sensitive to geology having significant magnetic susceptibility.

Limitations of this technology include the inherent difficulty in distinguishing metal objects by their EMI response; objects similar in size and shape generate similar responses, and even dissimilarly shaped objects may produce similar responses if the depth and orientation is within some particular range. Other limitations include difficulty in obtaining good s/n while surveying over rough terrain and surveying in heavy brush, dense forest, or steep terrain. Extreme magnetic-soil conditions also degrade data, though not to the point of inoperability. Maintaining adequate spatial coverage while meeting survey production needs over large areas is also a challenge.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The standard performance metrics for UXO detection/discrimination technology are shown in Table 1. Since the operators were the demonstrators for this demonstration, operator acceptance may be interpreted as evaluation by on-site Aberdeen Test Center (ATC) personnel, or their responsible parties in charge of demonstration oversight. Such evaluation was made by observation of production rates and field problems that arose. The quantitative objectives performance was determined by ATC, based on the scoring of the submitted dig sheets.

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance (Objective met?)
Qualitative	Ease of use	Operator acceptance	Acceptable
	Field worthiness	Operator acceptance	Acceptable
Quantitative	% detected	> 95%	15%-85%
	False alarms	< .1	.30-.70

3.2 SELECTING TEST SITES

The formal demonstration culminating this project was performed at the ATC facility at APG. Prior to the demonstration at APG, one was performed at a test grid on Kaho’olawe, Hawaii, an active cleanup site.

3.3 TEST SITE HISTORY/CHARACTERISTICS

Kaho’olawe

The Hawaiian island of Kaho’olawe was used by the military for ordnance testing and as a practice range from World War II to 1993, at which time Congress passed a law to return it to the state and to native Hawaiians. PACDIV has been given the task of UXO cleanup. To that end, clearing UXO has been ongoing, primarily surface clearing but including subsurface in select areas. Since it is a volcanic island, the magnetic properties of the rock and soil are mostly high susceptibility and remnant magnetization, making use of magnetometers marginally useful for finding buried UXO. A seeded test site has been created in a cleared area to test methodologies for buried UXO detection in the geologic environment representative of the island. This site is considered a stringent testing scenario for UXO detection and identification in magnetic geology. Four 30m x 30m calibration grids and twenty-two 30m x 30m blind test grids were used for this demonstration.

APG

The APG Standardized UXO Technology Demonstration Site is one of three 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 handheld 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.

APG 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, Maryland and Philadelphia, Pennsylvania. 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 1,600 m^2 rectangular grid including access lanes separating 400 discrete 1m 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 ±1m vertical relief, requiring manual data acquisition, likely handheld sensor configuration; (5) wooded—various vegetation including significant areas of dense trees (Figure 6).

Figure 6. Aerial Photograph of the APG Standardized UXO Technology Demonstration Site.

Both the handheld and cart-mounted systems were tested and "trained" (target libraries collected) in the calibration area as well as with in-air training using sample UXO provided by ATC. The blind test grid contains 400 actual interrogation squares that were tested using the handheld configuration. The open field was surveyed with the cart-mounted system at 0.5m line spacing with DGPS logged by the GEM electronics for georeferencing the data; all data were stored in the console flash memory and/or the user interface for later processing. The mogul and wooded areas were surveyed with the handheld configuration in a sweep-search fashion along 2m-wide lanes marked with cord, with real-time detection and identification active; detected targets were "flagged" for follow-up geo location, and DGPS data were collected over the target.

3.4 PHYSICAL SETUP AND OPERATION

Kaho'olawe

Equipment setup included assembly of the wheeled pushcarts (two) with the GEM-3 disks and consoles and DGPS rovers, and the DGPS base station. Some ordnance targets were provided for training on site (some had been provided at Geophex prior to mobilization). The first day on site was spent in the calibration/test grids, where ground truth was provided. Data were collected and detected anomalies correlated with ground-truth target locations.

APG

Equipment setup included assembly of the wheeled pushcart and ATV sled and mounting the GEM-3 and related hardware on the ATV, including the navigation computer, the 96cm sensor system with electronics console, DGPS, and user interface. Similarly, the handheld systems were assembled, and DGPS interfaced with an iPAQ™ for locating the flags. The DGPS base station was initially set up at the United States Geological Survey (USGS) reference point, and a rover was used to establish a more convenient reference point near the trailer, for line-of-site radio communication with the mobile units. The systems, including DGPS, were powered up and checked for normal functionality, and ambient noise levels were observed. The GEM-3 calibration was verified with a ferrite rod sample target for all systems. Survey line start/stop points for the pushcart were laid out, and lanes for the mogul and wooded areas were marked with string. The ATV navigation computer was set up with the site boundaries and planned line direction/spacing information.

Initially, we used a two-wheeled trailer cart for towing with the ATV but found this to be somewhat unstable over ruts and gullies and difficult to turn within the safety boundaries. A sled that had been made at Geophex for snow conditions (as encountered during the moguls survey) was delivered to the site and replaced the wheeled cart after confirming that it could be pulled over grass with better stability than the wheeled cart.

Handheld sensors used in the moguls and woods areas required no on-site setup.

3.4.1 Period of Operation

The period of operation at Kaho'olawe was October 8–21, 2001; no work was done on weekends. The period of operation at APG for the Moguls area only was December 9–13, 2002; and for the remaining areas, April 28–May 7, 2003. A repeat demonstration, funded by the ATC, in the moguls and (reseeded) blind grid with the handheld GEM-3 was performed during the periods of April 18–22, 2005, and April 25–27, 2005.

3.4.2 Area Characterized

The test area at Kaho’olawe included 30m x 30m areas designated A-1, A-2, B-1 to B-5, through E-1 to E-5, totaling 22 sections equal to 1.98 hectares. At APG, all areas, including the blind test grid (area 2), open field (area 3), rough mogul scenario (area 4), and the wooded area (area 5), were surveyed, for a total of approximately 6.5 hectares. The blind grid was surveyed three times – once with the handheld sensor and twice with the 96cm sensor, statically with the pushcart and dynamically while towing with the ATV. The calibration area was used only for training and testing, and data were not generally recorded; half of the calibration area was included in the ATV towed survey over the open area and recorded. The moguls and (reseeded) blind grid areas were repeated in 2005 with only minor changes to the technology, mostly related to software.

3.4.3 Operating Parameters for the Technology

Kaho’olawe

The 48cm-radius GEM-3 sensor disk configuration mounted on two-wheeled pushcarts was used for all areas at Kaho’olawe. Ten frequencies were recorded simultaneously—90, 150, 390, 750, 1,470, 2,970, 5,910, 11,910, 23,850, and 47,970 Hz, sampled over 1/15 s at 15 Hz repetition (i.e., continuous). The carts were pushed at typical walking speeds, with the disk approximately 20cm above the ground, along survey lines spaced 0.5m apart. Two systems were operated simultaneously during most of the survey, with a minimum 30m separation to avoid interference. Each 30m x 30m grid was surveyed between data downloads (initially two areas were surveyed at a time), with about 10 minutes time required to download data and change batteries between areas.

APG

Ten frequencies were recorded simultaneously—90, 210, 390, 750, 1,470, 2,910, 5,850, 11,430, 21,690, and 41,010 Hz, for all sensors; the motivation for the adjustment from Kaho’olawe was to back off from the upper limit of the system where the system response begins to roll off and to replace 150 Hz with 210 Hz where it is expected to have less cart-bounce induced noise (90 Hz is retained for potential discrimination value). The 96cm sensor recorded continuously 15 Hz samples (each integrated over 66.7 ms), whereas the handheld operated at 5 Hz continuous sampling (200 ms sample duration). The wheeled-cart mounted disk was about 30cm above ground, the ATV towed sled at about 12cm, and the handheld was operated 3-7cm depending on snow, vegetation, water, etc. Two handheld sensors were operated simultaneously during both the moguls surveys (over snow, December 2002) and wooded area survey (water-covered terrain, April 2003), with a minimum sensor separation of 20m to avoid interference. We operated the wheeled cart configuration and the ATV towed configuration simultaneously, with 30m separation required, and also while the wooded area was being surveyed. Nominal line spacing was 0.5m for the large-disk surveys, and for the handheld, sweeps were made such that most of the area was covered by the 40cm-diameter disk.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Table 2. Expected Performance and Confirmation Methods.

Performance Criteria	Expected	Confirmation Method	Actual
Kaho'olawe			
Response Stage (1) Probability of detection (2) Probability of false alarms (3) Background alarms	(1) > .90 (2) > 90% of total metal targets – UXO (3) < .025/m^2	Government evaluation	(1) .43 (2) .43 (3) 547/19800m^2 = .0276/m^2
Discrimination Stage (1) Probability of detection (2) Probability of false alarms (3) Background alarms (4) Efficiency (5) Rejection ratio	(1) > 80% (2) < .2 (< 20% clutter declared UXO) (3) < .01/m^2 (4) .9 (5) > 0.5	Government evaluation	(1) .40 (2) .39 (3) 496/19800m^2 = .025/m^2 (4) .94 (5) .07
APG Blind Grid—Handheld Configuration			
Response Stage (1) Probability of detection (2) Probability of false alarms (3) Probability of background alarms	(1) > 95% (2) > 90% of total metal targets – UXO (3) < .01	Government evaluation	(1) .80 (2) .85 (3) .30
Discrimination Stage (1) Probability of detection (2) Probability of false alarms (3) Probability of 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) .60 (2) .50 (3) .15 (4) .76 (5) .40
APG Blind Grid—96cm-Disk, Pushcart Mounted Configuration			
Response Stage (1) Probability of detection (2) Probability of false alarms (3) Probability of background alarms	(1) > 95% (2) > 95% of total metal targets – UXO (3) < .01	Government evaluation	(1) .85 (2) .85 (3) .40
Discrimination Stage (1) Probability of detection (2) Probability of false alarms (3) Probability of 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) .70 (2) .70 (3) .35 (4) .82 (5) .19
APG Blind Grid—96cm-Disk, ATV Vehicle Towed Configuration			
Response Stage (1) Probability of detection (2) Probability of false alarms (3) Probability of background alarms	(1) > 90% (2) > 90% of total metal targets – UXO (3) < .01	Government evaluation	(1) .30 (2) .40 (3) 0.0

Table 2. Expected Performance and Confirmation Methods (*continued*).

Performance Criteria	Expected	Confirmation Method	Actual
Discrimination Stage			
(1) Probability of detection	(1) > 80%	Government evaluation	(1) .20
(2) Probability of false alarms	(2) < .2 (< 20% clutter declared UXO)		(2) .30
(3) Probability of background alarms	(3) < .01		(3) 0.0
(4) Efficiency	(4) 0.9		(4) .71
(5) Rejection ratio	(5) > 0.5		(5) .22
APG Moguls Area—Handheld Configuration			
Response Stage			
(1) Probability of detection	(1) > 90%	Government evaluation	(1) .15
(2) Probability of false alarms	(2) > 90% of total metal targets – UXO		(2) .15
(3) Background alarms	(3) < .01/m^2		(3) .15
Discrimination Stage			
(1) Probability of detection	(1) > 80%	Government evaluation	(1) .00
(2) Probability of false alarms	(2) < .2 (< 20% clutter declared UXO)		(2) .00
(3) Background alarms	(3) < .01/m^2		(3) .05
(4) Efficiency	(4) 0.9		(4) .04
(5) Rejection ratio	(5) > 0.5		(5) .87
APG Woods Area—Handheld Configuration			
Response Stage			
(1) Probability of detection	(1) > 90%	Government evaluation	(1) .25
(2) Probability of false alarms	(2) > 90% of total metal targets – UXO		(2) .20
(3) Background alarms	(3) < .01/m^2		(3) .05
Discrimination Stage			
(1) Probability of detection	(1) > 80%	Government evaluation	(1) .20
(2) Probability of false alarms	(2) < .2 (< 20% clutter declared UXO)		(2) .10
(3) Background alarms	(3) < .01/m^2		(3) .05
(4) Efficiency	(4) 0.9		(4) .74
(5) Rejection ratio	(5) > 0.5		(5) .45
APG Open Field Area—96cm-Disk, Pushcart and ATV Towed Configurations			
Response Stage			
(1) Probability of detection	(1) > 90%	Government evaluation	(1) .35
(2) Probability of false alarms	(2) > 90% of total metal targets – UXO		(2) .30
(3) Background alarms	(3) < .01/m^2		(3) .05
Discrimination Stage			
(1) Probability of detection	(1) > 80%	Government evaluation	(1) .25
(2) Probability of false alarms	(2) < .2 (< 20% clutter declared UXO)		(2) .15
(3) Background alarms	(3) < .01/m^2		(3) 0.0
(4) Efficiency	(4) 0.9		(4) .68
(5) Rejection ratio	(5) > 0.5		(5) .44
APG—All Areas/Configurations, 2003			
Reliability	No downtime	Government log	Minor repairs
Maintenance	Battery charging	Government log	~4/day
Ease of use	Minimal training	Operator	Minimal training
Factors affecting performance	Some sensitivity to soil susceptibility and conductivity and target depth	Theory	
Versatility	Other metal detection	Other programs	Underwater UXO

Table 2. Expected Performance and Confirmation Methods (*continued*).

Performance Criteria	Expected	Confirmation Method	Actual
APG Blind Grid – Hand Held Configuration, 2005 repeat			
Response Stage (1) Probability of detection (2) Probability of false alarms (3) Probability of background alarms	(1) > 95% (2) > 90% of total metal targets – UXO (3) < .01	Government evaluation	(1) .80 (2) .85 (3) .05
Discrimination Stage (1) Probability of detection (2) Probability of false alarms (3) Probability of 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) .50 (3) .05 (4) .67 (5) .41
APG Moguls – Hand Held Configuration, 2005 repeat			
Response Stage (1) Probability of detection (2) Probability of false alarms (3) Background alarms	(1) > 95% (2) > 90% of total metal targets – UXO (3) $< .01/m^2$	Government evaluation	(1) .70 (2) .65 (3) 3.0
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) $< .01/m^2$ (4) 0.9 (5) > 0.5	Government evaluation	(1) .50 (2) .40 (3) 1.45 (4) .76 (5) .39

The tables above describe performance at the design thresholds (for response stage target and discrimination stage clutter) chosen by the demonstrator. In order to describe the performance potential over a range of thresholds, receiver operator characteristics (ROC) curves generated by the government are reproduced in the appendix of the Final Report.

4.2 PERFORMANCE CRITERIA

The performance criteria for the assessment of the technology under demonstration are described in Table 3.

Table 3. Performance Criteria.

Performance Criteria	Description	Primary Or Secondary
Probability of detection	# UXO detected / # UXO buried	Primary
False alarm rate	# anomalies not ordnance/m^2	
Reliability	Downtime	
Maintenance	Frequency, required training	
Ease of use	Operator productivity	
Factors affecting performance	Operating conditions affecting performance	
Versatility	Other potential applications	Secondary

4.3 DATA ASSESSMENT

During "sweep-search" mode, real-time detection and target identification were performed, with a goodness-of-fit (i.e., mean absolute error) reported for confidence ranking and clutter classification (discrimination stage). The response stage was indicated by the operator based on audio indication of amplitude. The results were manually logged for generation of dig lists after georeferencing the targets with DGPS. Data immediately over the target, with background removed, were recorded by the iPAQ™, and subsequent reprocessing of the recorded data was an option.

Following postprocessing survey data with target-picking and discrimination algorithms, prioritized dig sheets were submitted. These dig lists include (1) Grid square identification for the blind grid and UTM coordinates for the other areas, (2) Response Stage - detection signal level (i.e., the output above background of the selected detection algorithm, e.g. quadrature sum), (3) Discrimination Stage Ranking – a numerical ranking of likelihood that target UXO, (4) Classification – Empty, Clutter, or Ordnance Type – identify if ordnance, Depth, Azimuth, and Dip. The last two items may not be an output of the discrimination algorithm used.

4.3.1 Performance

Kaho'olawe

A detailed self-evaluation of the Kaho'olawe demonstration performance was submitted to the ESTCP in January 2003; a summary of key points follows.

Of 148 ordnance items not designated non-grade, 91 were detected and declared ordnance with varying confidence, but 26 of those were outside the 0.5m allowed position error radius (but within 1.0m); there was no data (i.e., an obstacle blocking the cart or surveying error) over seven items. Of the 50 ordnance items completely missed and data were available, 14 were 20mm and 11 were 40mm items (only 3 of the 20mm were detected, and 7 of the 40mm), indicating that the small items were problematic at Kaho'olawe.

Of ordnance declared non-grade (not defined in ground-truth tables but assumed to mean ordnance with missing parts but identifiable), 21 were detected and four missed. None of the ordnance (including non-grade) was classified as clutter. Of 158 seeded fragments, 67 were detected, five of which were classified as clutter. At Kaho'olawe, our ordnance/clutter threshold was excessively conservative and we thus classified most metal objects as ordnance.

There were a large number of picked targets (547) that did not correspond to seeded or known metal objects, and of these 496 were classified as ordnance, resulting in a very large false background score. However, there were a number of instances where multiple demonstrators identified the same target, and when followed up with a ground search, a metal object was usually found. Ground follow-up was undertaken only if at least four demonstrators had coinciding targets. We were convinced that a large fraction of our false backgrounds were caused by metal objects because many were associated with high s/n spectra clearly characteristic of metal (strong quadrature peak below 10 kHz).

Although Kaho'olawe poses a difficult geologic environment, the extreme magnetic geology was not the most important factor in our results. There was no correlation between the level of background susceptibility (which varied significantly) and our performance, and very few features in the processed detection channel obscuring anomalies that could be correlated to magnetic susceptibility.

On the other hand, we found that the low-frequency data (90 Hz and 150 Hz) that are particularly valuable for metallic targets were corrupted by platform motion, which we have since identified as angular motion of the receiver coil in the earth's magnetic field as the cart is rolled over rough ground. We also had navigation errors, both in terms of locating the target within the 0.5-m-halo, and in terms of the operator maintaining the 0.5m-line spacing. The latter impacts our ability to find small targets (20mm and 40mm) because line gaps ~0.8m were not uncommon; also, positioning targets from anomalies centered within these gaps is subject to greater error.

APG

The performance shown in the tables did not meet expectations, particularly for the PD with the handheld system in the moguls and woods. We believe that a systematic problem with locating the target flags resulted in reported position coordinates outside the 0.5m allowed halo; verbal feedback from ATC indicated that a 2- to 3-foot shift in all target positions in the mogul area increased the PD to about 0.4, still below expectations but more reasonable. A problem with the differential corrections may have occurred and may not have been exactly the same over the duration of the survey (so that one simple shift of all targets would not achieve the true sensor PD). These are speculative explanations, and only repeat experiments can ascertain the GEM-3 performance. Preliminary results from a repeat survey performed in 2005 over the mogul area achieved a .7 response stage PD.

The performance of the ATV towed system also was well below expectations. This may be attributed to a combination of positioning errors and data quality issues associated with a sensor towed at ~5 mph along unmarked traverses (some gaps in coverage were evident on the anomaly maps). The nominal 0.5m line spacing is difficult to maintain, and improvements in operator queued navigation is needed. Motion-induced noise is also greater in the towed configuration.

Discrimination, based on a simple single-point (spatial) matching algorithm, has not proved to reduce FAR while maintaining PD except at very low thresholds with associated low PD. The best discrimination performance occurred with handheld and pushcart configurations in the blind grid, where data were collected statically over the target. Survey (ATV-towed) mode degrades the discrimination performance, and the handheld in moguls and woods had a systemic problem with target detection/location that rendered discrimination performance invalid.

4.4 TECHNOLOGY COMPARISON

No performance data for other technology demonstrators are available.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Cost reporting consists of tracking production rates for each scenario, mobilization, and setup hours, including hours of training over calibration lanes. An itemized cost estimate for the demonstration, produced by ATC based on observer logs, is provided in Table 4. Costs for the various scenarios of the demonstration were combined.

Table 4. Demonstration Costs.

Equipment Costs (rental - variable)				
Item	**No.**	**Rate/Week ($)**	**Weeks**	**Cost ($)**
Handheld GEM	2	500	2	2,000.00
Towed GEM	1	750	1.5	1,075.00
DGPS	2	500	2	2,000.00
ATV	1	300	1.5	450.00
Subtotal				**$5,525.00**
	No. People	**Hourly Wage**	**Hours**	**Cost**
Initial Setup (Fixed)				
Supervisor	1	95.00	8.5	807.50
Data analyst	1	57.00	8.5	484.50
Field support	1	28.50	8.5	242.25
Subtotal				**$1,534.25**
Calibration (Variable)				
Supervisor	1	95.00	10.1	959.50
Data analyst	1	57.00	10.1	575.70
Field support	1	28.50	10.1	287.85
Subtotal				**$1,823.05**
Site Survey (Variable)				
Supervisor	1	95.00	100	9,500.00
Data analyst	1	57.00	100	5,700.00
Field support	5	28.50	100	14,250.00
Subtotal				**$29,450.00**
Demobilization (Fixed)				
Supervisor	1	95.00	1.28	121.60
Data analyst	1	57.00	1.28	72.96
Field support	1	28.50	1.28	36.48
Subtotal				**$231.04**
Total				**$38,563.34**

5.2 COST ANALYSIS

The demonstration costs shown in Table 4 are used to estimate production costs for an operational mission. Anticipated costs of GEM-3 system and support equipment for purchase and or rental will be estimated.

Initial setup, calibration, demobilization, and equipment are based on the premise that both hand-held and towed systems are used, i.e., the mission includes mixed conditions requiring use of both configurations.

Table 5. Operational Costs Estimate.

Initial setup	Mobilization	$1,500
	GEM-3 target training	$1,800
Site survey	Data acquisition	$1,500/hectare
	Data analysis	$500/hectare
Demobilization		$800
Equipment rental	4 handheld + towed GEMs	$4,000/wk

5.3 COST COMPARISON

Costs for conventional technologies for this site are not known. It is likely that in practice costs of conventional technologies would be similar—mag and flag less in the moguls and woods but more in the open area. The handheld GEM-3 operates similarly to any conventional handheld technology during the search-and-detect time, but requires 2 seconds of static data collection to acquire discrimination spectra, and sometimes requires a background reading as well. The cart-mounted GEM-3 operates similarly to an EM-61, requiring a half-meter line spacing and surveying at a normal walking speed; the ATV towed version is similar. The added cost of discrimination processing is small (done in real-time for the handheld and automated batch mode for the cart/sled configuration).

The savings is realized when false alarms have been reduced resulting in fewer unnecessary follow-up digs, typically costing $200/target. As yet, the reduced false alarms have not been demonstrated to a level that would eliminate a significant number of unnecessary digs.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Some problems with the equipment and logistics resulted in downtime and inefficiency that would be reduced with experience, since this was the first use of all the equipment except the wheeled-cart configuration. Refinement of field techniques and equipment will result in greater productivity. Some cost-driving issues were site specific—the moguls and woods areas have a high density of targets (more than 800 in the moguls, more than 400 in the woods) and are difficult to survey because of the respective “challenge” scenario characteristics of those sites. In addition to the rugged terrain of the moguls, we performed the survey during winter when they were covered with snow, ice, and slushy water. The woods and large areas of the open area were water covered, sometimes more than 6 inches deep. The open area buffer zone was narrow and we were restricted from going outside that area, which posed some survey maneuvering difficulties. We found that the large volumes of data from the open area were difficult to plot for on-site quality assurance/quality control (QA/QC). Some of these are simply challenges posed by the site, but some can be better handled after gaining experience.

6.2 PERFORMANCE OBSERVATIONS

The most glaring performance observation was the poor correlation between flagged targets in the moguls and locations of seeded targets, and, to a lesser extent, in the woods. We believe we had a problem surveying the DGPS positions of the flags, possibly with a base station error. We checked grid corners with provided coordinates, but evidently it did not show the problem (note that the mogul area was done at a different time than the other areas). The problem in the woods may have simply been normal degradation of DGPS with satellite signal interference from trees. (DGPS is still functional, but conversation with others who have worked there gave reports of only ~1m accuracy.) Some navigation issues with the ATV configuration resulted in a small percentage of the area missed—improvement in this regard should be achievable.

The most apparent deficiency with the GEM sensors in the context of this site is the inability to detect many of the deep targets; this was observed in the calibration grid where ground truth was known. The depth limitation scales with the target size, so the medium and large targets buried the greatest gave no discernable response. We feel these depths are likely not realistic or representative of typical depth distributions, but it would be useful if some statistical data from actual cleared sites were readily available to clarify what depth objective we should anticipate.

Finally, the target density in the moguls and woods is extreme—discrimination of individual objects is probably not practical, and a real site would need to be completely excavated down to a foot or so and then surveyed for remaining residual items.

6.3 SCALE-UP

The demonstration scale was large enough to provide a reasonable estimate for full-scale applications. Some increased efficiency will be expected with regard to startup and demobilization costs, as well as improved field procedures attained from learning a site. Some increased costs could result for more remote areas from logistical costs.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Some usability issues were observed, such as a need for more field-worthy iPAQ™ connectors (ruggedized versions exist at greater cost), and there is room for improvements in the sensor platforms. (The wheeled cart and the ATV towed sled which did not last the survey due to abrasion.) These are refinements that will be driven by user demand and/or continued Geophex use.

6.5 LESSONS LEARNED

We need to ensure georeferencing accuracy with more rigorous verification. We will improve our towed platforms and ATV navigation aids.

6.6 END-USER ISSUES

The end user must understand the depth of detection limit for the potential UXO at a given site and the detection depth requirements for that site (e.g., a 155mm target cannot be detected at 2m depth). Discrimination stage performance depends on the suite of potential UXO, clutter characteristics, and target depths; we have been significantly more successful during laboratory testing with a more limited set of UXO and clutter items and depths limited to provide high s/n than we have been at APG.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The only regulatory compliance issues relate to site access and DGPS base station radio frequencies used. Acceptance may require a definitive performance demonstration at a level that achieves the stated goals. The regulatory acceptance issues for the technology pertain to the intended depth to be cleared of UXO and the depth to which UXO can be detected, and whether a significant portion of clutter can be reliably classified as such without reduction in UXO PD, which must be demonstrated at each site with a statistical sample of verification digs.

7.0 REFERENCES

Demonstration Plan for the Handheld Broadband Electromagnetic UXO Sensor (ESTCP project 200036), submitted by Geophex, Ltd., November 2002.

Final Report for the Handheld Broadband Electromagnetic UXO Sensor (ESTCP project 200036), submitted by Geophex, Ltd., March 2005.

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, 2001a, *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, 2001b, *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.

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APPENDIX A
POINTS OF CONTACT

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