ESTCP
Cost and Performance Report

(UX-0208)

Combined Electromagnetic and Magnetometer Data Acquisition and Processing

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ACRONYMS AND ABBREVIATIONS

APG	Aberdeen Proving Grounds
ATC	Aberdeen Test Center
CEHNC	Corps of Engineers - Huntsville Center
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CRADA	Cooperative Research and Development Agreement
DAS	data analysis system
DoD	Department of Defense
EE/CA	Engineering Evaluation/Cost Analysis
EM	electromagnetic
EOD	explosive ordnance disposal
ERDC	Engineering Research and Development Center
ESTCP	Environmental Security Technology Certification Program
GPS	global positioning system
HTRW	hazardous, toxic, and radioactive waste
JPG	Jefferson Proving Grounds
MPC	magnetometer period counter
ms	millisecond
MTADS	multisensor towed array detection system
NAVEODTECHCEN	Naval Explosive Ordnance Technology Center
NRL	Naval Research Laboratory
OSHA	Occupational Safety and Health Administration
PI	Principal Investigator
PPS	pulse per second
ROM	rough order of magnitude
SAM	Sub Audio Magnetic
STOLS	surface towed ordnance location system
UBC	University of British Columbia
USAEC	U.S. Army Environmental Center
UXO	unexploded ordnance

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

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

In unexploded ordnance (UXO) detection demonstrations at Jefferson Proving Ground (JPG) and other places, active electromagnetic induction (EM) technology and magnetometry have consistently demonstrated the best UXO detection capabilities. Clearly, UXO site characterization is normally best accomplished using both EM and magnetometry, as each technology brings a complementary detection and discrimination capability; magnetometers typically perform better for large, deep ferrous objects, and EM sensors such as the Geonics EM61 typically perform better for small, shallow objects of all metals. However, simultaneous deployment of these two technologies on a single platform is difficult due to the active nature of electromagnetic induction technology, which generates noise that is picked up by magnetometers operated at close proximity. As economics often restrict site characterization technology to only one survey, this constraint leads most often to the down-selection and use of only one technology. Occasionally, sequential surveys with different sensors are employed but with attendant higher survey costs and added safety/risk exposures. Thus, for reasons of performance, economy, and safety, a single-platform magnetometer and EM61 solution would be widely used, if it existed.

Under this project, GEO-CENTERS and the U.S. Army Corps of Engineers developed and demonstrated a proof-of-concept synchronized data acquisition and processing system that allows simultaneous deployment of both EM61 and magnetometer sensors on a single vehicular-towed platform. New sampling electronics were designed and developed that interleave the magnetometer and the EM61 data, sampling the magnetometers only after the EM61 pulse has diminished, thereby eliminating EM61-induced noise on the magnetometers. This allows, for the first time, magnetometers and EM61 coils to be colocated on a single towed platform. GEO-CENTERS' existing vehicular towed array was employed as a development system; the vehicle, magnetometers, centimeter-level global positioning system (GPS) navigation, and data processing capabilities were all reused. A new nonmetallic proof-of-concept towed sensor platform was developed to host the magnetometers and EM61 sensors in a very low-noise environment. Corrected data are written out in a Geosoft Montaj-compatible format. Although the scope of the project did not extend to development of new discrimination algorithms, the spatially coregistered data can be made available to algorithm developers.

1.2 OBJECTIVES OF THE DEMONSTRATION

The demonstration objective was validation of the synchronous interleaved magnetometer and EM61 technology in a real-world environment where noise can be engendered in vehicular systems by motion induced by rough terrain. This included simultaneously acquiring magnetometer and EM61 data in a single survey pass, verifying that the magnetometer and EM61 data were of high quality and demonstrating that a high detection rate could be achieved by combining the data sets. Note that discrimination was not an objective as it was not part of the funded scope of the project. The demonstration environment was the Standardized UXO Technology Demonstration Test Site at Aberdeen Proving Grounds (APG)—a vehicularly navigable though extremely rugged 13-acre former impact area containing emplaced ordnance

items. The system was deployed at APG the week of October 10th, 2002, and surveyed the Calibration Test Grid, the Blind Test Grid, and Open Field. Data over the 13-acre Open Field was acquired in roughly a day and a half. In January 2004, the Aberdeen Test Center (ATC) released the scores in the printed report "Standardized UXO Technology Demonstration Site Blind Grid Scoring Record No. 40[7]." In August 2004, ATC released "Standardized UXO Technology Demonstration Site Open Field Scoring Record No. 187[8]." The APG demonstration proved that the system acquires high-quality magnetometer and EM61 data can be acquired in a single survey pass, roughly halving the time to acquire magnetometer and EM61 data in separate survey passes.

1.3 REGULATORY DRIVERS

Many OE projects are performed as Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) response actions. As such, a variety of local, state, and federal regulators participate in the development of project performance standards. Currently there are no numerical standards for detection rates, false alarm rates, etc., but DoD and regulators continue to press for technology improvements, and the multisensor system represents such a step. Note that the two sensors used—total field cesium vapor magnetometers and Geonics EM61 pulsed induction coils and electronics—are widely used within the industry and well-accepted by the geophysical and regulatory community.

1.4 DEMONSTRATION RESULTS

The system functions as designed. The APG demonstration proved that the system acquires high-quality magnetometer and EM61 data can be acquired in a single survey pass, roughly halving the time to acquire magnetometer and EM61 data in separate survey passes. In addition, the system has since been successfully deployed at high-visibility operations at The Former Lowry Bombing and Gunnery Range in Aurora, Colorado.

1.5 STAKEHOLDER/END-USER ISSUES

A successful multisensor towed array system represents a new tool in the OE detection toolbox. Its use would be determined on a project-by-project basis. Such a determination would be made by considering project objectives such as the type of munitions present and the desired depth of detection, the physical nature of the site including size, vegetation and terrain, cost, and availability. However, this system is expected to be very competitive from both a data quality perspective and cost perspective for large, relatively open sites, and there are no known stakeholder or end-user issues that would limit its use.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The simultaneous magnetometer and EM61 towed array developed on this project substantially leveraged GEO-CENTERS' existing surface towed ordnance location system (STOLS) GPS-integrated towed magnetometer array as a development platform and augmented it with newly designed interleaving hardware, a new nonmetallic towed platform and existing EM61 electronics and coils.

2.1.1 Technology Background and Technology Development

As a contractor to the Naval Research Laboratory (NRL) and the Naval Explosive Ordnance Technology Center (NAVEODTECHCEN) in the 1980s, GEO-CENTERS developed a proof-of-concept prototype version of STOLS that used seven total field cesium vapor magnetometers, a small skid-steered tow vehicle, an aluminum towed platform with no suspension, a microwave navigation system, custom data processing software, and a nonlinear least squares curve fit to a model of a point dipole with adjustable angular parameters. The system was among the first to perform what is now known as digital geophysical mapping. The project was technically successful but the proof-of-concept system was not robust and required frequent repairs. It was delivered to NAVEODTECHCEN in 1991. GEO-CENTERS continued development of the data processing software, porting it to a standard Unix platform, and providing it free of charge to NRL as the starting point for their Multisensor Towed Array Detection System (MTADS) data analysis system (DAS) software.

In 1993, leveraging the lessons learned from developing the prototype STOLS, GEO-CENTERS spent nearly $4 million of internal R&D dollars to develop the second generation commercial STOLS (Figure 1). With a rugged low magnetic self-signature tow vehicle and towed aluminum platform with suspension, GPS positioning, and upgraded hardware and software, the commercial STOLS towed magnetometer array successfully surveyed more than 100 government and commercial UXO and hazardous, toxic, and radioactive waste (HTRW) sites during the next 7 years.

Figure 1. GEO-CENTERS' Commercial STOLS as First Deployed in 1993.

During this period, GEO-CENTERS remained a contractor to NRL and developed the vehicle and towed sensor platforms for MTADS. The MTADS towed magnetometer platform was virtually identical to GEO-CENTERS', with the addition of extra sensor mounts to allow the magnetometers to be spaced ¼ meter apart. The MTADS vehicle was improved over the STOLS vehicle; the passenger cabin was better protected from the elements. The towed EM61 platform was a new design specifically for MTADS; STOLS had no towed EM61 capability at that time. Note that the magnetometer and EM MTADS survey platforms must be deployed one at a time on successive surveys, since MTADS is not a concurrent multisensor system.

In 1996, GEO-CENTERS deployed the STOLS towed magnetometer array, augmented with a front-mounted array of three ½-meter EM61 coils at JPG3 and was the first demonstrator to detect 100% of emplaced ordnance at a JPG scenario. Data from the demonstration verified that the magnetometers and the EM61 coils detected different objects. Although this multisensor system did deploy magnetometer and EM61 arrays concurrently, they were not synchronized, and the front-mounted coils (resulting from the 32-foot sensor-to-sensor separation needed to render the EM61-induced noise on the magnetometers to an acceptable level) made the system very ungainly to drive. As such, the system was impractical for real-world surveys.

This Environmental Security Technology Certification Program (ESTCP) project for concurrent synchronous multisensor data acquisition was possible under the funding constraints due to the availability of STOLS as a development platform. STOLS was "reversibly cannibalized," donating its low magnetic signature vehicle, total field magnetometers, GPS, EM61 electronics and ½ × ½-meter coils, wiring harnesses, and data processing infrastructure. Further, the fact that GEO-CENTERS had previously designed its own magnetometer period counter (MPC) board was absolutely central to the success of the project. The design of the existing interface needed to be modified to perform the synchronous interleaving of magnetometer data between EM61 pulses, but this was far easier than designing an entirely new period counter board from scratch.

2.1.2 Intended Use

The primary application is in detection of unexploded ordnance on impact ranges and training ranges, but the technology is also applicable to detection of HTRW in metal drums, underground storage tanks, and other metallic subsurface entities.

2.1.3 Target Types of UXO

Total field magnetometers are highly effective against medium-to-large objects at fairly substantial depths. EM61s are highly effective against small-to-medium objects at shallow-to-moderate depths. Together, total field magnetometers and EM61s are thought to be effective against all metal-cased UXO to their maximum natural depth of penetration (which is, according to the Corps of Engineers - Huntsville Center (CEHNC), 11 times the diameter).

2.1.4 Environmental Conditions

The simultaneous multisensor STOLS is a GPS-integrated vehicular-towed array. As such, the system can be deployed in areas that are traversable by an off-road vehicle and with a clear view of the sky. The system has been used in both summer and winter but has not been tested in arctic or desert temperature extremes. The magnetometers are susceptible to volcanic and other geology containing magnetite or other ferromagnetic material. The EM61 sensors are less geologically susceptible but also have difficulty in highly conductive soils.

2.1.5 Theory of Operation

2.1.5.1 <u>Interference Between EM61 and Magnetometers</u>

Historically, simultaneous deployment of magnetometers and pulsed EM such as the Geonics EM61 on a common platform has not been possible because the EM transmission pulse is asynchronous with the magnetometer sampling and is picked up by the magnetometers as noise. Figure 2 shows the EM61-engendered noise on the magnetometers as a function of sensor-to-sensor separation. This was measured using STOLS' magnetometer data acquisition system and placing an array of three EM61 ½-meter coils at distances behind the magnetometers. Note that even at 10 feet—a practical separation distance for sensor colocation on a common towed platform—the EM61-induced noise is more than 100 gammas.

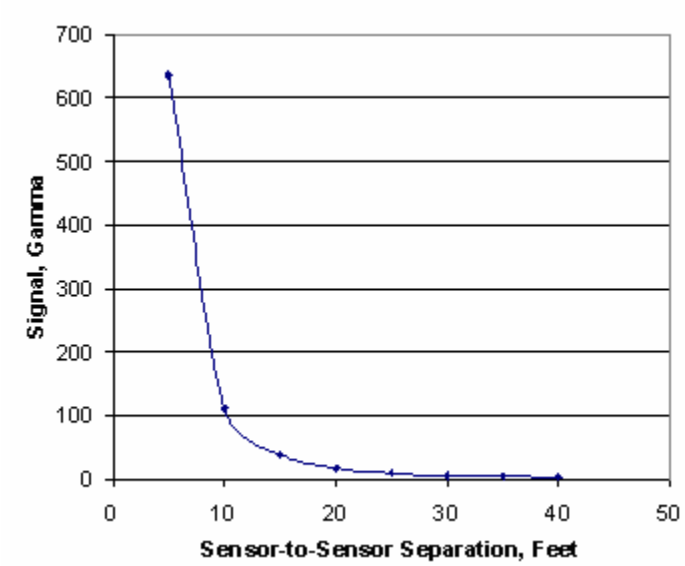

Figure 2. Noise Induced on Magnetometers by Asynchronous EM61 Transmission Pulse as a Function of Sensor-to-Sensor Separation.

2.1.5.2 <u>Interleaving Magnetometer and EM61 Data Acquisition</u>

The newly developed MPC board is designed to interleave the magnetometer and EM61 data acquisition cycles as follows. The MPC circuitry looks for the 1 pulse per second (PPS) from the GPS, then looks for the rising edge of the next EM61 transmission pulse. The system timing then

uses a programmable waiting period and a sampling period. The 75 Hz EM61 transmission pulse comes in every 13.3 millisecond (ms). The board waits 8 ms, at which point the EM61 transmission pulse has died off (this has been verified by direct measurement). The MPC board then samples the magnetometers for 5 ms, during the period in which the EM61s are not transmitting. In this way, the magnetometers are sampled only when the EM61s are quiet. The timing diagram for this interleaved synchronous data acquisition is shown in Figure 3. Note that in this new design, acquisition of magnetometer data is triggered by the receipt of a 75 Hz strobe from the EM61 electronics after the GPS' 1 PPS.

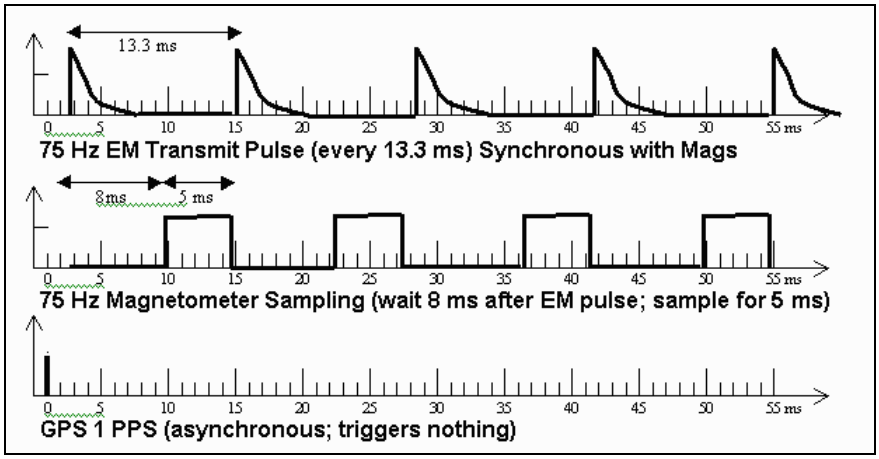

Figure 3. Timing Diagram of Synchronous EM61 and Magnetometer Data Acquisition.
(Note that magnetometer sampling occurs only when EM61 transmission pulse has died down.)

2.2 PROCESS DESCRIPTION

2.2.1 Mobilization, Installation, and Operational Requirements

The system is mobilized in a tractor/trailer owned by GEO-CENTERS. The towed platform and vehicle are backed out of the trailer and connected. EM61 coils are mounted on the platform and cables are connected to electronics. A GPS base station and reference magnetometer station are set up. The system is then driven over the survey area in the manner that most efficiently covers the survey area; grid-based surveying is not necessary.

2.2.2 Key Design Criteria

In addition to the interleaving electronics, the total system design that hosts both the magnetometers and the EM61s in a low-noise environment, resulting in a low-ferrous vehicle and a nonmetallic platform, is a key design factor.

2.2.3 Schematics, Figures, and Layout

The timing diagram for synchronous data acquisition is shown in Figure 3. The system, showing the low-ferrous vehicle, nonmetallic platform, magnetometer array, and EM61 array, is shown in Figure 4.

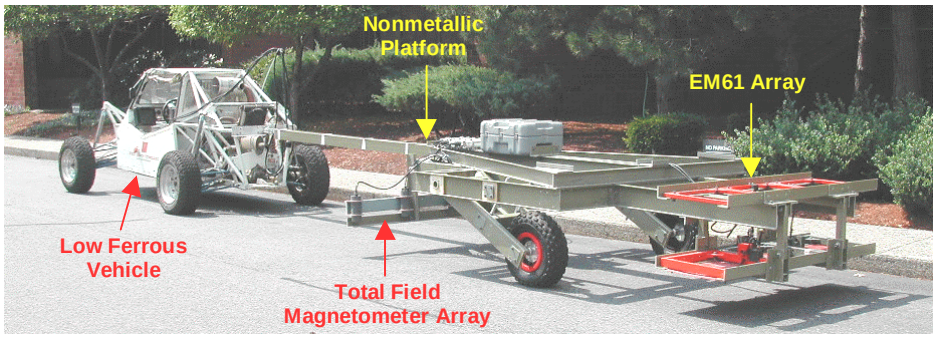

Figure 4. Simultaneous Multisensor STOLS.

2.2.4 Performance

In the test at APG, the system successfully surveyed 13 acres in a day and a half. In subsequent commercial and Department of Defense (DoD)-sponsored survey work, the system has had peak survey rates of nearly 20 acres per day and has achieved average survey rates of nearly 15 acres per day. Performance for probability of detection and false alarms on the Open Site and Blind Grid at APG is summarized in Table 1 and Table 2.

2.2.5 Personnel Training Requirements, Ease of Operation, and Health and Safety Requirements

To date, the system has been operated by the scientists and engineers who invented it. Note that this cannot be regarded in a vacuum; the wisdom of "taking the experts out of the loop" is debated in UXO geophysics. However, with training, anyone familiar with GPS, magnetometry, and EM61 operation could be trained to acquire high-quality data with the system. There are no specific health and safety requirements for operation of the system. The sites surveyed, however, typically require Occupational Safety and Health Administration (OSHA) certification.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Towed GPS-integrated magnetometer array technology has been proved out by both MTADS and GEO-CENTERS' STOLS and is well-documented in published reports from the multiyear exercises at Jefferson Proving Grounds. Prior to this ESTCP-funded project, no concurrent interleaved magnetometer/EM61 technology existed. In June 2001, in anticipation of the award this ESTCP project, CEHNC funded GEO-CENTERS to begin verifying the feasibility of the interleaved magnetometer/EM61 concept. This work is detailed in the Final Report.[5] No show-stoppers were identified, and project UX-0208 was awarded. In August 2001, GEO-CENTERS surveyed McKinley Test Range at Redstone Arsenal, Huntsville, with the newly-developed concurrent mag/EM system. Two plots of time series magnetometer data over an anomaly are shown in Figure 5 and Figure 6. Series 1 is the leftmost magnetometer, and Series 5 is the rightmost magnetometer. Figure 5 shows the time series plots from the five magnetometers with the EM61s switched completely off. Figure 6 shows the plots over the same object but when the EM61s were concurrently pulsing and the system was collecting EM data. From these time series plots, we can see that there is no discernable difference in the shape, amplitude, or

character of the magnetometer data whether or not the EM61s are pulsing. This provides the best validation that the interleaving hardware is functioning as designed; if it were not, hundreds of gammas of random noise would be visible in the data. The 15 Hz ring visible in the data is due to the 60 Hz hum from nearby power lines and is easily removed with smoothing or notch filtering. This work is detailed in the Final Report.

2.3.1 Advantages and Limitations of the Technology

The overriding advantage of the technology is the ability to collect both magnetometer and EM61 data concurrently in a single survey pass. MTADS, in both its NRL and Blackhawk-fielded configurations, has a separate towed magnetometer and towed EM61 platform, and thus would require two separate surveys to acquire both data sets. Further, the data from the simultaneous multisensor STOLS, because they are acquired on a common rigid sensor platform, are spatially coregistered, whereas data acquired in separate survey passes may not traverse the same objects in the same way, which may limit the efficacy of the data for discrimination algorithms. The main limitations of the technology as compared to MTADS are that the cross-track magnetometer spacing in MTADS is tighter than STOLS (¼ meter versus ½ meter). The EM61 electronics in MTADS have had the transmit moment increased, and the coils are larger than those used in STOLS (1 meter versus ½ meter). The MTADS sensor platforms are instrumented to measure pitch and roll, and their data processing software uses these data to more accurately position sensor updates. However, note that these are limitations on the specific implementation of the technology as manifested in the current simultaneous multisensor STOLS. The core technology—interleaving acquisition of magnetometer data between EM61 pulses—does not have these limitations. The main limitation of the core interleaving technology is that it applies only to pulsed induction EM systems and is not applicable to frequency-domain EM systems. There are other competing technologies for concurrent magnetometry and EM, but as of this date, none use a commercial-off-the-shelf industry-standard EM61, and none are conducting real-world 100-acre surveys.

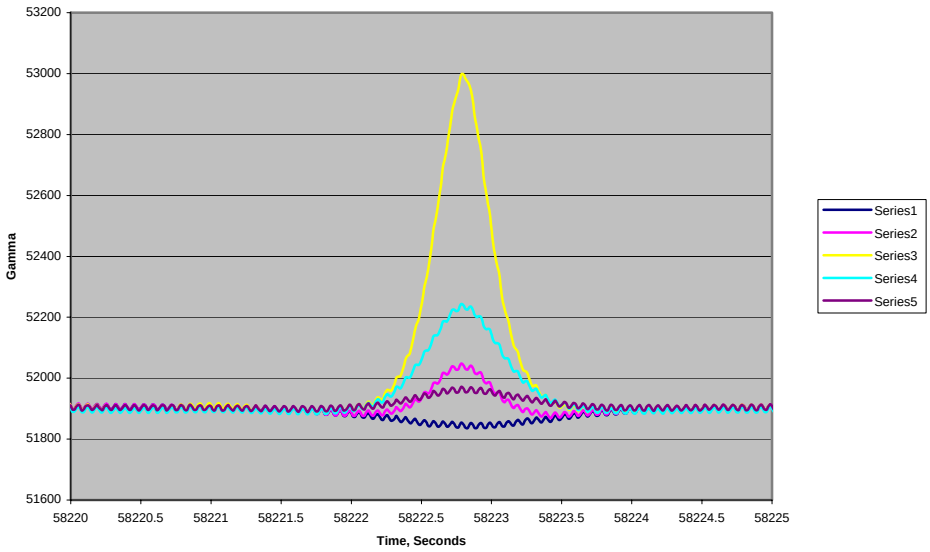

Figure 5. Magnetometer Data with EM61s Turned Off (Unsmoothed)**.**

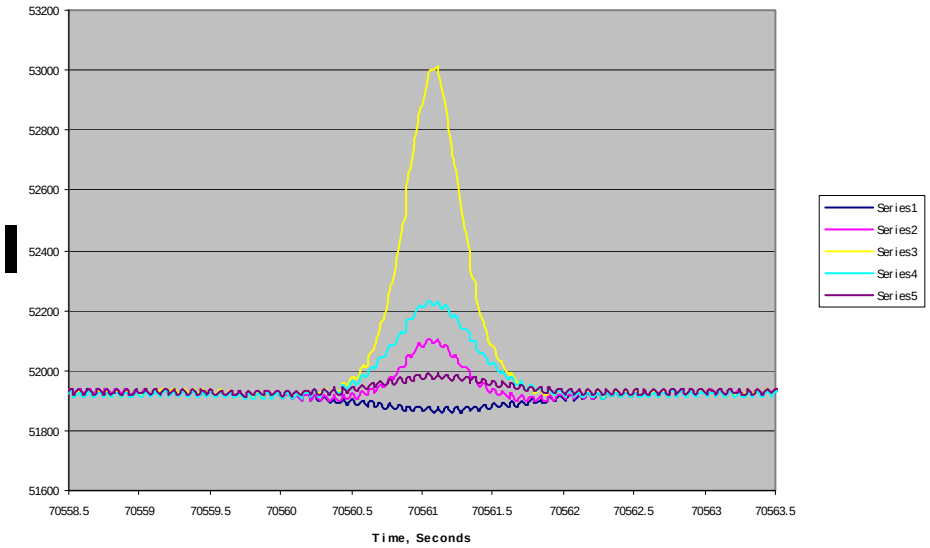

Figure 6. Magnetometer Data with EM61s Turned On (Unsmoothed)**.**

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The work plan for the demonstration listed the following performance objectives:

- To demonstrate the new multisensor STOLS' ability to acquire combined EM61 and magnetometer data in a single survey under controlled, but more realistic, field conditions
- To demonstrate the success of the project in terms of:
  - Faster multisensor survey time
  - Cheaper multisensor survey costs
  - Better (high-quality) synchronous, colocated magnetometer and EM61 data, which can be used for enhanced detection and discrimination algorithm development
- To identify design areas that would need improvement to robustly survive the rigors of sustained field work.

3.2 SELECTING THE TEST SITE

The following criteria were used for selecting a test site:

- Terrain hospitable to a vehicular towed array.
- Clear view of the sky hospitable to GPS.
- Accessible to all project participants within project budget (original plan called for Massachusetts Military Reservation, which is very close to GEO-CENTERS, but it was not available).
- A combination of a calibration area with known emplaced objects and a blind test area.

The selected test site was the Standardized UXO Technology Demonstration Test Site at Aberdeen Proving Grounds in Aberdeen, Maryland, which became available as the system was undergoing integration and testing.

3.3 TEST SITE HISTORY/CHARACTERISTICS

The Standardized UXO Technology Demonstration Test Site at Aberdeen Proving Grounds is operated and maintained by the U.S. Army Environmental Center (USAEC) with support from ATC and the U.S. Army Corps of Engineers Engineering Research and Development Center (ERDC). The Open Field Site is generally flat with a low area that is wet during a portion of the year, a power line area, and a section of gravel road, all of which provided technical challenges for the vehicularly towed multisensor STOLS. The site contains a Calibration Test Grid, a Blind Test Grid, and a mine lane, which were traversed along with the Open Field. The site also contains a wooded area and a mogul area, which were not surveyed.

3.4 PHYSICAL SETUP AND OPERATION

Because towed GPS-integrated magnetometry, EM61 surveys in general, and STOLS in particular have been validated at many test sites and because STOLS with front-mounted EM61s (simultaneous, noninterleaved) had been validated at JPG3, the experimental design centered around:

- Verifying that the quality of the magnetometer data were not compromised by the simultaneous acquisition of the EM61 data
- Verifying that the quality of the EM61 data were nominal.

As such, the main parameter that varied was collecting magnetometer data over the Calibration Test Grid while the EM61s were switched off versus collecting magnetometer data while the EM61s were switched on.

On Monday, October 7th, 2002, GEO-CENTERS' tractor-trailer truck arrived at the Standardized UXO Technology Demonstration Site at Aberdeen Proving Grounds with the multisensor STOLS equipment. Present were Rob Siegel, senior engineer, and Al Crandall, a geophysicist from USA Environmental. GEO-CENTERS' regular truck driver, Richard Kimball, was not present due to health problems, and a temporary truck driver was used. This is mentioned because Mr. Kimball, in addition to driving the truck, generally assists in general survey operations such as flagging survey lines to help the crew cover the site efficiently. Without Mr. Kimball, all survey operations were conducted by the two-person crew of Rob Siegel and Al Crandall.

The survey crew typically consists of two people, a vehicle operator and a data analyst. Although equipment setup and vehicle operation may be performed by a single person, it is typically performed by two people, with the data analyst setting up the GPS and the vehicle operator setting up the diurnal variation station and the vehicle systems. Although a two-person crew was sufficient for the Open Field, additional crew members are sometimes required for UXO or site safety reasons, or if vehicle traverses are not plainly visible and require "flaggers."

The vehicle driver planned the survey traverses to maximize area coverage and minimize time spent turning the vehicle around, while being mindful of location of the tree line and any cultural obstacles. Although the vehicle computer has track guidance software that allows an operator to follow preplanned survey traverses, this is rarely used, and instead the vehicle operator follows his visible survey tracks along the ground. Flags are employed to help the operator see the end of the last survey track to aid in positioning of the next survey track. This method was effectively used to traverse the Open Field. In fact, Mr. Siegel had to leave for a day to attend an ESTCP interim program review, and Mr. Crandall surveyed large sections of the Open Field himself (Rick Fling from ATC was on site at all times).

The data analyst typically QA/QCs data at lunchtime and again at the end of the day, and corrects and processes data in the evening. Sometimes the data analyst is stationed off site and data are sent to him via modem.

The multisensor STOLS was inspected, unpacked, assembled, and operated statically to verify that it was not damaged in transit. The GPS base station was set up on the corner farthest from the tree line (the southernmost corner), and the magnetometer reference station was set up in a magnetically clean area. The tractor/trailer that transports STOLS is equipped with two diesel generators to provide onboard electricity generation for on-site data processing and recharging of the batteries that power the tow vehicle's electrical systems, the GPS base station, and the reference magnetometer. The survey work was accomplished as follows:

Monday, 10/7/2002	Mobilize to the site and survey Calibration Test Grid with both magnetometers and EM61s operating simultaneously. QA/QC data.
Tuesday, 10/8/2002	Resurvey Calibration Test Grid with only magnetometers operating. Survey Blind Test Grid with both magnetometers and EM61s operating simultaneously. QA/QC data.
Wednesday, 10/9/2002	Resurvey Blind Test Grid with both magnetometers and EM61s operating simultaneously. Begin surveying Open Field with both magnetometers and EM61s operating simultaneously. QA/QC data.
Thursday, 10/10/2002	Complete surveying Open Field with both magnetometers and EM61s operating simultaneously. QA/QC data.
Friday, 10/11/2002	Final QA/QC. Pack and demobilize.

Magnetometer and EM61 data were immediately processed and imaged on site to judge data quality. The magnetometer data were of very high quality. The data from the EM61 system contained fixed offsets that generally did not change over the course of the survey and were able to be background-leveled using standard STOLS processing techniques.

The Open Field was vehicularly traversed in the manner in which STOLS and other towed arrays have historically been used for real-world surveys—not by laying out grids but by running parallel lines along the longest axis of the survey area to cover the survey area as completely as possible in the most time-efficient manner possible. A 1.5 meter lane spacing was used. This effectively put the innermost sensor ½ meter from the outermost sensor on the previous pass, emulating the ½-meter sensor spacing on the platform. Lane spacing was estimated by driving the vehicle in a pattern that overlapped the inner tire with the outer tire track on the previous pass. Vehicle traverses over the Open Field are displayed in Figure 7. Data collected in different files are displayed in different colors. These traverse data, along with interpolated image data, were used to judge that the data coverage was sufficient; only two small slivers of unsurveyed area are apparent.

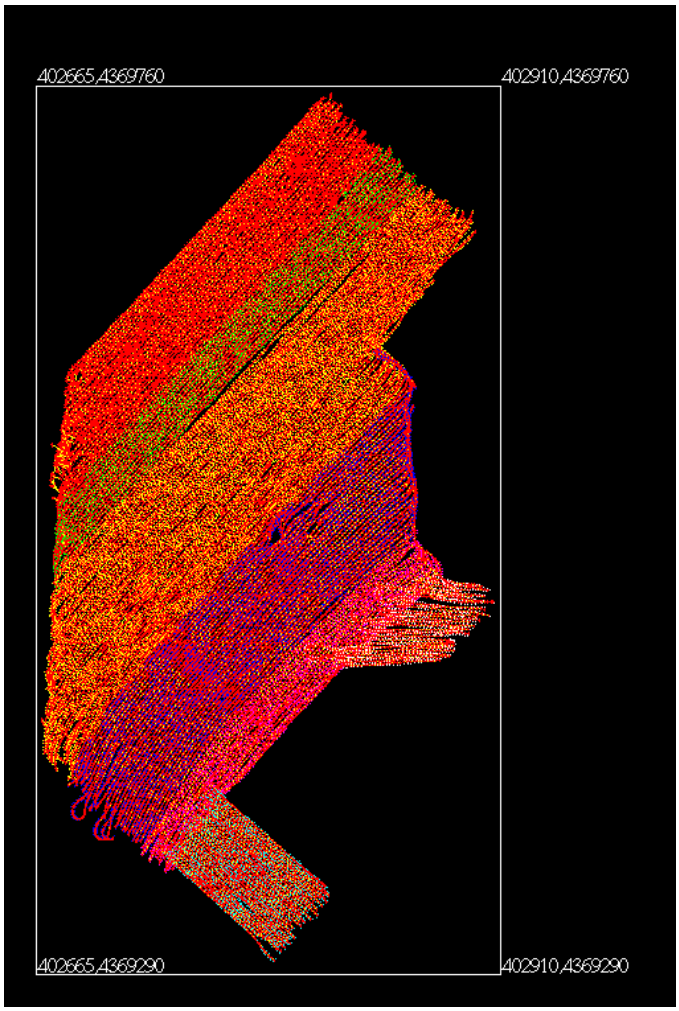

Figure 7. Traverses from the Simultaneous Multisensor STOLS over the Open Field.
(Survey lines oriented along the longest axis of the site were used to survey the site in the most efficient manner.)

3.5 ANALYTICAL PROCEDURES

As described in detail in the Final Report, all sensor data were navigation-corrected and background-leveled. In addition, magnetometer data were median-filtered to remove spurious values, smoothed to remove 60 Hz-induced noise subsampled with the 75 Hz sampling rate, reference-corrected, and directionally divided to optimize background leveling. EM61 data were navigation offset-corrected and dynamically background leveled.

A 25-meter quadrant's worth of data was displayed and analyzed at a time, with magnetometer and EM61 images viewed simultaneously. The operator picked out anomalies from the data by eye and used the mouse to draw an area of interest around each chosen anomaly. This area of interest could be drawn over either the magnetometer image or the EM61 image, and would automatically appear over the other image. For the magnetometer data, a nonlinear least squares three-dimensional curve fit to a model of a point dipole was performed. GEO-CENTERS

software does not currently include an EM model, however, so for EM61 data, the peak anomaly value and its location were logged. Although a nominal 2-5 gamma threshold was used for the magnetometer data, the effects of varying geologic background level and geologic noise make it such that a simple fixed threshold could not be applied without engendering an unnecessarily high false alarm rate. Instead of fixed thresholding, the operator used his judgment, along with a sliding colorization tool, to pick out magnetic dipole-like anomalies and EM61 anomalies. Priority was given to anomalies that were round and had good clear adjacent positive and negative lobes. In this way, the operator attempted to screen out the magnetic "ripples" along the survey site that were most likely due to local geology. Similarly, when viewing the EM61 data, although a 2-5 millivolt threshold was nominally applied, anomalies that were strong and had a round shape were given priority over those that were weak, unnaturally elongated along the direction of travel, or appeared on only one of the three EM61 coils.

While hand-picking each anomaly, the operator entered one of three heuristic classes of target confidence:

- *High-confidence targets* were those with anomalies that were strong and round. These high-confidence targets usually appeared in both the magnetometer and EM61 images, but the operator could still flag a target as high confidence if it appeared in only one image (magnetometer or EM61), as long as it had a textbook strong, clear, round, completely unambiguous signature.
- *Medium-confidence targets* were those with anomalies that were clear but appeared in only one of the two images (magnetometer or EM61), or targets that appeared in both the magnetometer and EM61 images with weaker, less defined, less round anomalies.
- *Low-confidence targets* were those with small, weak, ill-defined anomalies that the operator thought most likely to be due to debris, clutter, geology or noise (though anomalies specifically thought by the operator to be geology or noise were not picked at all). In most cases, a low-confidence target appeared on the magnetometer or the EM61 image but not both, and the anomaly was of such small spatial extent that it was caused by a single sensor (e.g., one magnetometer or one EM61 coil).

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

The goal of Project UX-0208 was to develop electronic hardware and a towed platform to demonstrate the ability to generate high-quality, spatially coregistered magnetometer and EM61 data in a single survey without the magnetometer data being compromised by noise engendered by the EM61s. The best indications that the technology performs as intended are: the system acquires high-quality magnetometer data regardless of whether the EM61s are turned on, and the quality of the concurrently collected EM61 data are nominal. This is verified in detail in the Final Report and is summarized below in Section 4.3. Note that the system is being used successfully for 100-acre real-world surveys, including a very high visibility project at The Former Lowry Bombing and Gunnery Range. Note also that the system has since been outfitted with new EM61 Mk2 receivers and 1 × ½-meter coils, and the improved system resurveyed the Blind Test Grid and Open Site at APG in August 2004 and at Yuma Proving Ground in October 2004.

In August 2002, the system surveyed the Blind Test Grid and Open Site at APG. The data was then formatted to submit the target lists in ATC's data submission template, a challenging task for several reasons. GEO-CENTERS was one of the first demonstrators on the APG site, and the multisensor nature of the system did not fit ATC's scoring paradigm. Further, the density of targets on the Blind Test Grid was very high, and the total field magnetometer signatures "bleed" into each other, resulting in signatures of, at times, several hundred gamma in grid squares that are likely empty because of signals from objects in adjacent grid squares. Lastly, GEO-CENTERS was not funded by ESTCP to perform discrimination, yet a discrimination stage was required in ATC's data submission template. At an interim program review, ESTCP provided guidance to GEO-CENTERS on the discrimination stage question, saying that we could use any method we liked to rank-order targets in the discrimination stage as long as we documented how it was done. We provided discrimination-stage ranking while simultaneously saying that we did not claim to be able to discriminate, but the result was a further misfit to ATC's scoring paradigm. While attempting to clear up these issues, GEO-CENTERS logged many hours on the phone with ATC, exchanged many e-mails, and resubmitted target lists four times at ATC's request. Columns in the submitted spreadsheets were prepared as follows:

Response Stage Column: In formatting the target list to comply with ATC's data submission requirements, there is a column required for "response stage" intended to contain the signal strength of each chosen anomaly. The multisensor STOLS generates both magnetometer and EM61 data, so there would normally be two such columns. In order to comply with the format and concatenate the two columns from the multisensor target picks into a single response value, the peak magnetometer value and the peak EM61 value were added together and divided by the goodness of fit (chi squared) from the magnetometer's dipole model match. ATC subsequently requested that GEO-CENTERS submit individual magnetometer and EM response sheets. GEO-CENTERS complied, submitting separate spreadsheets with the peak mag/EM response for each grid square. We defer the question of exactly how these data were used to ATC.

Discrimination Stage Ranking Column: The discrimination ranking was determined as follows. Individually, within the classes of high confidence, medium confidence, and low confidence targets that were heuristically assigned by the operator and hand entered, the data were sorted by response stage, which, as described above, is calculated as (peak_mag + peak_EM61)/chi_squared. A column was then added that contained the row number of these targets once they were sorted by hand-assigned confidence, then by response. As with the response stage, this was not intended to provide discrimination capability; it was merely a way to rank the targets to comply with the data submission requirements. We defer the question of exactly how these data were used to ATC.

Classification Column: Because we do not claim to be able to discriminate, this column was set to "O," indicating ordnance.

Type Column: Because we do not claim to be able to discriminate, this column was left blank.

Depth Column: The depth extracted by the magnetometer model match was used.

Angular Columns: The angle of incidence and angle of orientation are output from the curve fit to the magnetic dipole model.

Reports containing official scored results from the Blind Test Grid were provided to GEO-CENTERS in January 2004 and Open Site results in August 2004. The following summary tables are reproduced from the reports. As discussed above, GEO-CENTERS' simultaneous multisensor system did not fit into ATC's scoring paradigm. Because of these issues, GEO-CENTERS defers questions on exactly how the data was scored and what the results mean to ATC. In particular, it is unclear why the Blind Test Grid results contain individual EM and magnetometer response stage values and combined mag/EM values (and the combined Pd values are lower than the individual values, which seems impossible unless the data was "and-ed" together instead of "or-ed" together), whereas the Open Site results contain only combined mag/EM values.

From Table 2, it is clear that the magnetometers outperformed EM61s on the Blind Test Grid for large, deep objects, and that the EM61s outperformed the magnetometers for smaller, shallower objects.

Table 1. "Summary of Open Field Results" Table from ATC Report.

Metric	Overall	Standard	Non-Standard	By Size			By Depth, m		
				Small	Medium	Large	< 0.3	0.3 to <1	>= 1
COMBINED MAG/EM RESPONSE STAGE									
P_d	0.60	0.65	0.55	0.50	0.65	0.85	0.65	0.60	0.60
P_{fp}	0.50	-	-	-	-	-	0.40	0.55	0.80
P_{ba}	0.30	-	-	-	-	-	-	-	-

Table 2. "Summary of Blind Test Grid Results" Table from ATC Report.

Metric	Overall	Standard	Non-standard	By Size			By Depth, m		
				Small	Medium	Large	<0.3	0.3 to <1	>= 1
EM RESPONSE STAGE									
P_d	0.80	0.80	0.75	0.80	0.75	0.80	0.90	0.70	0.50
P_d Low 90% Conf	0.71	0.72	0.62	0.71	0.61	0.55	0.82	0.58	0.27
P_{fp}	0.85	-	-	-	-	-	0.85	0.90	1.00
P_{fp} Low 90% Conf	0.80	-	-	-	-	-	0.74	0.79	0.63
P_{ba}	0.50	-	-	-	-	-	-	-	-
MAG RESPONSE STAGE									
P_d	0.85	0.90	0.70	0.75	0.85	1.00	0.80	0.85	0.90
P_d Low 90% Conf	0.77	0.84	0.59	0.66	0.76	0.79	0.71	0.72	0.66
P_{fp}	0.90	-	-	-	-	-	0.90	0.90	1.00
P_{fp} Low 90% Conf	0.85	-	-	-	-	-	0.81	0.82	0.63
P_{ba}	0.70	-	-	-	-	-	-	-	-
COMBINED MAG/EM RESPONSE STAGE									
P_d	0.65	0.75	0.45	0.50	0.70	0.90	0.65	0.70	0.20
P_d Low 90% Conf	-	-	-	-	-	-	-	-	-
P_{fp}	0.75	-	-	-	-	-	0.70	0.75	1.00
P_{fp} Low 90% Conf	-	-	-	-	-	-	-	-	-
P_{ba}	0.10	-	-	-	-	-	-	-	-

4.2 PERFORMANCE CRITERIA

The performance criteria are shown in Table 3.

Table 3. Performance Criteria.

Performance Criteria	Description	Primary or Secondary
Functionality of sensor interleaving	Demonstration that the hardware designed to acquire magnetometer data between pulses from the EM61 system is functional	Primary
Data quality	Demonstration that the magnetometer data acquired through interleaving is high quality	Primary
Efficiency	Demonstration that the simultaneous acquisition of magnetometer and EM61 data is more efficient than surveying the same area twice in separate surveys	Primary
Data collection	Collection of high-quality data sets that could be used for discrimination algorithm development	Secondary
Deployability	Define shortcomings and itemize additional modifications to the technology that would be necessary for further deployment	Secondary

The functioning of the interleaving hardware was confirmed by evaluating whether a full set of multisensor data was successfully collected at the end of surveying the Calibration Test Grid.

The presence of high-quality data was confirmed by individual visual examination of magnetometer and EM61 data over the Calibration Test Grid, each displayed at a tight, high-contrast display scale to accentuate any noise.

Efficiency was evaluated and efficient performance confirmed by examining the multisensor survey time over the Calibration Test Grid and by comparing it to single-sensor survey time over the Calibration Test Grid.

The collection of data for further algorithm development was evaluated and confirmed by simultaneously visually examining magnetometer and EM61 data over the Open Field and verifying that both sets of data had minimal noise on a tight, high-contrast display scale and that anomalies in one data set spatially corresponded to anomalies in the other data set.

Further system deployability was evaluated by making an itemized list of system shortcomings. This list is contained in the Final Report. Through the Cooperative Research and Development Agreement (CRADA), nearly all listed shortcomings have already been addressed, and the system is being used for real-world UXO surveys.

Table 4 summarizes the confirmatory methods.

Table 4. Performance Confirmatory Methods.

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Method	Actual (post demo)
Functionality of sensor interleaving	Functioning	Visual examination of data from the Calibration Grid	Functioning
Data quality	High	Visual examination of data from the Calibration Grid	High for magnetometer; adequate for EM61
Efficiency	Both sensor streams in a single pass	Comparison of survey times from the Calibration Grid	Both sensor streams acquired in a single pass
Data collection	High-quality co-located data	Visual examination of data from the Open Field	High-quality co-located data
Deployability	Prototype system	List of improvements	Prototype system

Note that the adequate categorization for EM61 data quality is due primarily to the nature of the EM61 equipment itself. This project did not purchase any new EM61 equipment; it utilized the existing EM61 (single time gate) sensors and ½ × ½-meter coils owned by GEO-CENTERS and already used with STOLS. More up-to-date EM61 Mk2 (multiple time gate) electronics and 1 × 1-meter or 1 × ½-meter coils would likely yield higher quality EM61 data.

4.3 DATA ASSESSMENT

Since the concept of GPS-integrated vehicle-towed magnetometer and EM61 surveys has been well-validated, the overarching goal of this project was development and demonstration of the ability to simultaneously acquire magnetometer and EM61 data on a common towed platform without the EM61-induced noise usually engendered in the magnetometer data. As described above, the primary confirmation of this is visual—the magnetometer data with the EM61 array

transmitting looks like the magnetometer data with the EM61 array switched off, and the simultaneously acquired EM61 data is of adequate quality.

This visual confirmation is displayed in Figures 8 through 10. Figure 8 shows magnetometer data acquired over the Calibration Test Grid while the EM61s were switched off. Figure 9 shows magnetometer data over the same area acquired while the EM61s were synchronously collecting data. Both images are displayed to a very tight ±25-gamma scale to highlight magnetic anomalies as well as any noise. Heuristically comparing these two images, they are extremely similar; the image of magnetometer data obtained while the EM61s were running does not visually contain noise that is not also present in the image of the magnetometer data obtained while the EM61s were switched off. This provides visual confirmation that the acquisition of magnetometer data between EM61 transmit pulses is not adversely affecting magnetometer data quality. (For a time-series representation of this, see Section 2.3.)

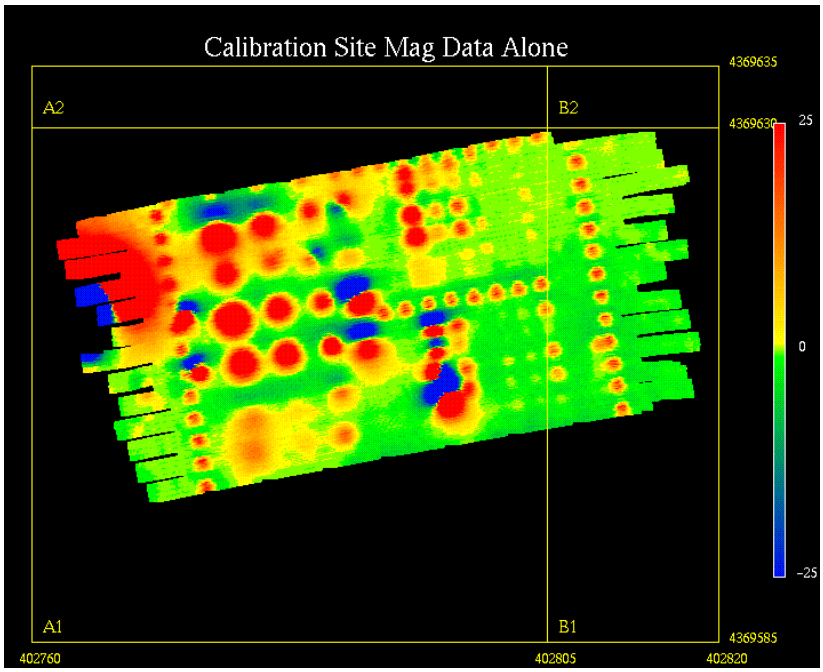

Figure 8. Magnetometer Data from the Calibration Test Grid Acquired with the EM61s Switched Off.
(Image scale ±25 gamma)

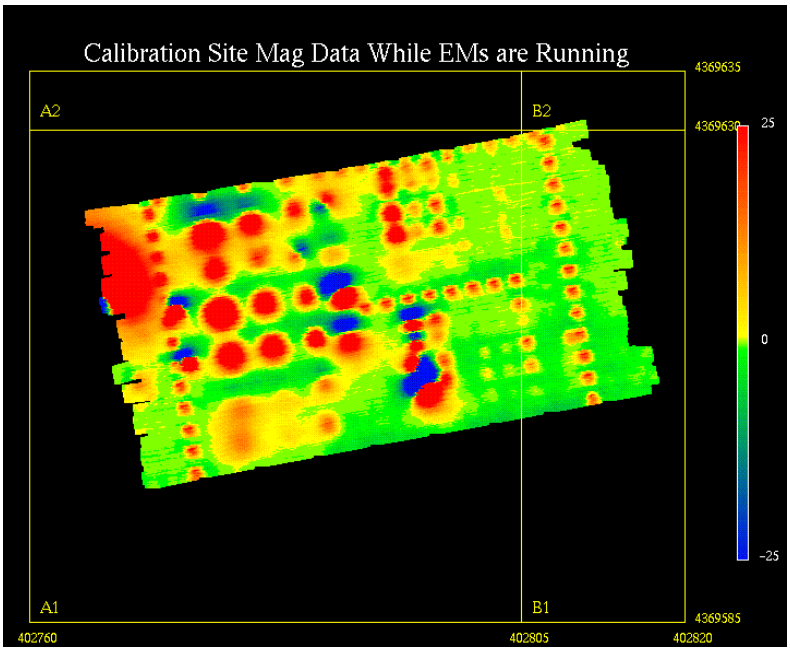

Figure 9. Magnetometer Data from the Calibration Test Grid Acquired While the EM61s Were Simultaneously Acquiring Data.
(Image scale ± 25 gamma)

Figure 10 shows an image of EM61 data acquired while the magnetometer data in Figure 9 were also being acquired. The streak-free appearance of the data and the roundness of the anomalies verify that nominal-quality EM61 data is being acquired.

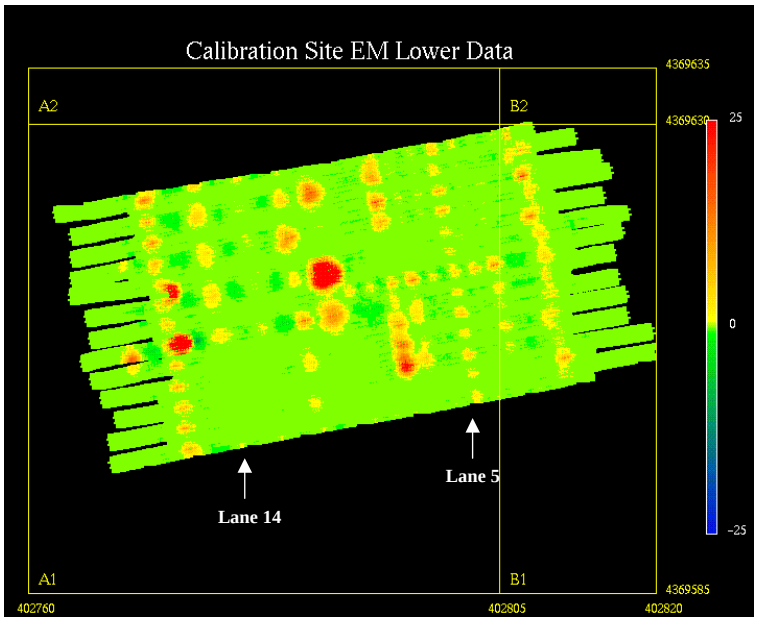

Figure 10. EM61 Data from the Calibration Test Grid Acquired While the Magnetometers Were Simultaneously Acquiring Data. (Image scale ±25 millivolts)

In addition to verifying system functionality, several things are clear from viewing the Calibration Test Grid data. The EM61 array does a better job than the magnetometers at detecting the line of objects BLU-26 and BDU-28 objects along line 5, but the magnetometers do a much better job at detecting the 105mm objects in lane 13 and the 155mm objects in lane 14. While the better performance of magnetometers against large objects at depth is documented in studies from JPG, the falloff in detectability in these EM61 data is probably due to the fact that ½ × ½-meter coils are being used. These are smaller than standard 1 × 1 meter and 1 × ½-meter EM61 coils and were used because GEO-CENTERS had them left over from a data collection exercise at JPG3 in 1996 (no new EM61 equipment was purchased under this project).

A similar visual analysis of data from the Blind Test Grid and the open field is contained in the Final Report.

In addition to visual analysis, a signal-to-noise analysis was conducted on data from McKinley Test Grid at Redstone Arsenal in Huntsville, Alabama, to verify that the magnetometers performed equally well whether or not the EM61 was simultaneously operating. McKinley data was chosen for this analysis over APG data because the first traverse of each McKinley data set ran directly over the edge of the test plot, the corners of which were marked by two pieces of rebar driven into the ground with very strong signatures. This resulted in two clear, unambiguous targets that could be easily extracted and compared in mag-only and concurrent mag/EM configurations.

Figure 11 shows the time-series profile of the southernmost line of data from McKinley Test Range without the EM61 concurrently operating. The peak values of the two anomalies from the rebar without the EM61 operating are 1059.9 and 1043.1. The average of the two peaks is a signal level of 1051. A remnant noise level of between 1 and 2 gammas exists in the data, with occasional noise spikes on one-second boundaries as large as 4 gammas. These larger noise spikes are a result of a slight sampling bug in mag-only mode. All plots were obtained after notch-filtering the data to remove the 15-Hz ring resulting from subsampling the 60-Hz ambient electrical hum at 75 Hz (note that a 60-Hz power line runs right through both the McKinley Test Range and APG test sites). Using the worst-case value of 4 for noise yields a signal-to-noise of 1051/4 or 262.

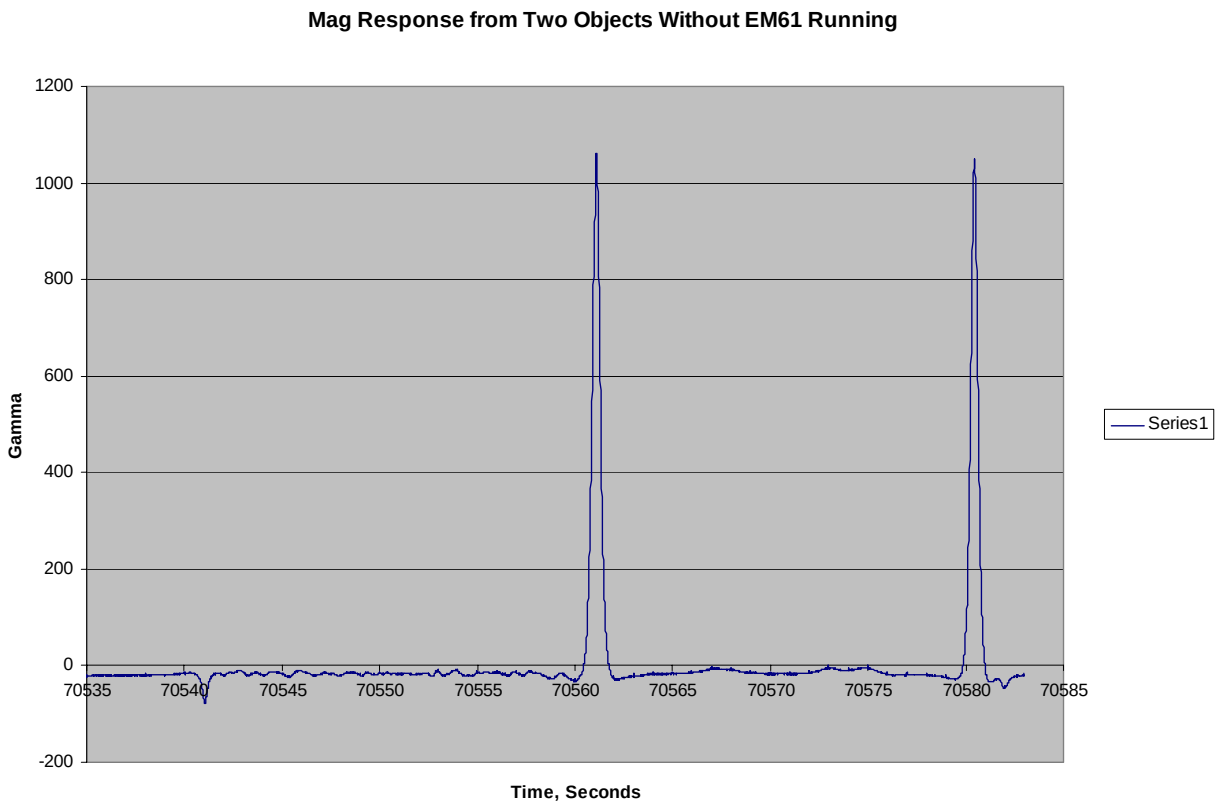

Figure 11. The Magnetometer Response from the First Traverse at McKinley Test Range Without the EM61s Running.

Figure 12 below shows the profile over the two rebar objects acquired while the EM61 was simultaneously operating. The two peak values are 1063.7 and 1025.3, yielding an average value of 1044. We see that this signal level is within about 1% of the value, 1051, obtained in the mag-only mode. The noise level in this data is between 1 and 2 gammas. As with the mag-only plot above, this noise is the remnant of filtering the 15-Hz ring due to a nearby 60-power line being sampled at 75 Hz. This yields a signal-to-noise of 1044/2, or 522. However, the noise is actually *less* than in mag-only mode; the larger 4-gamma noise signal, visible every second in the magnetometer-only data, is not present in the concurrent mag/EM data. This is because the 4-gamma noise signaling the mag-only triggering mode is an artifact of a sampling bug. Near power lines, there is somewhat more noise, thus somewhat lower signal-to-noise, in the mag-only mode. If this bug were repaired, the two signal-to-noise levels would be nearly identical.

These results are summarized in Table 5.

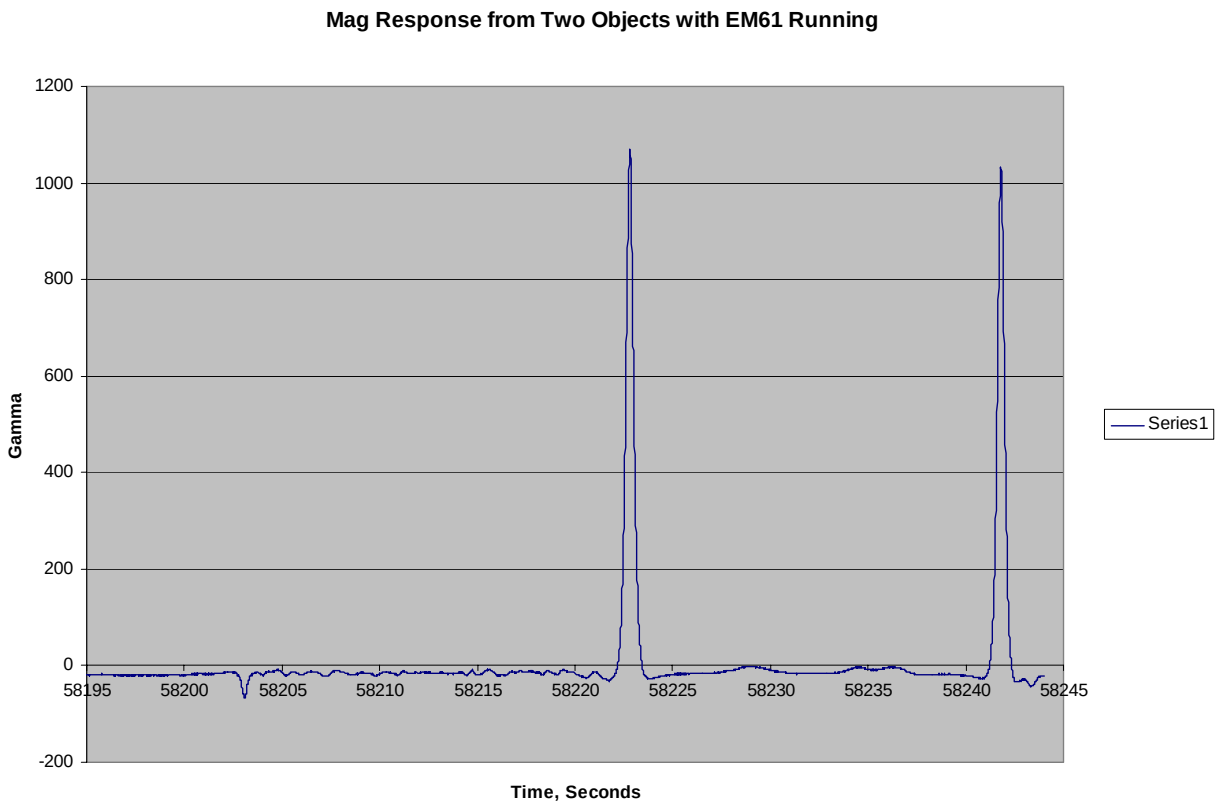

Figure 12. The Magnetometer Response from the First Traverse at McKinley Test Range with the EM61s Running.

Table 5. Comparison of Signal-to-Noise Levels in Mag-Only Mode and Concurrent Mag/EM Mode.

Mode	Signal-To-Noise
Magnetometer only (with sampling error)	262
Magnetometer only (if sampling error were fixed)	514
Concurrent magnetometer and EM61	522

Training Requirements and Ease of Operation: The system was operated by the principal investigator, Rob Siegel, and a longtime user, Al Crandall. Training and health and safety requirements were as planned. Use by expert operators is necessary at this stage to ensure acquisition of high-quality data. For example, a slowly-drifting EM61 was flagged and replaced with rental equipment. Continued drift of the EM61 data was solved by in-field development of a time-varying background subtraction algorithm (it was later solved for good by powering the EM61s off batteries rather than a power supply). These things are not unusual in geophysical surveying and are easily handled by expert operators.

Limitations: Even though APG is a very rugged site, the proof-of-concept fiberglass platform survived extremely well. As a precaution, the platform has since been strengthened and augmented with a suspension. The magnetometer interface's picking up the 60 Hz hum from power lines was easily handled through smoothing of the data. The main limitation came from using the older, single time-gate EM61 electronics and small ½ × ½-meter coils; these coils generate weaker signals over objects than the more standard-sized larger coils. GEO-CENTERS has since augmented the platform to host five 1 × ½-meter coils, and is in the process of adapting the system to host EM61 Mk2 (multiple time gate) electronics.

4.4 TECHNOLOGY COMPARISON

Comparing the STOLS sensor swath width (2 meters for magnetometers; 1.5 meters for EM61) to man-portable systems with swath widths roughly half the size shows that surveying the site with two sequential handheld surveys (magnetometry followed by portable wheeled EM61) would have approximately quadrupled the time and cost. Surveying the site with single-sensor vehicle-towed arrays (magnetometry followed by EM61) would have required two sequential surveys, roughly doubling the time and cost.

At the 2004 UXO/Countermine Forum, where GEO-CENTERS presented data taken with the simultaneous multisensor STOLS at three sites (at APG, at a 100-acre site at The Former Lowry Bombing and Gunnery Range, and at an 85-acre site at a former Army Air Base in the Pacific Northwest), three other concurrent mag/EM technologies were presented. The Sub Audio Magnetic (SAM) system by G-Tek uses a high-update magnetometer to sample both the magnetic field and the ring-down of the EM field but requires each grid square to be surrounded by a coil of wire. The man-portable mag/EM system presented by AETC uses a custom frequency domain EM sensor that engenders substantial heading errors into the magnetometer data. The system presented by Blackhawk appears to employ an interleaving similar to that developed under this project, but also uses a custom EM sensor and does not yet appear to be operational. Of these four systems, the technology developed under UX-0208 is the only one that uses a commercial off-the-shelf industry-standard EM61; is the only one in a vehicle-mounted configuration to efficiently survey hundreds of acres; and along with the G-Tek system, is out in the real world collecting data at actual UXO sites.

5.0 COST ASSESSMENT

5.1 COST REPORTING

5.1.1 Cost of Demonstration at APG

The cost of performing the demonstration of the simultaneous multisensor STOLS at the Standardized UXO Technology Demonstration Site at APG consisted of:

- Mobilization/demobilization, including driving the tractor/trailer to the test site at APG
- Deploying the two-man field crew for a week at APG to survey the calibration grid several times, the Blind Grid once, and the 13-acre Open Field once
- A week for correcting, processing, and analyzing the data back at GEO-CENTERS

Note that no rental charge for the equipment was included for this demonstration; see Section 5.1.2 and 5.2 below.

These costs are summarized in Table 6.

Table 6. Actual Cost of APG Demonstration.

Labor	$15,831.73
Other direct costs (ODCs)	$10,455.80
Rental	$0.00
Total	$26,287.53

5.1.2 Cost of a Real-World Implementation at the Scale of the Demonstration

The nominal $1,950 daily rental charge for STOLS was waived during this project as part of GEO-CENTERS' contribution to the CRADA with CEHNC, but it is charged on commercial survey work performed with the simultaneous multisensor STOLS. As such, it is included in the calculation shown in Table 7 for a real-world implementation at the scale of the demonstration.

If a 13-acre survey were being bid commercially, it would include 1 day of mob, 1 day for setup and prove-out, 1 day of surveying, 1 day of demob, and the $1,950/day rental charge for STOLS for 2 days of survey time and 2 days for data processing. The rough order of magnitude (ROM) cost for this activity would be approximately $24,000, slightly less than the actual costs for the APG demonstration. Note that these costs are only for the mobilization, the geophysical investigation, and nominal data processing, and that other real-world survey-related activities such as developing a work plan, a health and safety plan, a quality control plan, target relocation, remediation, and a final report are not reflected in this estimate, as they were not reflected in the estimate for the actual demonstration (the reports were part of a different task).

Table 7. Cost of Real-World Implementation at the Scale of APG Demonstration.

Labor	$9,019.86
ODCs	$10,083.20
Rental	$4,485.00
Total	$23,588.06

5.1.3 Cost Extrapolated to a Full-Sized Site

Because the simultaneous multisensor STOLS has been used at several large survey sites since the close of this ESTCP-funded project, actual survey costs for a full-sized site can be stated rather than simply extrapolated. The 110-acre survey of the Jeep/Demo Range at The Former Lowry Bombing and Gunnery Range is used as an example. The mob/demob charge was $15,850. Folded into the $5,800 daily rate for Lowry was a two-man crew of expert operators working 10-hour days, 2 additional hours of data correcting and preprocessing per day, plus the $1,950/day rental charge for the simultaneous multisensor STOLS. For this survey, no data analysis was performed, since the data were given to Shaw Environmental for the PIG discrimination study performed by AETC and Billings and Pasion from University of British Columbia (UBC). Breaking these numbers into labor, ODCs, and STOLS rental categories yields the results shown in Table 8. Dividing the total cost by 110 acres yields a cost per acre of $708.

Table 8. Cost Extrapolated to a Full-Sized Site.

Labor	$39,983.38
ODCs	$14,583.91
Rental	$23,400.00
Total	$77,967.29

5.2 COST ANALYSIS

The successful demonstration of the simultaneous multisensor STOLS is a synergy of GEO-CENTERS, CEHNC, and ESTCP-funded efforts. The original single-sensor commercial version of STOLS was developed by GEO-CENTERS in 1993 at a cost of nearly $4 million. As we entered into a CRADA with CEHNC for this simultaneous multisensor project, GEO-CENTERS' ante-on-the-table was STOLS itself, which we allowed to be "reversibly cannibalized." The fact that the basic architecture, the low-ferrous vehicle, the centimeter-level GPS, the total field magnetometers, the EM61 sensors, the cabling, the software, and the many tricks for collecting high-fidelity, low-noise data came from the existing STOLS, and the development of the interleaving hardware and the non-metallic platform came from ESTCP and CEHNC, is a triumph of cooperative development, but also makes it difficult to determine accurate cost estimates to duplicate another system from scratch.

During initial development of the single-sensor STOLS in 1993, GEO-CENTERS performed a detailed cost assessment and calculated a daily rental charge to amortize the original $4 million cost of developing the equipment on the basis of assumptions such as the number of large Open Sites hospitable to vehicle-towed GPS-integrated arrays, the size of the crew, the number of working days per year, downtime, and other factors. We also performed ongoing cost analysis

during the ensuing 10-year period, comparing budgeted costs to actual costs. Many of the initial assumptions, it turned out, were incorrect, and over the 10-year period, GEO-CENTERS revised the daily rental charge downward to help in the bidding and winning of commercial survey work. The current rate is $1,950/day. Despite detailed cost analysis, this number is heuristically determined and has more to do with not being out-of-scale with other digital geophysical mapping services that fold EM61, magnetometer, and GPS rental costs into their daily rate, and less to do with amortizing actual development costs.

In the MTADS cost and performance report, they estimated the replacement cost of their vehicular system at roughly $800,000. GEO-CENTERS recently had the opportunity to quote a new multisensor vehicular system for a high-risk venture and made an ROM estimate of the replacement cost at $1.2 million, which included contingency to cover risk. From these rough estimates, a replacement cost of $1 million with a 20% uncertainty seems reasonable. However, as per the above discussion on amortization, there is enormous risk in making assumptions on the basis of equipment usage.

Lastly, in analyzing cost, it cannot be stressed enough that each site has different requirements. For surveys for the Corps of Engineers requiring a work plan, a site-specific safety and health plan, a quality control plan, and a final report, the geophysical investigation is only one piece of a total statement of work. As such, the estimates below include only mobilization, geophysical investigation, and a nominal amount of data processing**.**

5.2.1 Major Cost Drivers

Because of the high cost sensitivity of bidding and performing commercial survey work, GEO-CENTERS does not employ the degree of logistical support utilized by MTADS; we do not contract for portable office space, generators, etc. STOLS is transported in a trailer owned by GEO-CENTERS, and this space is used for maintenance, storage, and data processing. We also employ fewer personnel on site. GEO-CENTERS generally performs surveys using a crew of two expert operators which is sufficient except when survey traverses are difficult to see due to site size or terrain; in this case, “flaggers” are employed, usually as local temporary labor, to hold flags to help the vehicle driver see his previous traverse. For surveys on active UXO ranges contracted through the Army Corps of Engineers, a higher level of on-site explosive ordnance disposal (EOD) support is mandated.

With that in mind, the major cost driver is the vehicular hospitability of the survey site and the ability to run long survey lines, factors that minimize the number of times the vehicle must be turned around. The original single-sensor STOLS routinely averaged 30 acres per day, with peak production reaching 60 acres per day. The simultaneous multisensor STOLS must drive somewhat slower due to the proof-of-concept nature of the fiberglass towed platform and the degradation of the EM61 data quality with increased speed, but even with these limitations, we have easily acquired 15 acres per day on large, smooth, rectangular sites.

5.2.2 Sensitivity Analysis

In Table 9, we set up four variants of the Lowry survey. The second column represents the actual 110-acre survey, conducted in 12 days at an average of roughly 9 acres per day for a cost per acre of roughly $700. The third column simulates less hospitable site conditions, which increase

the survey to 18 days and the cost to nearly $1,000/acre. The fourth column simulates gentle terrain; covering 180 acres in 12 days, for a realistic average of 15 acres per day, drops the survey cost to $433/acre. The last column shows the economy gained by having a large, gentle site. For a 220-acre site covered in 18 days, the total cost is the same as in the third column, but the cost is almost half that of the rugged site.

Table 9. Sensitivity to Site Size and Coverage Rate.

	Actual Survey	Less Hospitable Conditions	Gentle Terrain	Large, Gentle Site
Acres	110.00	110.00	180.00	220.00
Days	12	18	12	18
Labor	$39,983.38	$55,858.63	$39,983.38	$55,858.63
ODCs	$14,583.91	$18,089.04	$14,583.91	$18,089.04
Rental	$23,400.00	$35,100.00	$23,400.00	$35,100.00
Total	$77,967.29	$109,047.67	$77,967.29	$109,047.67
Acres/Day	9.17	6.11	15.00	12.22
Cost/Acre	709	991	433	496

5.3 COST COMPARISON

STOLS, like MTADS, is a vehicle-towed GPS-integrated array that performs digital geophysical mapping. The estimated savings of the basic technique of vehicle-towed array geophysics as compared with mag-and-flag operations is documented in the MTADS Cost and Performance Report.[2]

The technology unique to project UX-0208—interleaving magnetometer data between EM61 pulses, allowing total field magnetometer and EM61 data to be acquired simultaneously—will result in a 50% cost reduction in geophysical data collection efforts compared to towed array technologies such as MTADS, which use magnetometers and EM61s sequentially instead of simultaneously. Sites that may require surveys with multiple sensors (magnetometers and EM61s) include sites with complex geology, or sites where the detection and discrimination requirements are very stringent.

The Jeep/Demo Range at The Former Lowry Bombing and Gunnery Range in Aurora, Colorado, is such a site. At this site, PIGs—pipes containing possible chemical training sets—were found. Because excavation of possible chemically contaminated objects requires extra precautions and is thus extremely expensive, the prime contractor (Shaw Environmental) came up with a detection and discrimination methodology involving both total field magnetometers and EM61 Mk2 sensors. The simultaneous multisensor STOLS was deployed on the site, and the resulting data was used to aid in reducing the total set of potential chemical anomalies from 28,000 to 250. According to presentations at the 2004 Countermine/UXO Forum by Jerry Hodgeson at The U.S. Army Corps of Engineers, Omaha District, Dr. Jack Foley, formerly of Shaw Environmental, and Drs. Steven Billings and Leonard Pasion of UBC, the projected cost savings of the multisensor discrimination technique was as high as $200 million.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Terrain: The economics of surveys bid at a fixed acreage rate per day depends on coverage rate. Smooth grassy areas that have already been run over by heavy equipment are far more vehicularly navigable than rocky or stumpy areas, and lower coverage rates engender higher survey cost. This is particularly true due to the proof-of-concept nature of the fiberglass towed platform, which has no suspension and thus must be treated gently.

Physical Size of System: Because the system is a vehicular-towed array, it requires a tractor/trailer to transport it, which is inherently more costly than using man-portable systems than can be cheaply shipped. As such, driving services must be contracted.

Required Expertise: The system is a proof-of-concept prototype and, at least initially, should be accompanied by Mr. Rob Siegel when deployed.

Swath Width: The system uses five magnetometers on ½-meter spacing, but only three ½-meter EM61 coils on ½-meter spacing, so the effective multisensor swath width is only 1.5 meters. This is because all sensors were COTS from GEO-CENTERS' existing STOLS equipment (no sensors were purchased under the program's budget). Widening the EM61 swath width to match the 5-magnetometer swath width (2.5 meters) would increase area coverage rates and thus further reduce survey costs. [This modification has been performed, but additional channels of EM hardware has not been purchased.]

6.2 PERFORMANCE OBSERVATIONS

Nature and Age of EM61 Equipment: The EM61 coils, electronics, and cabling used on this project were purchased by GEO-CENTERS for use at JPG3 in 1995. The coils are ½ × ½ meter. This configuration was originally specified by GEO-CENTERS in 1995 to aid in the detection of small, shallow targets for the JPG3 exercise, but it is a nonstandard size; conventional 1 × 1-meter or 1 × ½-meter coils would probably be better at detecting objects deeper. The use of 1 × ½-meter coils, in particular, is appealing, as it could be done with virtually no modification to the existing towed platform. The EM61 electronics are of the older "Mk1" variety (single time gate). EM61 drift was problematic, and was finally solved outside this project by powering the EM61 array off a pair of isolated automotive batteries.

Terrain: In addition to reducing the coverage rate, uneven terrain affects data quality of both the magnetometer and EM61 data. The platform is not instrumented with inclinometers and other additional sensors to mitigate these effects, so the result can be incorrectly positioned data causing the resulting target locations, depth, and size estimates to suffer.

Geology: The effects of magnetic geology on magnetometers and EM61s are well-documented and are not contravened by the fact that the system operates both sensors concurrently. However, by having both sensors deployed concurrently, there is opportunity for each sensor to detect an object if the other sensor's performance is compromised by geology or environmental factors.

GPS Coverage: Centimeter-level GPS depends on adequate satellite geometry. Incorrectly positioned sensor data affects the accuracy of results.

6.3 SCALE-UP

GEO-CENTERS already has moved from demonstrations to real-world implementation of the system, having conducted two 100-acre surveys in 2003. This "last mile" of engineering development is difficult. Bolts, bearings, cabling and connectors may be mundane, but their proper engineering is essential to survivability in the field. The interleaving electronics that is the heart of the concurrent mag/EM technical approach has functioned nearly flawlessly.

In May 2003, GEO-CENTERS outfitted the simultaneous multisensor STOLS with a simple suspension and surveyed the 100-acre Jeep/Demo Range at The Former Lowry Bombing and Gunnery Range for the U.S. Army Corps of Engineers Omaha District and Dr. Jack Foley at Shaw Environmental (see Figure 13). Production averaged nearly 10 acres per day. The magnetometer data were judged to be of extremely high quality, and were used by Shaw to aid in the process of discriminating objects of interest on the site from clutter. Recent presentations at the 2004 UXO Countermine Forum by Dr. Jack Foley (now of Sky Research), Jerry Hodgeson, and Dr. Stephen Billings and Dr. Leonard Pasion, both of UBC and Sky Research, prominently featured the simultaneous multisensor STOLS and the role it played in generating high-quality data that helped reduce the number of excavations that could contain chemical training test sets from 28,000 to 250, resulting in cost savings estimated as high as $200 million (see Figure 14).

Figure 13. STOLS Inside the Demolition Pit at Lowry.

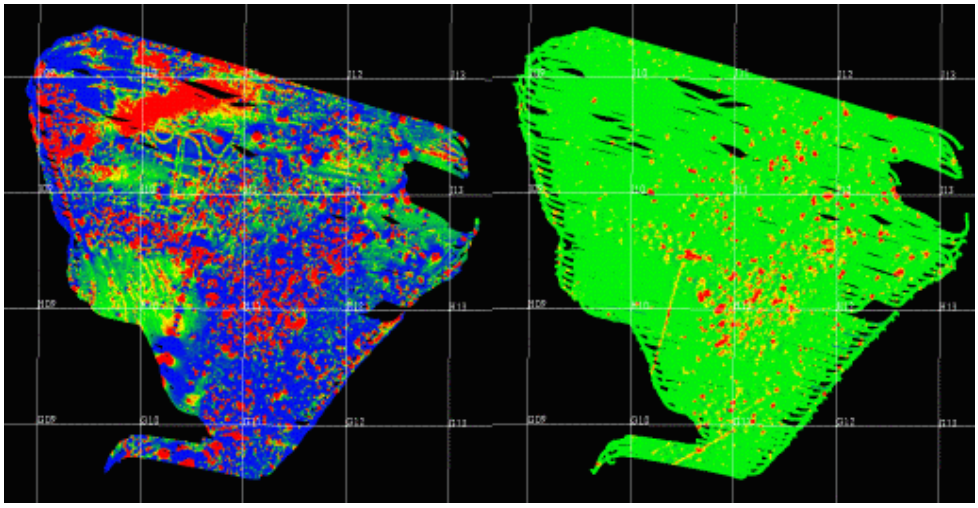

Figure 14. Fifteen Acres of Concurrently Collected Magnetometer Data (left, ±150 gamma) and EM61 Data (right, ±50 mV) from the Pit at the Jeep/Demo Range. (High object density results in complex magnetometer data, but the sharper response of the EM61 helps to separate signals from closely spaced objects.)

In November 2003, GEO-CENTERS replaced the three ½ × ½-meter EM61 coils with five 1 × ½-meter coils and performed a geophysical investigation at The Former Portland Army Air Base (now Portland International Airport) to search for an anecdotal trench potentially filled with a million rounds of small munitions. Since the trench was anecdotal in nature, the exact nature of its expected signature was uncertain, and it was felt that a system that utilized both total field magnetometers and pulsed induction sensors would provide the greatest chance of detecting and locating the trench, if it existed. Also, since the site was on an active airfield, there was concern over the degree to which potential noise sources might interfere with detection and mask candidate signals. The concurrent use of multiple complimentary sensors also offered the possible additional benefit of detection if one sensor was susceptible to unavoidable site noise (see Figure 15 and Figure 16).

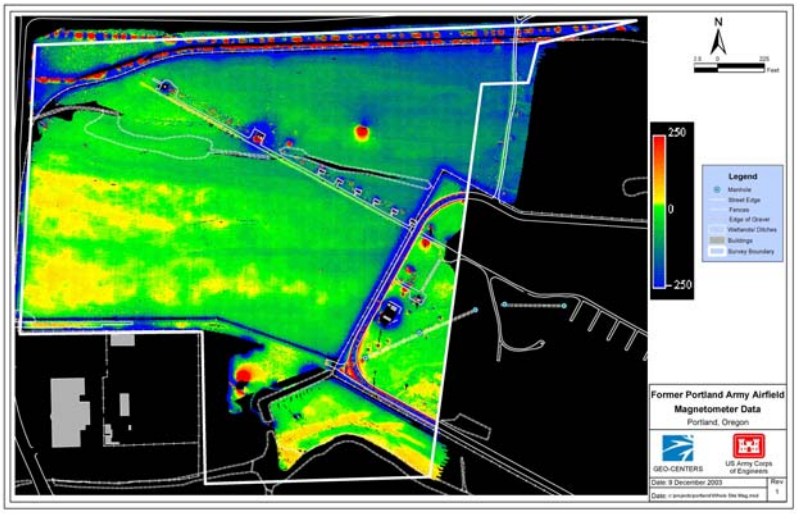

Figure 15. Eighty-five Acres of Concurrent Magnetometer Data from The Former Portland Army Air Base.

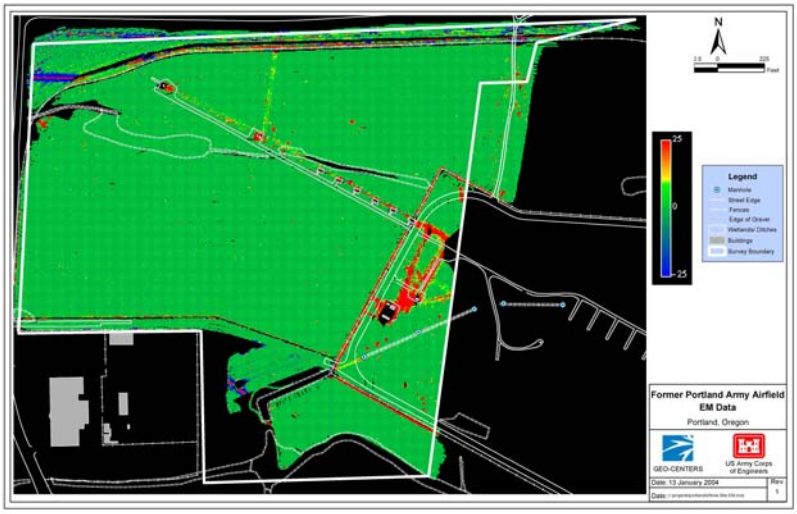

Figure 16. Eighty-five Acres of Concurrent EM61 Data from The Former Portland Army Air Base.

GEO-CENTERS surveyed the 85-acre site with the simultaneous multisensor STOLS with an average production rate of nearly 15 acres per day. The system functioned flawlessly, collecting very high quality magnetometer and EM61 data (Figure 15 and Figure 16). As with the data from Lowry, there were clear advantages to using both sensors. On the airfield itself, strong fields from high-voltage equipment rendered the EM61 data noisy, whereas the magnetometers continued to function. Conversely, one section of the site had a high concentration of anomalies that showed up weakly in the magnetometer data but rang out very clearly in the EM61 data, possibly indicating a collection of nonferrous objects intermixed with ferrous ones, or a collection of objects with both ferrous and nonferrous components. Although no signature that correlated with the description of the anecdotal trench was found, the use of both sensors helped to "prove the negative."

Through the CRADA with CEHNC, tighter integration with researchers at UBC and Sky Research (Dr. Stephen Billings and Dr. Leonard Pasion) is being pursued so that their ESTCP and ERDC-funded discrimination algorithms can be applied to data collected by the system in upcoming surveys. We are also integrating modern EM61 Mk2 (multiple time gate) electronics to the system for upcoming surveys.

6.4 OTHER SIGNIFICANT OBSERVATIONS

The successful implementation of this technology and other digital geophysical mapping technologies on a site depends on the program manager's willingness to use technology. We have been extremely fortunate in this regard.

With the emphasis on projects that entail research in discriminating UXO from clutter, we are frequently asked discrimination-related questions. While we do not doubt the absolutely central importance of discrimination research, it is important to realize that, irrespective of discrimination, the concurrent use of magnetometers and EM61s can be extremely useful in the

Engineering Evaluation/Cost Analysis (EE/CA) Report or site assessment phase of a project. This can help to reduce surprise and thus reduce risk and cost in future phases of a project.

6.5 LESSONS LEARNED

It is difficult to collect high-quality, low-noise magnetometer data with a vehicular system, as even a low-ferrous vehicle such as the STOLS vehicle has some remnant self-signature that must be removed with processing. It is likewise difficult to collect high-quality, low-noise EM61 data, as any metal, even nonferrous metal, near the EM coils may engender noise in the data. Therefore, deploying magnetometers and EM61s on a vehicular system requires both a low-ferrous vehicle *and* a nonmetallic towed platform—a very substantial engineering development. Developing interleaving electronics, as we did in this project, solves only the first—but the most important—problem of dealing with noise.

6.6 END-USER ISSUES

It has been enormously helpful that the co-Principal Investigator (PI) on this project was Mr. Roger Young, Director of Innovative Technology at CEHNC. It is one thing for GEO-CENTERS to say "concurrent mag/EM would be used if it were available"; the fact that Mr. Young was co-PI shows that CEHNC not only says it but believes it. Because of Mr. Young's involvement, and because of the interest from other technology advocates such as Mr. Bob Selfridge and Mr. Andrew Schwarz at CEHNC, and Mr. Jerry Hodgeson at The Corps of Engineers Omaha District, the system was used at a high-visibility survey at The Jeep/Demo Range at The Former Lowry Bombing and Gunnery Range in Aurora, Colorado.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Because the technology involves combining the two sensors most "validated" against UXO for digital geophysical mapping—total field magnetometers and EM61 pulsed induction coils—there are no specific regulatory hurdles.

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APPENDIX A

POINTS OF CONTACT

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