ESTCP
Cost and Performance Report

(UX-9811)

Man-Portable Adjuncts for the Multi-Sensor Towed Array Detection System (MTADS)

June 2004

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
ESTCP Project: UX-9811

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

Page

TABLE OF CONTENTS (continued)

Page

FIGURES

Page

FIGURES (continued)

Page

TABLES

Page

ACRONYMS AND ABBREVIATIONS

2-D	two-dimensional
AEC	Army Environmental Center
BDU	bomb demonstration unit
BRAC	base realignment and closure
CRADA	Cooperative Research and Development Agreement
DAQ	data acquisition system
DAS	data analysis system
DoD	Department of Defense
EM	electromagnetic
EMI	electromagnetic induction
EMMS	electromagnetic man-portable system
ERDC	U.S. Army Engineer Research and Development Center
EODT	Explosive Ordnance Detection Technologies, Inc.
ESTCP	Environmental Security Technology Certification Program
FAR	false alarm rates
FUDS	formerly used defense sites
GIS	geographical information system
GPS	global positioning system
GUI	graphical user interface
JPG	Jefferson Proving Ground
MMS	man-portable magnetometer system
MTADS	Multi-Sensor Towed Array Detection System
NBS	National Bureau of Standards
NAVEODTECHDIV	Naval Explosive Ordnance Disposal Technology Division
NIST	National Institute of Standards and Technology
NRL	Naval Research Laboratory
OE	ordnance and explosives
OEW	ordnance explosive waste
P_d	probability of detection
P_{fa}	probability of a false alarm

QA	quality assurance
QC	quality control
RFP	request for proposal
ROC	receiver operating characteristic
RTK	real-time kinematic
USACE	U.S. Army Corps of Engineers
USRADS	Ultra Sonic Ranging and Data System
UTM	Universal Transverse Mercator
UXO	unexploded ordnance

ACKNOWLEDGEMENTS

The development and demonstration of the man-portable adjuncts of the Multi-Sensor Towed Array Detection System (MTADS) were supported by the Environmental Security Technology Certification Program (ESTCP) Program Office as was this program, whose aim was to extend the reach of the MTADS system into areas inaccessible to the vehicular system.

The Naval Research Laboratory managed all MTADS man-portable adjunct activities. The principal investigator during the development of the MMS was Dr. J. R. McDonald and during the development of the EMMS, Dr. H. H. Nelson.

We wish to express our grateful appreciation to Dr. Jeff Marqusee, the ESTCP director, and to Dr. Anne Andrews, the UXO program director, for their unflagging commitment to developing and refining automated UXO detection and remediation technologies. This commitment has led to the demonstration and validation of fully field-hardened man-portable prototypes and their transition to the commercial sector.

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

This page left blank intentionally.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The U.S. Army Corps of Engineers (USACE)–Huntsville estimates that approximately 20 million acres of land are contaminated with unexploded ordnance (UXO) or ordnance explosive waste (OEW) within the continental United States. This is the result of operations that include training, testing, manufacture, storage, disposal, and intentional burials. Now, through either congressional mandates such as the formerly used defense sites (FUDS), base realignment and closure (BRAC), or state litigation, these sites are being evaluated, remediated (as required), and certified as safe for the intended ultimate public use. This is a very slow and costly process, and in some cases, impossible to do with existing technologies and resources.

Within the Environmental Security Technology Certification Program (ESTCP), the goal of the UXO Cleanup Thrust is to develop automated, economical, and efficient methods to accomplish UXO site cleanups through the demonstration and fielding of new technologies. One of these funded programs was the Multi-Sensor Towed Array Detection System (MTADS) developed by the Naval Research Laboratory (NRL) [1]. This system consists of a tow vehicle and two low self-signature tow platforms, one for an eight-sensor magnetometer array and the other for a three-sensor time domain electromagnetic (EM) pulsed induction array. MTADS uses the global positioning system (GPS) for navigation, sensor position location, and survey guidance and has a sophisticated data analysis system for interpreting field data. Target analyses include target position, depth, orientation, predicted target size, and a goodness-of-fit value [2]. Based on the success of extensive field demonstrations, NRL signed a Cooperative Research and Development Agreement (CRADA) with a commercial company, Blackhawk Geometrics, Inc., and non-government systems have been designed and built based on the NRL vehicular and man-portable MTADS. These systems are currently in commercial use providing UXO services to the Department of Defense (DoD) [3].

The USACE has estimated that vehicle towed-array survey systems can be used effectively on only about 30% of UXO-contaminated land because of rugged terrain, buildings on or near the site to be surveyed, or wooded sites. GPS navigation systems do not operate effectively without a clear view of the sky, which limits use of systems like MTADS under forest canopies. ESTCP funded NRL to develop an MTADS man-portable magnetometer system (MMS) in FY 98 and an EM man-portable system (EMMS) in FY 99. Each platform was implemented with both GPS and acoustic navigation systems to allow surveying in areas without sky view. The system hardware designs allowed MMS and EMMS survey data to be incorporated with vehicular survey data. This required implementation of a new data acquisition system for both the vehicular and the man-portable systems and modification of the data analysis system to incorporate and seamlessly overlay all data sets [4].

The Navy Tri-Service Environmental Quality Research Development Test and Evaluation Strategic Plan specifically addresses, under Thrust Requirements l.A.1 and 1.A.2, the requirements for improved detection, location, and removal of UXO on land and under water. The requirements document states:

> There are more than 20 million acres of bombing and target ranges under DOD control. Of particular concern for the Navy are the many underwater sites which have yet to be characterized. Each year a significant fraction (200,000-500,000 acres) of these spaces are returned to civilian (Private or Commercial) use. All these areas must be surveyed for buried ordnance and other hazardous materials, rendered safe and certified for the intended end use. This is an extremely labor intensive and expensive process, with costs often far exceeding the value of the land.... Improved technologies for locating, identifying and marking ordnance items must be developed to address all types of terrain, such as open fields, wooded areas, rugged inaccessible areas, and underwater sites [5].

The MTADS addresses all aspects of the Tri-Service Requirements for land-based buried UXO. It is capable of detecting all classes of buried UXO at their maximum likely penetration depths. The system correctly locates buried targets, determines their burial depths, classifies the likely ordnance size, and provides for future target way pointing, as well as creating geographical information system (GIS)-compatible target output maps and sorted target tables. The man-portable adjuncts extend this capability into areas of rugged terrain and areas with poor sky visibility [4].

1.2 L-RANGE DEMONSTRATION

1.2.1 L-Range Demonstration Objectives

In August 1999, the man-portable systems were evaluated in a demonstration at the L-Range at Blossom Point, Maryland.

The great strengths of the MTADS are its sensitivity, which allows detection of all ordnance to its maximum self-burial depths; the position location accuracy of the navigation and positioning system; the target analysis algorithms that allow location of buried objects to within the actual ordnance volume; and the analysis output products that provide for the efficient reacquisition and remediation of the targets. A design goal for the man-portable projects was to preserve the detection sensitivity for buried ordnance while extending the survey capability to include rugged terrain and open forest areas.

The performance objectives for the L-Range demonstration were to:

- Conduct MMS and EMMS surveys of the entire survey area using the acoustic navigation system;
- Conduct MMS and EMMS surveys of the accessible areas using the GPS navigation system;
- Serially conduct MTADS target analyses for all man-portable surveys and the vehicular surveys — using the 3-ß classifier for analyzing the vehicular EM survey data;

- Develop dig lists based on each analysis and prepare dig images to reacquire and flag all targets picked from each survey;

- Dig all targets using UXO-qualified technicians—document location, orientation, and identification of all recovered targets and photograph all UXO in place before removal; and

- Analyze results to determine the relative performance achieved using each survey approach.

1.2.2 L-Range Demonstration Results

The MMS and the EMMS were demonstrated on the L-Range at the Army Research Laboratory during the week of September 13, 1999. Part of the site was in the open near a tree line, the remainder in the woods where the acoustic system was exclusively used for navigation. In open areas, duplicate surveys were conducted with each navigation system.

The following is a summary of the key results from the L-Range demonstration.

- The MMS system uses the same sensors as the MTADS vehicular system. Data from the two systems are effectively equivalent, interchangeable, and indistinguishable.

- The man-portable EM survey equipment is much less sensitive than the vehicular array. Depending on target size and depth, the 0.5 m X 1.0 m coil produces peak signals 12 to 16 times smaller than that of the vehicular array.

- Coverage in open areas was relatively good. Coverage in wooded areas was unsatisfactory with relatively large areas unsurveyed. The difficulty of using the EMMS in tight areas, combined with excessive backpack loads, difficulty following lane layouts, poor site survey management, and operator frustration all contributed to poor performance.

- The MMS detected all the targets that were characterized using the vehicular magnetometer array. The vehicular magnetometer survey and the MMS/GPS survey results demonstrated that the MMS can provide equivalent field performance to the vehicular system.

- In the EMMS survey using GPS navigation, 14 targets were missed that were characterized in the vehicular EM survey and in all the magnetometer surveys. In every case, a target was missed because either there was no measurable signal in the EM data, or the signal-to-noise ratio placed the target below the limit required for analysis. The navigation error caused by the rocking of the GPS antenna created an additional noise source that tended to smear out a target signal and make it very ragged.

- The acoustic navigation system transmitter does not significantly interfere with the EM sensor. However, use of the acoustic navigation system degrades the location accuracy relative to the GPS system.

Following the L-Range demonstration, it was concluded that although the adjuncts met most of the design performance specifications, they were unsuitable in their present configurations for use as commercial field instruments. Numerous upgrades and modifications were made during FY 2000, the third year of the program, in preparation for the final demonstration of both adjunct systems at the U.S. Army Jefferson Proving Ground (JPG) in southeast Indiana in August 2000.

1.3 JEFFERSON PROVING GROUND DEMONSTRATIONS

1.3.1 JPG-V Demonstration Objectives

The focus of the JPG-V demonstration was to assess the capabilities of the top detection technologies identified during previous JPG demonstrations under more realistic conditions. The intent was to quantify each system's detection, discrimination, cost, and production rates while operating at several areas within JPG containing natural (magnetic rocks and soils) and man-made (munitions fragments) clutter. The survey test areas consisted of three 1-hectare prepared sites located near the 40-acre site used during the JPG-IV demonstrations [6].

The demonstration approach was built around a scenario intended to evaluate technologies that might address the particular demands of the Kaho'olawe Island cleanup. Both inert UXO, ordnance and explosives (OE) scrap, and magnetic soils and rocks were incorporated into the test. Two of the three sites took advantage of naturally occurring magnetic soil deposits. These were augmented by soil and rock samples from Hawaii. The third site was relatively benign geologically. Each demonstrator was required to conduct digitally mapped georeferenced surveys and to conduct target analyses on site as though concurrent remediation would take place. Consequently, each demonstrator was responsible for determining the best method of employing his system to: (a) ensure full coverage of each test area; (b) collect high-quality sensor data to support detection and discrimination requirements; (c) achieve high production rates; and, (d) minimize man-hour requirements and costs.

1.3.2 JPG-V Demonstration Results

The NRL EMMS demonstrated the highest degree of maturity and preparation, and conducted the field surveys and onsite analysis with no problems. Both the MMS and the EMMS demonstrated the capability to suppress high magnetic background from geologic sources and to provide high-quality (well-localized, high signal-to-background target signatures) georeferenced data. The EMMS outperformed the mag-and-flag approach at all three test areas, and the single-point performance points met the Kaho'olawe Tier II requirements. However, the EMMS did not achieve 100% detection at any of the three sites. EMMS mean depth estimation errors were well within the 0.5 m allowable error.

In terms of production rates, the EMMS was the best performer among the advanced technology demonstrators, achieving an average of 1 hectare per 6.56 hours and requiring a field survey crew ranging from one to four persons. In terms of costs, the EMMS was again the best performer with total costs, including assessed penalties, ranging from 11.4% to 27.1% lower than the other demonstrators.

1.4 THE KAHO'OLAWE DEMONSTRATION

During the fall of 2001, ESTCP sponsored a demonstration of hand-held and man-portable electromagnetic induction (EMI) systems on prepared sites on the island of Kaho'olawe [7]. The three better demonstrators from the JPG-V demonstrations were invited to participate [8] and GTL, using a TM-5 EMU frequency domain sensor was incorporated into the demonstration. GTL had worked on the main island cleanup the previous year and the site managers felt the system had merit. Parsons-UXB employed the EM61 systems used on the main island cleanup. For the primary surveys, the wheeled EM61 were used in an EM-and-Flag mode using pin flags to mark targets. During the ESTCP demonstration, the pin flag positions were acquired using hand-held GPS systems. Parsons-UXB used the standard EM61 integrated with a GPS system in a gridded survey of the ESTCP demonstration areas, the system also used in this mode for quality assurance (QA) studies on the main island cleanup.

The demonstration managers prepared a calibration survey area, seeded with ordnance and frag challenges. Ground truth was provided to each demonstrator before they occupied the site. Demonstrators were allowed 1 week to work with the calibration site before moving on the main demonstration sites during the second week.

The demonstration site was adapted from the QA range, which had previously supported the main island cleanup. Additional ordnance and clutter targets were installed prior to the ESTCP demonstration surveys. The demonstration area was divided into three contiguous sites. Area A was 60m X 60 m, Area B was 60m X 90 m and Area C was 90m X ~110 m (1 hectare).

1.4.1 The Kaho'olawe Demonstration Objectives

The demonstration objectives were effectively identical to those incorporated into the JPG-V demonstration. Each demonstrator was required to conduct digitally mapped georeferenced surveys and on-site target analyses as though concurrent remediation would take place. Consequently, each demonstrator was responsible for determining the best method of employing his system to ensure full coverage of each test area, collect high-quality sensor data to support detection and discrimination requirements, achieve high production rates, and minimize man-hour requirements and costs. Deliverables were ranked target dig lists and 2-dimensional anomaly survey maps. Each demonstrator was required to provide location, depth, and size information for each selected anomaly; to attempt to identify ordnance by type for ordnance declarations, and to attempt to differentiate between ordnance and clutter.

1.4.2 Kaho'olawe Demonstration Results

Following analysis of the data from the calibration site during week one of the demonstration, NRL concluded that only about 50% of the UXO targets on the site were realistically detectable. Sensor noise, metallic clutter noise, and geological interferences made the smallest shallow targets and the deeply-buried bombs and projectiles undetectable. The enhanced sensitivity of the NRL EMI system, its relocation with minimal ground clearance, and the shock sensitivity of the receive coil units worked as disadvantages for the EMMS relative to the other EM61 units demonstrated at this site.

1.5 REGULATORY DRIVERS

There are no regulatory issues unique to the man-portable MTADS adjuncts. The primary regulatory issue affecting UXO detection and discrimination technologies is gaining confidence and approval from federal, state, and local regulators, stakeholders, and users. Acceptance of these innovative technologies from agencies such as the USACE and the Naval Facilities and Engineering Command is needed to ensure that future requests for proposals (RFP) for UXO cleanup projects will be written in a manner that will either sanction these technologies or at least allow their inclusion in proposals for UXO site work.

2.0 TECHNOLOGY DESCRIPTION

2.1 BACKGROUND AND APPLICATIONS

The MMS and the EMMS have many common components. The primary platform for each sensor, a wheeled cart, provides relatively smooth operation, permits coordinated deployment of all sensor and navigation hardware during surveys, and maintains the sensors at a fixed height above the ground. By restricting sensor dimensions and the array design to the width of a person's shoulders, the system should be deployable in areas where a person could easily walk.

The initial system requirements and specifications for the MMS and EMMS are summarized in Table 1 [4]. Note that these requirements and specifications were for the MMS and the EMMS as configured for the L-Range demonstrations.

Table 1. System Requirements and Specifications for the MTADS Man-Portable Adjuncts.

System Specification/ Requirement	MMS	EMMS
Continuous operating time	2 hours	2 hours
Survey area (single setup)	1 acre	1 acre
Lane spacing	0.5 m	0.5 or 1.0 m
Sensor sensitivity	0.1 nT (same as vehicular MTADS)	Scalable to vehicular MTADS
Sensor data rate	10 Hz	10 Hz
Navigation data rate	GPS 5 Hz Acoustic 1 Hz	GPS 5 Hz Acoustic 1 Hz
Sensor position accuracy	GPS 0.1 m Acoustic 0.25 m	Same as MMS
Sensor height above ground	0.25 m (fixed)	0.25 m (fixed)
Data acquisition system (DAQ)	Compatible with vehicular DAQ based on modified Geometrics 858 data recorder	Same data recorder as the MMS
Data analysis system (DAS)	Seamless integration with vehicular data	Same as MMS

2.2 COMPONENT DESCRIPTIONS [4]

2.2.1 Sensors

The MMS sensors are Geometrics 858 ROV Cesium Vapor magnetometers, identical to those on the MTADS vehicular system. Geonics, Inc. developed new EM sensors for the EMMS. The design of the 0.5 m X 1.0 m coil system allows the system to be used as 0.5 m-wide instrument in tight or confined spaces or as 1.0 m-wide system in more open applications. The sensitivity of the 0.5 m coil was supposed to be increased by additional turns in the transmit coil.

2.2.2 Platforms

Both the MMS and the EMMS are designed with the sensors and the navigation antennas mounted on two-wheeled carts. The operator wears a specially designed backpack containing batteries and navigation hardware. Figure 1 shows the prototype MMS survey system operating with the GPS navigation system.

The commercial Geonics EM61 coils are delivered with a two-wheeled transport system (Figure 2). Either the 0.5 m X 1.0 m or the 1.0 m X 1.0 m coils may be used as a single cart. The cart and antenna support system rigidly hold the top and bottom coils in place, with the GPS or acoustic antenna center-mounted above the upper EM coil. Rigidity is required because the GPS antenna has a significant signal at the upper coil, which must be nulled as part of data preprocessing. Because of the excessive weight of the system batteries and the GPS instrumentation, the equipment was split between two backpacks for the L-Range demonstration (see Figure 2). When using the acoustic navigation system, all equipment fits into one backpack thus permitting a single operator to take survey data.

Figure 1. MMS Prototype System Deployed at the L-Range Demonstration.

Figure 2. EMMS Prototype System Deployed at the L-Range Demonstration.

Figure 3. Geometrics Model 858 Data Logger.

2.2.3 Data Acquisition System (DAQ)

The modified Geometrics 858 data recorder shown in Figure 3 is the backbone of the man-portable survey equipment. The standard Model 858 commercial system is configured with dual cesium vapor sensors and comes with one RS-232 COM port access to the palmtop data storage device. Two battery packs are included with operating times of 6 hours each. The data logger stores 2.5 Mb of data or about 4.5 hours in the MMS configuration in which the GPS is recorded at 5 Hz and the sensors at 10 Hz.

The Model 858, as modified for use with the MMS and the EMMS, has three additional COM ports to accommodate GPS GGK string input at 5 Hz, acoustic navigation data from the Ultra Sonic Ranging and Data System (USRADS) Data Pack at 1 Hz, and either 1 pulse per second from the Trimble 7400 receiver or the sync pulse from the acoustic navigation system.

The Geometrics 858 can be mounted on the sensor platform as shown in Figure 3 or worn in a fanny pack on the operator's waist.

2.2.4 Navigation

Trimble Model 7400 GPS receivers, currently used by the vehicular MTADS, were also used for the MMS demonstration at the L-Range. This system, operating with a Model 4000 SSI base station receiver, provides the full range of GPS location options. In the highest precision or level 3 fix (real-time kinematic [RTK]), the base station provides differential position fixes with fully resolved numerical ambiguities, yielding real-time location accuracies of 2-5 cm. A level 2 fix (Float) is accurate only to 10-50 cm because some of the integer ambiguities remain unresolved in the solution. The level 4 fix, the traditional differential solution, may have its accuracy degraded to 0.5-1.0 m depending on the number and position of the satellites in the solution. MTADS surveys are begun with only a level 3 fix. During a survey, if the fix quality briefly drops to level 2, offsets and corrections are implemented in the data cleanup process. Survey data based on lower quality fixes are generally not used in MTADS surveys.

The Chemrad Navigation System (USRADS Model 2300) provides acoustic navigation data when satellite visibility will not support GPS navigation. This system includes an acoustic transmitter on the rover platform and a network of up to 10 transponders at fixed stations deployed about the perimeter of a survey site. The system uses time-of-flight (speed-of-sound) data to triangulate among all possible pairs of transponders to create a location position which is updated at 10 Hz. Based on evaluation testing in wooded areas, the USRADS system can provide navigational fixes accurate to ~25 cm when 10 stationary receivers are used to enclose a 1-acre wooded site. Under good conditions, the acoustic sensors have a range of about 200 ft. This accuracy is degraded in either high wind or high noise environments, or when visibility is limited by obstructions. Deployment strategies are critical to the successful use of this system.

2.2.5 Data Analysis System (DAS)

The MTADS data analysis system (DAS) has been modified to accept data from the MMS, to fully integrate vehicular and man-portable data or multiple MMS data sets, and to provide the same analysis capabilities. When preprocessing is complete, magnetometry data from either the MMS (using either GPS or acoustic navigation systems) or the vehicular system can be combined into single survey data sets. For instance, wooded areas within a larger vehicular survey area would be surveyed with the MMS (and acoustic navigation) and edited to fill in areas inaccessible to the vehicular MTADS. In general, data from multiple surveys of the same areas are not commingled, the better data being used for any given area.

This approach is not used for data taken with the EMMS. Because of the different sensitivities of the various EM coil systems and the various deployment options, EMMS data are processed separately from vehicular EM data. The baseline MTADS DAS currently has all necessary utilities, routines, and switches to allow processing of data from all vehicular and man-portable setups regardless of the navigation system used to survey.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

The MTADS vehicular system, on which the MMS and EMMS are based, was extensively demonstrated at the following locations.

- NRL's Chesapeake Bay Detachment, Chesapeake Beach, Maryland, October 1996 [8].
- Marine Corps Air Ground Combat Center, Twentynine Palms, California, December 1996 [9].
- Jefferson Proving Grounds, Madison, Indiana, January 1997[10].
- Badlands Bombing Range on the Pine Ridge Reservation, South Dakota, July 1997 [11].
- The former Fort Pierce Naval Amphibious Base, Vero Beach, Florida, January 1998 [12].
- The former Buckley Field, Aurora, Colorado, June 1998 [13].
- Laguna Pueblo Reservation in New Mexico, July 1998 [14].
- Portsmouth Naval Shipyard, Kittery, Maine, October 1998 [15].
- The JPG-IV Data Fusion Demonstration, October 1998 [16].
- Walker River Reservation, Shurz, Nevada, November 1998 [17].

Based on the success of these field demonstrations, NRL signed a CRADA with a commercial company, and a nongovernment system has been designed and built based on the NRL MTADS. This system, including both the vehicular and man-portable platforms, is currently in commercial use.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

There are many advantages associated with these systems. The MMS and EMMS were designed to extend the MTADS survey capability into rugged terrain that cannot be traversed by the tow vehicle. The acoustic navigation system extends the survey capability into areas with limited sky view, including those under forest canopies. The wheeled MMS cart is designed to be pushed ahead of the operator, allowing the operator to maneuver through fairly tight spaces. The width of the cart and sensor arrays are designed to be at or below the width of the operator's shoulders. Wider EM coils are available for areas with less severe space constrictions.

One disadvantage of this design is that access is precluded by areas that are very tight and by areas that have difficult ground cover such as brush, deep mud, or extremely rugged terrain.

3.0 L-RANGE DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary objectives of the MMS and EMMS projects were to develop and demonstrate man-portable adjuncts to the vehicular MTADS to support UXO surveys and remediation operations in areas that are too rugged for operation of the vehicular MTADS and in areas without adequate sky view for effective use of the GPS navigation system [18].

The overall performance objectives for the MMS and EMMS adjuncts to the vehicular MTADS include the following.

- The detection sensitivity of the adjunct sensor platforms should match those of the vehicular arrays to the greatest extent possible.
- A single DAS should support both the magnetometer and EM platforms operating with either GPS and acoustic navigation.
- Acoustic navigation data must be compatible with and mergeable with GPS-based data.
- The man-portable DAQ output formats must be compatible with the vehicular MTADS DAS.
- Survey data from the man-portable platforms must seamlessly merge with vehicular data.
- Performance of the man-portable systems must meet the requirements and specifications in the program development plan.

3.2 PERFORMANCE METRICS

3.2.1 Target Location Accuracy

The test field surveys were conducted with each of the vehicular MTADS platforms and with the MMS and EMMS using both GPS and acoustic navigation. The man-portable demonstration area on the L-Range was seeded with 18 inert ordnance items, 12 in GPS-accessible areas, and six in the woods. The positions of these items were precisely known. Twelve of the items appear in all six surveys. The six items in the woods were surveyed only with the man-portable systems. Comparisons among the systems are made as well as evaluations of the absolute target location accuracies.

3.2.2 Survey Integration

MMS and EMMS surveys from the wooded areas were integrated with their GPS counterparts on the open range and with vehicular MTADS surveys. Target analyses were carried out on these merged data sets to verify that the DAS software modifications accommodated integration of man-portable data with vehicular data and integration of acoustic navigation data with GPS navigation data.

3.2.3 System Operational Performance

Field logs, to be kept for all survey activities, provided information about setup times, survey times, production rates, and equipment performance. Specific attention was paid to issues relating to battery operational times in the field, file creation and data storage capabilities, and the performance of the highly modified Geometrics Model 858 data recorder. Field notes were made about the operational performance of the man-portable carts in open areas and in the woods. Experiences with the setup of the acoustic sensors in open areas and in the woods were recorded along with weather conditions at the time of the surveys.

The electronic data files provided additional information about field survey performance by documenting survey data collection times, the course and paths used in data collection, stoppages during data collection, how turnarounds were accomplished, and how well surveyors lined up to begin their survey paths. Missed areas were determined, and difficulties with navigational data were documented.

3.2.4 Detection Capability

The magnetometers on the vehicular and man-portable systems are identical, as are their spacing and heights above ground. Data acquisition rates are set to provide similar data densities from both man-portable and vehicular surveys. Therefore, differences between man-portable and vehicular surveys should be a result of platform and motion-induced noise levels and the relative ability of the navigation systems to accurately track the positions of the sensors. MTADS DAS-generated plots of individual sensor measurements as a function of time were used to evaluate and quantify the relative importance of various noise sources in the data and their effect on the detection sensitivity of the man-portable and vehicular magnetometry systems.

The EMMS sensor records a significantly smaller signal over any individual target than does the vehicular EM array. The absolute detection sensitivity of the EMMS system was determined from test pit and test field data. Relative signal-to-noise issues and their effect on detection sensitivity were evaluated in the same manner as described in the previous paragraph for the man-portable and vehicular magnetometry systems.

3.3 SITE SELECTION

An area at the Army Research Laboratory Blossom Point facility was chosen for the man-portable demonstration site. A part of the L-Range is shown in an aerial photograph in Figure 4. This area, 800 feet wide by 5000 feet long and encompassing about 95 acres, has been a test range for various munitions. The range is bordered on the south (river side) by a mixed pine and hardwood forest. The range itself is generally flat, grass covered, and regularly mowed. The forest bordering the range varies from open woods to rugged areas with extensive underbrush. The 3-acre area designated for the ESTCP data fusion demonstration is outlined in yellow. The MMS and EMMS demonstration areas are outlined in red. The entire area within the red boundary was surveyed with the EMMS and MMS platforms using the acoustic navigation system. The portion of the site accessible to the GPS navigation system was similarly surveyed with each portable system. The entire area within the yellow boundary was surveyed with both the magnetometer and EM vehicular MTADS arrays.

Figure 4. L-Range at Blossom Point.

3.4 TEST SITE/FACILITY HISTORY AND CHARACTERISTICS

The Army Research Laboratory's Blossom Point Test Range in Charles County, Maryland, on the tip of Cedar Point Neck near La Plata—approximately 50 miles south of Washington, D.C.—has been used for ordnance testing and research since 1942. During World War II, Harry Diamond and his team at the National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST), needed open areas where they could test fuzes. In early 1943, NBS leased land, establishing this proving ground for proximity fuzes at Blossom Point. By September 1945, 14,000 rocket and mortar rounds had been fired on various ranges on the site.

In 1953, the lease on the property was transferred to the Army, which operated the property as a fast-reaction, low-cost range for experimental work. During the Vietnam War, the Army's Harry Diamond Laboratory was very active at the site. After the war, the Army phased out Blossom Point, intending to transfer the work to Aberdeen. The facility was reactivated in January 1976 for continued research on fuzes. In 1980, the Army purchased the property for $2.7 million.

3.5 PHYSICAL SETUP AND OPERATIONS

The entire L-Range was surveyed using the vehicular MTADS magnetometer array. Survey areas were selected to assure that many buried targets would exist within the demonstration area, but that the density of buried clutter would not be so high as to preclude analysis of most buried targets as single items. This was particularly important in the data fusion demonstration, as analysis algorithms intended to recover target shape information were being evaluated. The survey areas selected could be extended seamlessly into the woods and included both open and wooded areas.

UXO benchmark items were seeded into the demonstration area to provide additional ground truth for evaluating the relative performance of the MMS and EMMS using each navigation system. The dimensions of the survey area were expanded over those shown in Figure 4 (in red) to allow placement of seed targets in relatively clear areas. Figure 5 shows a portion of the vehicular MTADS magnetometer survey with the expanded site perimeter outlined in white. This image provides an impression of the densities of buried ferrous targets on the L-Range. The man-portable survey area extends an additional 35 meters into the woods.

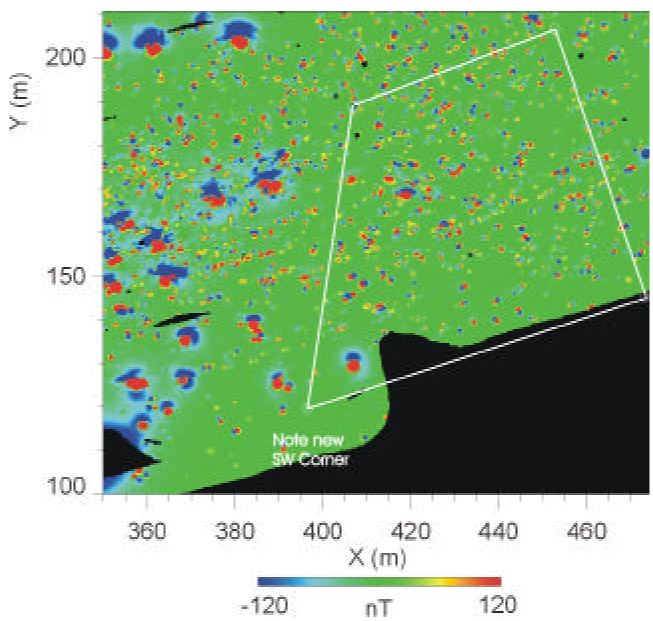


Figure 5. Magnetic Anomaly Map from a Vehicular MTADS Survey.

The inert items detailed in Table 2 range in size from M-23s (three-lb practice bombs) to 105-mm projectiles. Vehicular MTADS surveys were used to choose burial sites near the woods that were relatively clear of other buried objects. Inert UXO seed targets buried in the woods were sited using hand-held metal detectors to define relatively clear burial sites. Backhoes and shovels were used to excavate for the seeded items. Items buried in open areas were located using GPS, whereas items buried in the woods were located using laser survey equipment operating from GPS benchmarks. Orientations and depths to the ordnance centers were recorded prior to backfilling and tamping of the soil to minimize subsidence. While the seed items were being buried, the wooded survey site was partially cleared of brambles and underbrush. No trees or large saplings were removed, and some areas were left with brush cover that would be difficult to walk through with the MMS and EMMS. It was expected that 10-15% of the wooded site would not be accessible to either man-portable instrument.

Before beginning the man-portable surveys, the vehicular MTADS was used to survey the area outlined in yellow in Figure 4, again using both the magnetometer and EM arrays. The survey was extended to get as close as possible to the woods while maintaining acceptable GPS navigation fix quality.

Table 2. Identification and Locations of the Inert UXO Seed Targets.

Target No	UXO ID	Location		Location Universal Transverse Mercator (UTM)		Depth (m)	Azi.* (deg)	Incl.** (deg)
		Longitude	Latitude	Northing	Easting			
T-1	81-mm	38.408114616	-77.103106356	4253192.0	316371.4	0.21	45	45
T-2	M-23	38.408182890	-77.103135897	4253199.7	316369.0	0.15	0	0
T-3	4.2-in	38.408279866	-77102816841	4253209.8	316.397.1	0.63	45	45
T-4	105-mm	38.408362672	-77102673710	4253218.7	316409.8	0.69	45	45
T-5	2.75-in	38.408226790	-77.102714295	4253203.7	316405.9	0.30	90	0
T-6	M-23	38.408258385	-77.102623238	4253207.0	316413.9	0.18	45	0
T-7	81-mm	38.408306797	-77.102575035	4253212.3	316418.2	0.43		90
T-8	81-mm	38.408288164	-77.102524670	4253210.1	316422.6	0.28	0	0
T-9	2.75-in	38.408321734	-77.102495520	4253213.8	316425.2	0.28	0	45
T-10	81-mm	38.408324947	-77.102430749	4253214.0	316430.9	0.51	45	0
T-11	M-23	38.408367373	-77.102281185	4253218.4	316444.0	0.20		90
T-12	M-23	38.408374777	-77.102240512	4253219.2	316447.6	0.15	45	45
T-13	2.75-in	38.407993265	-77.102011424	4253176.4	316466.7	0.30	0	90
T-14	2.75-in	38.408122587	-77.102093780	4253190.9	316459.8	0.30	90	
T-15	M-23	38.408107204	-77.102238338	4253189.5	316447.1	0.15	0	0
T-16	M-23	38.40993279	-77.102292141	4253176.9	316442.2	0.15	45	0
T-17	60-mm	38.407977164	-77.102425350	4253175.4	316430.5	0.30	0	45
T-18	81-mm	38.407903350	-77.102445624	4253167.3	316428.5	0.48	45	45

* Azi. = Orientation in the plane of the Earth's surface; 0 (deg) is the vector pointing true north.
** Incl. = Target dip angle relative to the Earth's surface; 0 (deg) is in the surface plane; 90 (deg) refers to the target nose pointing down.

The corners of the survey areas were established by the GPS surveyor and marked by bicycle flags. In preparation for the man-portable surveys, wooden stakes were driven at 1-m intervals along the east and west boundaries of the survey area. Twine was used to connect the east and west stakes defining the survey lanes. In the woods, additional stakes were used within the site to maintain lane spacings as the twine snaked around trees and through the brush.

3.6 SAMPLING AND MONITORING PROCEDURES

MMS and EMMS surveys were conducted using 0.25-m lane spacings. During surveys using the GPS navigation system, survey times were chosen to allow good GPS coverage while working adjacent to the woods. A single acoustic navigation beacon setup was used to conduct the MMS and EMMS surveys in the open area shown in Figure 5. A second acoustic navigation beacon setup was used to conduct the surveys within the woods. Man-portable surveys of the open area required 3-3.5 hours with each system. Surveys of the wooded area required about 3 hours each, including setup of the acoustic navigation system.

As shown in Table 3, parts of the man-portable survey area were covered by seven separate surveys—two vehicular EM surveys, one vehicular magnetometer survey, two MMS surveys (with GPS and acoustic navigation), and two EMMS surveys (GPS and acoustic navigation). The area in the woods was surveyed only by the MMS and EMMS using the acoustic navigation system.

Table 3. Survey Log for the Vehicular and Man-Portable Surveys.

Platform	Navigation	Survey Area	Survey Date	Survey Time
Vehicle/mags	GPS	Fusion/MP open area	7/28/99	126 minutes
Vehicle/EM (East/West)	GPS	Fusion/MP open area	8/3/99	294 minutes
Vehicle/EM (North/South)	GPS	Fusion/MP open area	8/3-4/99	267 minutes
MMS	GPS	MP open area	8/5-6/99	208 minutes
EMMS	GPS	MP open area	8/6/99	196 minutes
EMMS	Acoustic	MP open area MP woods	8/9-11/99	216 minutes 145 minutes
MMS	Acoustic	MP open area MP woods	8/12/99 8/10-11/99	170 minutes 165 minutes

4.0 L-RANGE PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

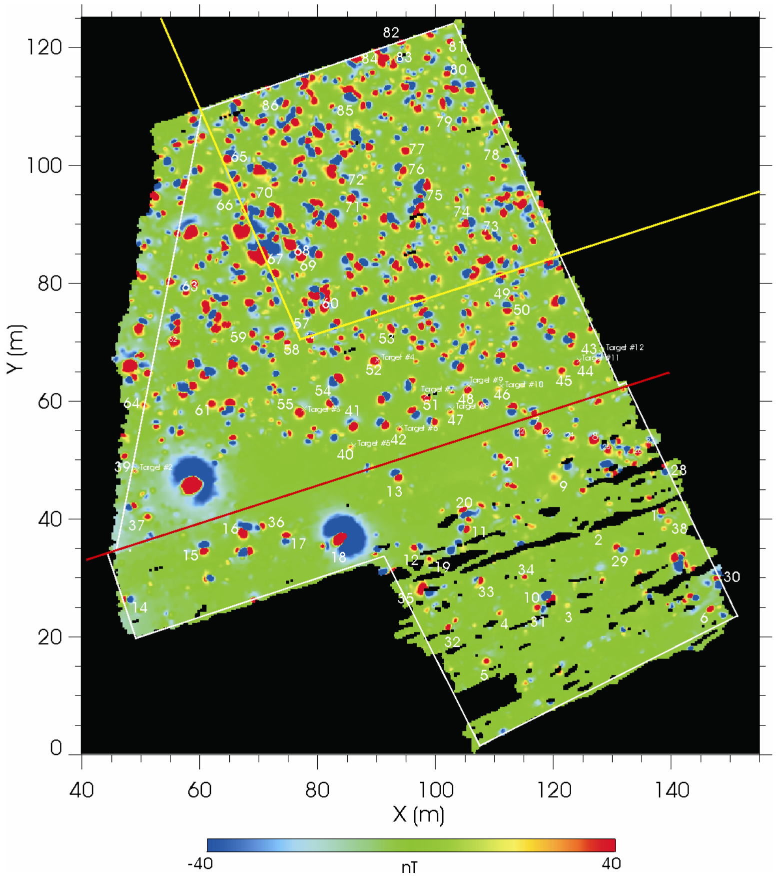


Figure 6. Magnetic Anomaly Image of the Man-Portable Survey Area Taken Using Acoustic Navigation.

In the man-portable magnetic survey shown in Figure 6, the area within the white perimeter constitutes the man-portable survey area. The area south of the red line was within the woods and could not be surveyed using the GPS navigation system. The largest missed area within the woods was excluded because it contained a dead deer. Because there were no seed targets within that area, it was not surveyed. Other apparent missed areas included groups of trees or brush that could not be navigated with the magnetometer cart. Some of the seeded targets are identified in the image and labeled with their target numbers.

Figure 7 shows two of the EM surveys. The east-west vehicular MTADS survey is shown on the left, whereas the EM man-portable survey using acoustic navigation is shown on the right. Two visual impressions are immediately apparent. First, the man-portable EM survey equipment is much less sensitive than the vehicular array. Note the sensitivity levels on the plots. Depending on target size and depth, the 0.5 m X 1.0 m coil produces peak signals 12-16 times less intense than that of the vehicular array. The peak signal strength from the 1.0 m X 1.0 m man-portable EM coils is about four times less intense than that of the vehicular array. The sensitivity of the 0.5 m and 1.0 m coils scale directly with the area of the transmit and receive coils. Only the 0.5 m X 1.0 m man-portable coils were used in this demonstration. The results of this decreased sensitivity becomes apparent when the performance of the system is analyzed.

Second, the EMMS survey coverage in the woods was poor compared with the coverage of the MMS survey, the result of poor quality control in the survey process. Either a complete survey was not taken or survey files were lost, leaving gaps in the coverage. The extent of the missed areas was not realized until it was too late to recover and resurvey those areas. In retrospect, the wooded areas should have been surveyed in orthogonal directions to improve coverage. In a real

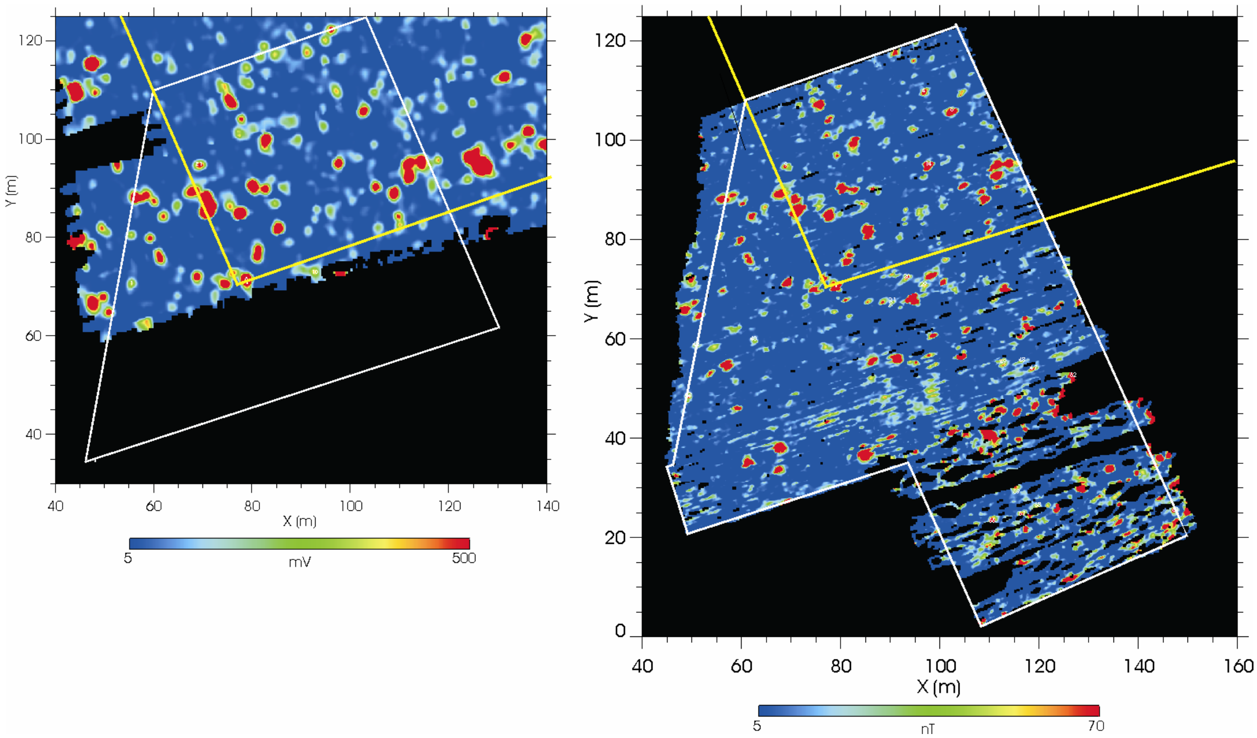


Figure 7. EM Anomaly Images of the Man-Portable Survey Area Showing the MTADS Vehicular Survey Using GPS (left) and the EMMS Survey Using Acoustic Navigation (right).

world operation, to assure complete coverage and detection of all UXO, hand surveys using metal detectors would be required to survey in brushy areas and in missed areas adjacent to trees.

A summary of the recovered items is shown in Table 4. Recovered OE scrap items included shrapnel, tail fin assemblies, and spent fuzes. Nonordnance related materials included pieces of iron or steel such as angle iron, bolts, hardware, or coils of wire or cable. Some ordnance items recovered were split, broken, or bent. Several were challenged with 1-in shape charges.

Table 4. Results of Target Recovery in the Man-Portable Survey Area.

Item	Seed Targets	60-mm Mortar	81-mm Mortar	4.2-in Mortar	25-lb Frag Bomb	5-in Rocket	OE Scrap	Non-OE Scrap
Number recovered	18	1	14	1	1	1	43	11

4.2 PERFORMANCE CRITERIA

Performance evaluation criteria include system detection sensitivity, accuracy of location and depth predictions, navigation system performance, and operational and ergonomic efficiency of the man-portable units.

4.3 PERFORMANCE ASSESSMENT

4.3.1 Detection Sensitivity

The ability to detect targets depends primarily on the sensitivity of the sensors, the completeness of the survey coverage, and the signal-to-noise ratio in the survey data. The MMS system uses the same sensors as the MTADS vehicular system. The sensor's horizontal separation and height above the ground are identical to the vehicular system, and data sampling rates are such that the sampling density of the two systems are approximately equivalent. The signal-to-noise ratios in data taken by the two systems are also similar. Carefully laid out surveys conducted with the MMS provide similar detection and performance capabilities to the vehicular system. Data from the two systems are effectively equivalent, interchangeable, and indistinguishable.

The EMMS, as configured for the L-Range demonstration, was deployed with 0.5 m X 1.0 m coils. Based on the areas of the send and receive coils and a 50% overlap of transmitters in the vehicular system, one would expect the 0.5 m instrument to record six times lower signal strengths than the vehicular system for the same test object. Although this would lower the sensitivity of the EMMS relative to the MTADS array, it was not expected to significantly limit its ability to detect targets because the MTADS array system is extremely sensitive to small, shallow targets. In reality, the new coil systems were not completely equivalent to the units in the MTADS array. Measurements with electronic test equipment showed somewhat different system setup parameters. Measurements on a test stand using standard objects confirmed the lower sensitivity.

In addition, as deployed at the L-Range, the EMMS using the wheel mounting system supplied with the instrument placed the lower coil 0.4 meters above the ground. The vehicular MTADS, depending on the suspension system being used on the tow vehicle, typically deploys the coils about 0.25 meters above the ground. Figure 8 shows a comparison of a small part of the L-Range survey area taken from the vehicular and man-portable surveys. Note the difference in display scales. The EMMS, as used in this demonstration, is 10-15 times less sensitive than the vehicular MTADS. The absolute differences are also a function of the size and depth of the test objects. The EMMS, as configured for this demonstration, provides data sample densities equivalent to, or slightly higher, than the vehicular system.

The deployment of the GPS antenna high above the coils on the EMMS introduces an additional noise source in the data. When the system traverses over rough areas, side-to-side rocking motions can easily displace the antenna by half a meter horizontally from the center of the coils. Because the system is behind the operator, this motion often goes unnoticed or uncontrolled.

The acoustic navigation system transmitter does not significantly interfere with the EM sensor. The transmitter is typically deployed at the center of the upper EMMS coil.

Target detection capability depends on being able to deploy the sensor. To test the ability of the man-portable systems under realistic survey conditions, much of the survey area was in the woods and much of that area was left relatively uncleared. The EMMS coils were deployed in the narrow (0.5 m wide) orientation, and 0.25 m survey lanes were used to maximize coverage. As shown in Figure 7, coverage in open areas was relatively good. Coverage in wooded areas was unsatisfactory with relatively large areas left unsurveyed. Some of the area was inaccessible because of system design limitations. The difficulty of using the EMMS in tight areas, combined with excessive backpack loads, difficulty following lane layouts, poor site survey management, and operator frustration all contributed to poor performance.

Survey performance in the woods could have been improved either by conducting a second survey in an orthogonal direction to fill in some of the missed areas or by using the bush hog to clear remaining brush and undergrowth before a resurvey. In reality, however, the primary lesson learned from the EMMS deployment at the L-Range was that more development was required.

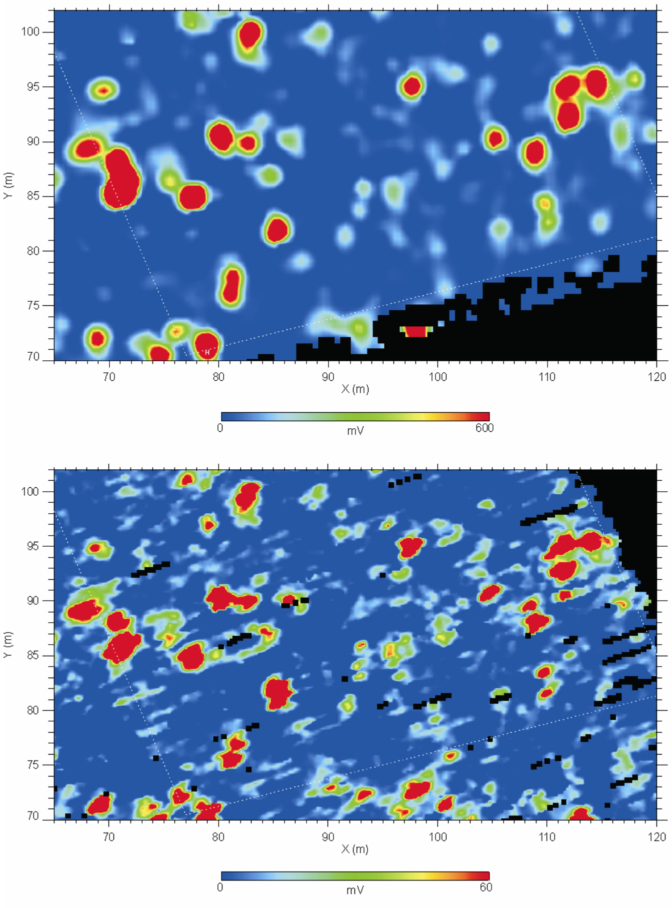


Figure 8. Vehicular (top panel) and EMMS (bottom panel) EM Surveys from the L-Range.

4.3.2 Missed Targets

Primary system performance was measured against the seeded targets. Secondary considerations were given to the performance of the man-portable systems relative to the MTADS vehicular system, the performance of the man-portable systems using GPS versus acoustic navigation, and the performance of the MMS compared with the EMMS. The MMS detected all targets characterized using the vehicular magnetometer array and with one exception, detected and analyzed all the seed targets in each of the surveys that covered their positions. (Seed target T-14 was not detected by the MMS because it fell in a missed survey area.)

In the EMMS survey using GPS navigation, 14 targets were missed that were characterized in the vehicular EM survey and in all the magnetometer surveys. Coverage by the EMMS in the open range area was good. In every case, a target was missed because either there was no measurable signal in the EM data or the signal-to-noise ratio placed the target below the limit required for analysis. The navigation error caused by the rocking of the GPS antenna created an additional noise source, which tended to smear out a target signal and make it very ragged. (See

Figure 8.) In some cases, this created a situation in which the fit algorithm would not converge. In other cases, it was difficult to identify a target signal in the relatively noisy background.

Performance evaluation on the entire range area can be made by comparing the MMS and EMMS surveys using the acoustic navigation system. The MMS survey contains 21 targets that were undetected in the EMMS survey. Of the 21 missed targets, 9 targets (in the woods) were in areas missed by the EMMS survey. In the remainder of the cases, the EM signal was undetectable or too weak for analysis.

4.3.3 Target Location

Table 5 summarizes the performance of the various systems in pinpointing the positions of the seed targets. The ground truth positions are those measured by the surveyor at the time the targets were buried.

Table 5. Errors in Predicted Location and Depth for Seed Targets at the L-Range.

Survey	Vehicular Mag/GPS	Vehicular EM/GPS	MMS/ GPS	MMS/Acoustic	EMMS/ GPS	EMMS/Acoustic
Horizontal error (cm)	11	21	11	43	26	60
Depth error (cm)	5	29	5	11	(*)	(*)

(*) At the time of the demonstration, the fitting algorithms in the DAS were not calibrated with the new coil signals to provide meaningful depth predictions.

The location and depth prediction capabilities of the vehicular MTADS systems were equivalent to that system's performance in many prior demonstrations. Targets are typically located to within 10-15 cm with the magnetometer array and 20-25 cm with the EM array. Depth predictions of the MTADS DAS based on magnetometer data are typically within the volume of the UXO item. Depth predictions using the point dipole algorithm with EM data are less reliable. The vehicular magnetometer survey and the MMS/GPS survey results demonstrate that the MMS can provide equivalent field performance to the vehicular system.

4.3.4 Acoustic Navigation System

Use of the acoustic navigation system degrades the location accuracy relative to the GPS system. With careful use, however, position uncertainties of 0.25 m with the acoustic navigation system can be used to hold target location predictions to <0.5 m. In conducting acoustic navigation surveys in open areas, site dimensions should not exceed 200 feet in any direction. Antenna locations should surround the perimeter of the site, and it is helpful to have an antenna centrally located within the site. System performance degrades when there is high background noise interference. Even wind blowing through knee-high grass raises the operational threshold of the antennas (to exclude noise) to a level that noticeably degrades system performance.

A single antenna setup was used to survey the wooded part of the L-Range. This setup worked satisfactorily even though many of the antennas were not directly (line-of-sight) visible to each other because of elevation changes or because trees and brush obstructed visibility. A careful initial setup is required. Three of the antennas should be at known coordinates, and it is recommended that system performance be evaluated against a known position within the survey area before undertaking a survey. Even though this system was difficult to use, it was the best available (non-GPS) automated navigation/location system that could be used to conduct digitally mapped UXO surveys.

4.3.5 Ergonomics

Mechanically, the MMS performed satisfactorily in the L-Range demonstration, and the system performance as a UXO survey tool met all system design specifications. However, the system was not appropriate for transition to commercial applications where it would be used in more demanding conditions by less skilled operators.

EMMS system performance was disappointing on several levels. Cost constraints in system development and integration led to use of existing equipment that was too heavy and bulky for backpack applications. The system design, based on a narrow coil mounted on a trailing cart supported by high wheels, had poor usability. The electronic performance of the newly purchased coil systems proved to be too insensitive for dependable UXO surveys for either shallow or deep targets. A complete redesign of the EMMS was undertaken in preparation for the final demonstration.

5.0 TECHNOLOGY MODIFICATIONS PRIOR TO JPG-V DEMONSTRATION

5.1 COMPONENT CHANGES IN THE FINAL PROTOTYPES

Following the L-Range demonstration, additional system development and a new system demonstration was required to produce MTADS man-portable adjuncts that could be commercialized. ESTCP supported this development. The final prototypes were demonstrated during field surveys at the Jefferson Proving Ground in the summer of 2000 [6, 18].

5.2 SUBSYSTEM COMPONENT UPGRADES

Each system subcomponent was reconsidered from a requirements and performance perspective [18]. Only one significant change was made to the system performance specifications. Given the difference in performance of the vehicular EM arrays and what would become the final man-portable EM array, it was unrealistic to attempt to develop the DAS so that man-portable and vehicular EM survey data could be used interchangeably. The DAS was modified to separately accept and fit either vehicular or EMMS data, but no attempt was made to create a conversion that would make the two data sets equivalent.

5.2.1 Cabling

There were too many cables and connectors used to interconnect system components (batteries, sensors, navigation components and data logger) and they were not rugged enough for sustained field work, so the number of cables was reduced. New cables with improved strain-relief connectors were designed for connection to interface plates in the new backpacks.

5.2.2 Batteries

Each component of the man-portable prototypes was delivered by its manufacturer with an individual battery pack. The capacity of these battery packs ranged from several days for the acoustic location system to 1.25 hours for the EM61. In operation, this meant that EM battery change-out occurred every hour while carrying other heavy long-life batteries. New battery requirements were established that required 1-hour performance with a 25% excess capacity. Powering the new EM coils required a new lead-acid battery, which was placed on the system cart as discussed below. Battery chargers and batteries were purchased to permit day-long, continuous surveys.

5.2.3 Data Logger

The original modifications to the Geometrics 858 data recorder greatly increased its flexibility and usability with the MMS and the EMMS. However, the operator did not have real-time display access to GPS fix quality. For the L-Range demonstrations, fix quality requirements were accommodated by planning to survey when good satellite visibility was assured. In a real-world environment, this was unacceptable. Additional modifications to the data logger were made to display the GPS fix quality and to sound an alarm when the quality dropped below Fix

Quality 3. The enhanced Geometrics 858 data logger is now commercially available from Geometrics.

5.2.4 MMS Sensor Cart

The design of the magnetometer cart for the L-Range demonstration with its mounts for the antenna/transponder, introduced ease of use and minimal weight. Although the cart performed acceptably, the tests were not in difficult terrain. Subsequent analysis showed that a major increase in strength and reliability could be obtained with a small weight penalty.

Figure 9. MMS Deployed with Protective Hood and GPS Navigation Hardware.

Figure 10. MMS Deployed on Area 3 at JPG.

The magnetometer cart was redesigned for improved ruggedness and ergonomics. The new cart, shown in Figure 9 with the hood on and in Figure 10 with the hood off, is constructed of a combination of fiberglass and plastic components. With wheels side by side between the sensors, this design works better in tight spaces and on rugged and uneven terrain. The hood protects the sensors and the antenna and allows the system to slide through grass and low brush without snagging the cart or sensors. The height of the handles and the weight that the operator has to carry in his hands represents a considerable ergonomic improvement over earlier designs. The complete system can be operated by a single operator for an extended time without tiring. MMS weighs 52 pounds with the hood and 38 pounds without. The total backpack weight is 18 pounds.

5.2.5 EMMS Sensor Cart

In the case of the EM61, deploying the prototype with the wheels provided by the manufacturer positions the transmit coil 40 cm above the ground. Because the measured EM signal falls off as $1/r^6$, a large increase in signal (and thus sensitivity for relatively shallow objects) can be obtained by lowering the sensor. Following delivery and acceptance of the new EM sensor, a new EM cart was designed and built to support the system. It is more rugged, more pitch and roll stable, provides better weight balance in front of and behind the wheels to minimize carry weight for the operator, and incorporates a new design that put the sensors in front of the operator.

The design of the sensor trays permits the sensor to be mounted with the long dimension either across the track or pointing down the track, as shown in Figure 11. The new sensor coils require a heavy lead-acid battery for power. The system is designed to collect data for 1 hour before battery change out. Depending on the orientation of the coils, the battery is mounted to minimize the signal from the plates at the receive coils and to balance the weight over the wheels. The weight the operator has to lift is not large, but the weight of the total system, including battery, cart, coils, and antenna, is 110 pounds, and pushing this load proved difficult in rugged terrain or in deep mud. The redesigned backpack and system components permit the operator to carry all components in a 31-pound backpack.

Figure 11. EMMS Shown with Digital Inclinometer and GPS Navigation Hardware.

The MMS and EMMS, when deployed with the acoustic navigation system, have the ceramic transmitter deployed directly above the sensors. The transmitter does not interfere with either sensor. The transmitter is shown deployed on the EMMS in Figure 12.

Figure 12. EMMS Deployed with the Acoustic Navigation Transponder.

5.2.6 EM Coil

Geonics developed a new 0.5 m X 1.0 m coil system that is more sensitive than any prior EM61 system. Changes in coil design, power delivery system, and detection electronics improved both the transmit power and the signal detection sensitivities of the sensor. The coil, as currently deployed on the EMMS, can be purchased as a standard product from the manufacturer. The increased transmit power required a substantial increase in battery capacity. The Powersonic Model 12330 (33 amp-hours) met the increased requirement. A battery charging system allows five batteries to be charged simultaneously, permitting continuous operation of the EMMS for a full day.

5.2.7 DAS

An upgrade to the MTADS data analysis system accommodates new developments in this program as well as other ESTCP UXO programs. The current DAS has switches to allow target analysis of survey data with algorithms tailored for the new coil. As part of the shakedown process for the new MMS and EMMS instruments, new data sets were obtained from the test pit for a wide range of inert ordnance items. These data sets were incorporated into the ordnance library.

This page left blank intentionally.

6.0 JPG-V DEMONSTRATION DESIGN

ESTCP funded technology demonstrations at the JPG in Madison, Indiana, at three 1-hectare areas near the 40-acre site used during the JPG Phase IV demonstrations [16]. The technical objective of this demonstration [19] was to evaluate detection and discrimination capabilities and cost and production rates of three advanced UXO systems in magnetic clutter environments such as those encountered at Kaho'olawe, Hawaii.

This demonstration was intended to collect information from this limited range of test scenarios to quantify the advantages and disadvantages of each of the three technologies. A long-term objective of this demonstration was to provide high-quality, georeferenced data to support sensor development and improvements in UXO analysis technologies.

The three demonstrated technologies include:

- The Geophex Ltd. GEM-3, a multichannel frequency domain EMI sensor system operated by Geophex Ltd. personnel with processing support from AETC Incorporated.

- The NRL Man-Portable EMMS adjunct[20] to the MTADS, a single time-channel time domain EMI sensor operated by personnel from NRL with processing support from AETC Incorporated.

- The Geonics Ltd. EM63, a multichannel time domain EMI sensor operated by personnel from NAEVA Geophysics, Inc.

Each of the three sensors was integrated into a man-portable platform that included data acquisition/storage and differential GPS receivers.

6.1 PERFORMANCE OBJECTIVES

The performance objectives of the demonstrations were as follows [19]:

- Evaluate demonstrators' detection and discrimination capabilities under realistic target, geologic clutter, man-made clutter, and topography scenarios while operating as efficiently and cost-effectively as possible.

- Evaluate demonstrators' ability to (a) analyze survey data on-site; (b) provide prioritized "dig lists" that include detection, discrimination, and identification estimates with associated confidence levels; and, (c) provide georeferenced anomaly maps.

- Collect manpower, time, and cost data for all tasks.

- Compare the performance of the systems with baseline mag-and-flag technology.

- Provide high quality, ground-truthed, georeferenced data for post-demonstration analysis and for use by other government, university, and industry researchers to develop improved models and analysis technologies.

Operations and maintenance costs include labor costs associated with setup, calibration, survey, analysis, and maintenance, as well as any required support equipment, consumables, and supplies. For evaluation purposes, all demonstrators used the following (loaded) labor rates:

- Supervisor—$95/hour
- Data Analyst—$57/hour
- Logistics/field support—$28.50/hour

In addition to the costs listed above, cost penalties were imposed for false positives and for UXO misclassified as clutter.

6.2 TEST SITE CHARACTERISTICS

Figure 13 shows magnetic anomalies from data collected by the MTADS vehicular system in Area 1, which was selected because it contains high magnitude magnetic anomalies from geologic sources that cover a fairly large, contiguous area. The long magnetic anomaly (red area) appearing near the center of Area 1 represents variations from the background mean of +150 nT to -100 nT. Area 1 has sparse tree/shrub coverage and its topography includes rolling terrain and ditches. Area 1 was seeded with the largest concentration of UXO and clutter items; a substantial number were placed within the high magnetic background locations.

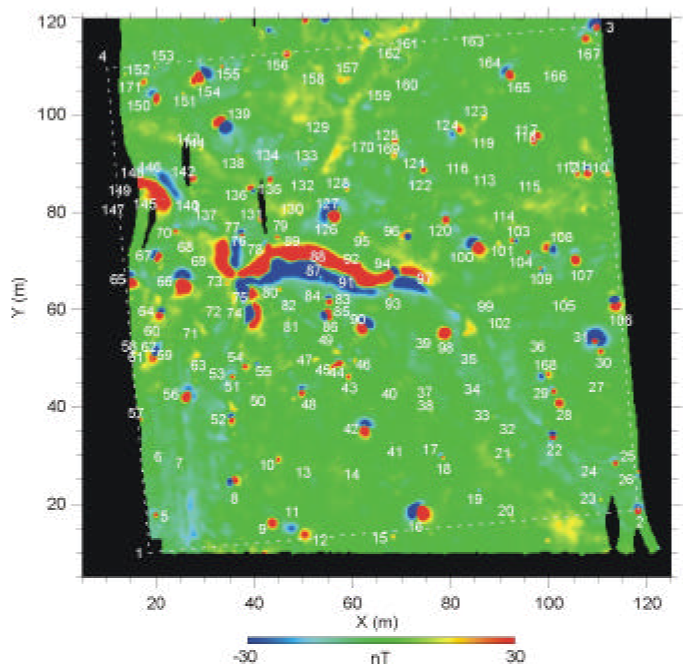


Figure 13. Magnetic Anomalies in Area 1 from Data Collected by the MTADS Vehicular System.

Figure 14 shows magnetic anomalies from data collected by the MTADS vehicular system in Area 2, which was chosen because it has a significant number of magnetic geologic anomalies (the patchy red areas). The geological interferences in this area are more compact and lower in magnitude (+ 35 nT), thus providing a different interference problem from that of Area 1. The topography in Area 2 also includes rolling terrain and a small ravine. Area 2 was seeded with a smaller number of UXO and clutter items than Area 1.

Figure 15 shows magnetic anomalies from data collected by the MTADS vehicular system in Area 3, which was chosen because it has very low amplitude geologic interferences and very flat terrain. This area has a variation from the mean background of only + 6 nT. Area 3 was seeded with the fewest UXO and clutter items.

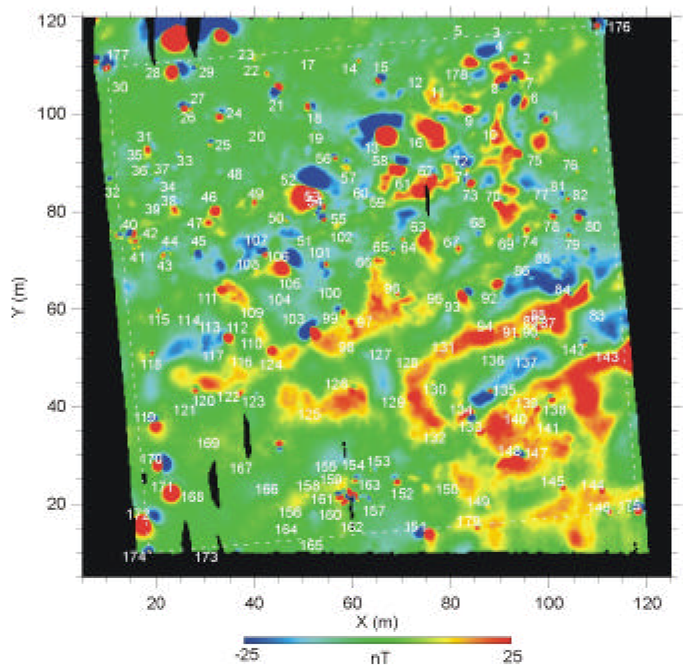


Figure 14. Magnetic Anomalies in Area 2 from Data Collected by the MTADS Vehicular System.

6.3 PHYSICAL SETUP AND OPERATION

6.3.1 Physical Setup

The inert UXO items emplaced for these demonstrations include all the items present at the Kaho'olawe quality control (QC) range with the exception of large air-delivered bombs. The UXO items ranged from 20-mm projectiles buried near the surface to 155-mm projectiles buried up to 1.2 m deep. Clutter items emplaced ranged from small (less than 0.5 kg) to large (up to 5 kg) munitions fragments and other man-made clutter such as horseshoes and metal banding. In addition, magnetic rocks (basalt) and soils obtained from sites in Kaho'olawe and other U.S. sites were emplaced.

Burial depths of the inert munitions used for field tests at JPG did not exceed those specified for the Kaho'olawe Tier II clearance requirements. For the tests at JPG, the 20-mm targets were emplaced without the casing, and burial depths ranged from flush with the surface to 15.2 cm.

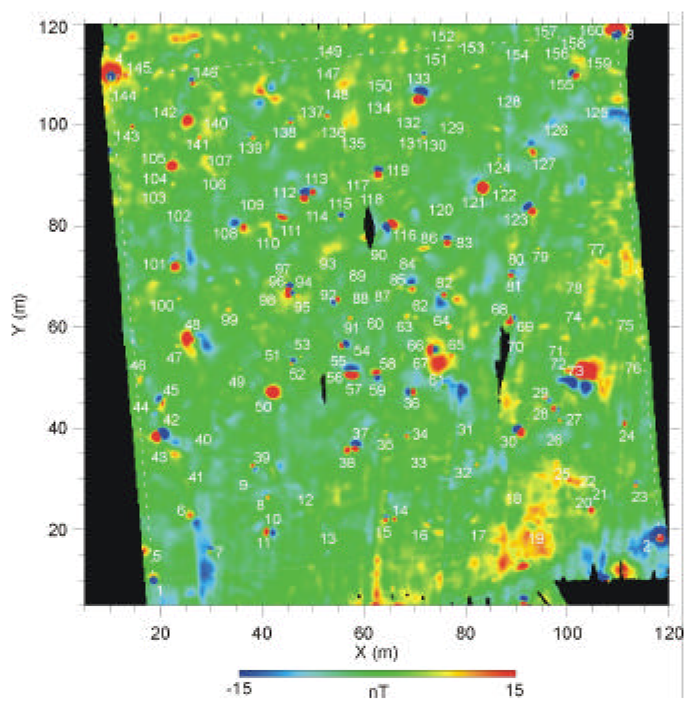


Figure 15. Magnetic Anomalies in Area 3 from Data Collected by the MTADS Vehicular System.

6.3.2 Operation

Area 3 was staked, gridded and surveyed with the EMMS on August 28, 2000. Area 1 was staked, gridded, and surveyed with the EMMS on August 29, 2000. Area 2 was similarly completed on August 30, 2000. The setup and survey production rates are summarized in Table 6.

Table 6. Production Rates Associated with Various JPG-V Survey and Analysis Activities.

Survey	Area 3 (Man-Hours)	Area 2 (Man-Hours)	Area 1 (Man-Hours)	Total (Man-Hours)
Stake and grid	9.5	9.2	10.3	29
EMMS survey	18	21.5	19.3	59
EMMS analysis (on-site)	20.5	18.8	23	62.5
Target reports				23.5
MMS survey	20			20
Vehicular mag survey	4.75	3.5	4.5	12.8
Clean up/pack out				15

6.4 SAMPLING AND MONITORING PROCEDURES

The NRL predictions of ordnance type were grouped into categories of similarly sized items (e.g., 57-/60-mm, 76-/81-mm, 105-mm/4.2-in, 152-/155-mm). In some situations, predicted sizes fell between more disparate items such as 60-/81-mm mortars. Type predictions attempted to reflect these uncertainties. In general, size predictions resulting from combined EM and magnetometer analyses are more precise and reliable than those resulting from EM data alone.

6.5 ANALYTICAL PROCEDURES

The evaluation factors and procedures related to this demonstration include:

1. Equipment setup, calibration time, and man-hour requirements
2. Actual survey time and man-hour requirements for each of the three test areas
3. Downtime because of system malfunctions and maintenance requirements
4. Reacquisition/resurvey time and man-hour requirements
5. Actual data processing/analysis time and man-hour requirements (all performed on-site)
6. Prioritized dig lists with associated confidence levels
7. Discrimination capability—ability to separate detected anomalies into UXO and non-UXO objects
8. Identification capability—ability to classify UXO targets by class (e.g., mortar, projectile) and type (e.g., 152-mm
9. Predicted target location accuracy, including depth estimates
10. Georeferenced anomaly maps
11. Probabilities of detection (P_d)
12. False alarm rates (FAR)

The method for determining and documenting the first three items involved on-site government representatives tracking and recording the number of personnel and time spent performing each task. If, during data analysis, the demonstrator determined a need to resurvey any part of the test areas or any previously detected anomalies, all setup, calibration, survey, downtime, reacquisition times, and man-hour requirements were recorded individually (as in items 1 through 3), but were compiled separately as reacquisition/resurvey time (item 4).

To evaluate item 5, the government required that all data processing and analysis tasks required to produce items 6 through 10 be conducted in the JPG office trailer, and that no data be taken off-site until these items were submitted to the on-site government representative. Demonstrators provided all computer hardware, software, and support equipment needed to produce the required analysis products.

Development and evaluation of items 6 through 10 were as follows.

- Each demonstrator was required to provide two-dimensional (2-D) anomaly maps of each 1-hectare area. The anomalies were tabulated into a dig sheet for each test area, organized to ensure as high a P_d as possible for the full range of UXO targets.

- Each anomaly in each list contained the (x, y) location and an estimated burial depth; an attempt to separate (discriminate) UXO from clutter items and to identify UXO by class and type; and a ranked list in the following order:

  1. UXO—high confidence
  2. UXO—medium confidence
  3. UXO—low confidence
  4. Clutter—low confidence
  5. Clutter—medium confidence
  6. Clutter—high confidence

- Each demonstrator was then required to specify a threshold on each prioritized list where he would recommend that all objects at or above that threshold be excavated and those below be left in place. To add realism to this discrimination decision, the following cost factors were applied:

  - ❖ For every clutter item selected for "digging," a $200 cost penalty was assigned.

  - ❖ To reflect the unacceptable risk of leaving UXO in the ground, if one or more UXO items were placed in the "no dig" portion of the list, it was assumed that the grid (i.e., the entire 1-hectare area) failed QA and a cost penalty equal to the cost of a resurvey was assigned.

  - ❖ One or more missed targets in each area were also assigned a cost factor equal to the cost of a resurvey.

P_d and FAR values were calculated from the prioritized dig lists as follows: Maximum achievable P_d for each area was calculated as the number of items in the entire list that correspond to emplaced UXO targets (even though they may have been misclassified as clutter) divided by the actual number of UXO targets emplaced in that site. A receiver operating characteristic (ROC) curve was developed by varying the dig threshold and computing P_d and FAR at each increment until the maximum P_d was reached.

After the demonstrators submitted the dig sheets described above, they were given the opportunity to reanalyze the data to develop prioritized dig sheets that took into account only targets larger than 20-mm projectiles (20-mm projectiles were assumed to be clutter for the evaluation).

7.0 JPG-V PERFORMANCE ASSESSMENT

7.1 JPG-V DATA

Georeferenced anomaly maps produced by the EMMS in Areas 1, 2, and 3 are shown in Figure 16, Figure 17, and Figure 18, respectively. The only overall conclusion that can be derived from these maps is that the EMMS demonstrated the capability to suppress the high magnetic background from geologic sources, and the capability to provide high-quality (well-localized, high signal-to-background target signatures) georeferenced data.

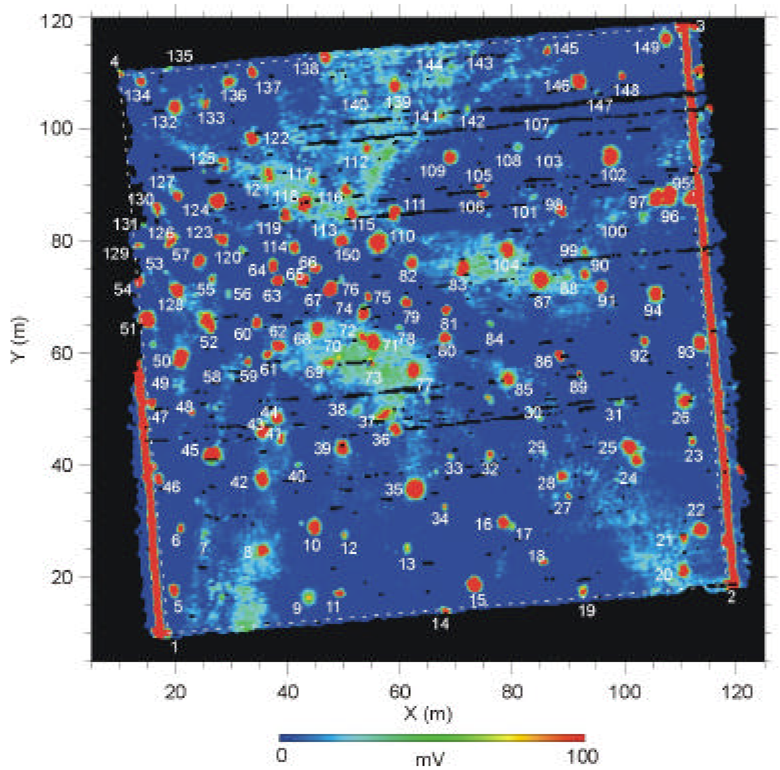


Figure 16. EMMS Survey of Area 1 at JPG.

Analyses of field survey data were performed in three stages. The data were initially analyzed before leaving the JPG test site to produce three prioritized dig lists (one for each survey area) containing all anomalies investigated. The data were also analyzed off-site to produce additional prioritized dig lists that included only targets estimated to be larger than a 20-mm projectile (i.e., the smallest object of interest corresponded to a 57-mm projectile). After submitting the second set of dig lists, the demonstrators were provided with the MTADS mag data and requested to submit two additional sets of prioritized dig lists (with and without 20-mm) that included combined mag and EM analysis results.

A number of post-demonstration adjustments to the ground truth were necessary in order to accurately account for anomalies resulting from metallic objects that were neither detected nor emplaced during the site preparation for this demonstration. After initial evaluation of the submitted dig lists, it became apparent that each demonstrator declared targets at locations where no items had been emplaced and where the magnetic anomalies from geologic sources were not significant. A decision was made to excavate those locations within the three test areas where two or more demonstrators had declared UXO targets.

Digging revealed that in Area 3 (the site north of the former 40-acre site during prior JPG demonstrations) all the declarations corresponded to farm-related ferrous objects such as portions of horseshoes, plow points, and harness hardware and did not include any items from previous JPG demonstrations. As a result, it was decided to include all declarations not corresponding to emplaced items in Area 3 as false alarms because of non-UXO ferrous objects.

On the other hand, in Areas 1 and 2 (which were inside the 40-acre site), limited digging revealed a number of inert UXO remaining from previous JPG demonstrations, including projectiles, mortars, flares, and fabricated clutter items. Even though JPG-IV ground truth had been used to clear these areas, items emplaced during earlier demonstrations had remained. As a result, the government examined JPG-I through JPG-III ground truth and identified items that matched the locations of anomalies declared by any one of the demonstrators as UXO targets. These objects were then removed from the evaluation of results. All other UXO target declarations that did not correspond to items that were emplaced as part of this ESTCP project, and that were not included in the ground truth from prior JPG demonstrations, were evaluated as false alarms. The option of limiting the evaluation to only the objects emplaced for this demonstration was considered and rejected because it would defeat the primary objective of the test, which was to evaluate system performance in high natural magnetic background environments.

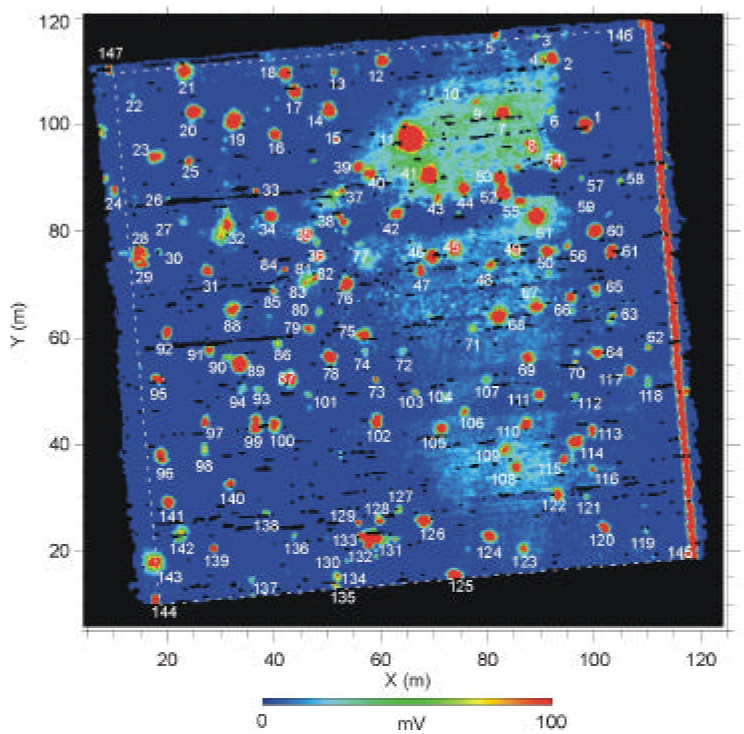


Figure 17. EMMS Survey of Area 2 at JPG.

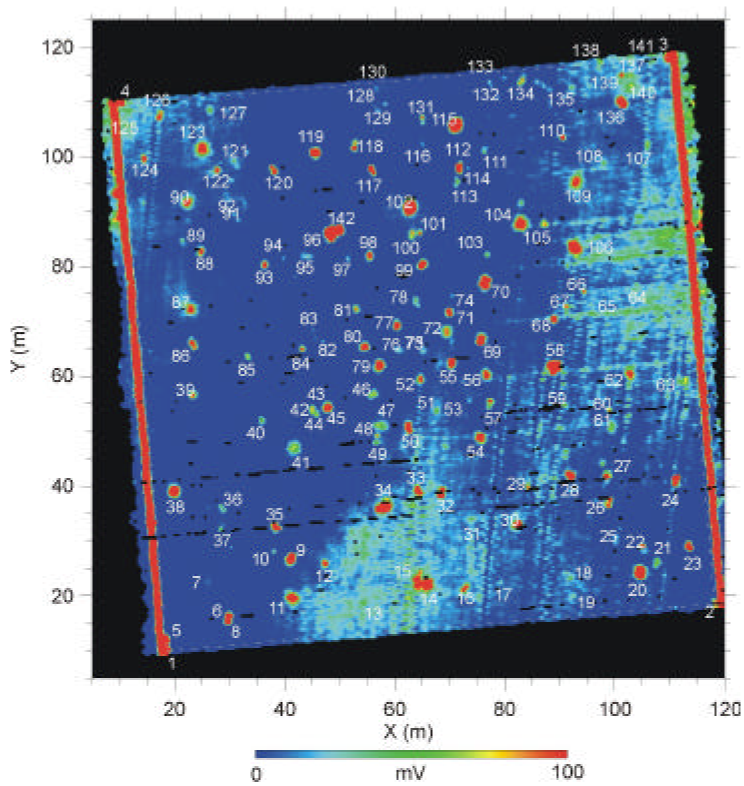


Figure 18. EMMS Survey of Area 3 at JPG.

One of the critical evaluation factors for this demonstration is the detection performance of advanced UXO detection systems. The metrics used to quantify the detection performance consist of the pseudo-ROC curves, the single-point P_d/FAR, and the maximum achievable P_d. The methods used to estimate these metrics from the prioritized dig lists were described in Section 6. Briefly, the pseudo-ROC curve, which graphically represents the target detection percentage versus the number of false alarms (or false alarm rate in number of false alarms per hectare), is calculated by sequentially moving from the top of the prioritized dig list (i.e., the highest confidence UXO target declaration) and determining if each object on the list (whether classified as a UXO target or clutter) corresponds to an emplaced UXO target location (a detection) or not (a false alarm). The single-point P_d/FAR performance is based on the point on the pseudo-ROC curve that corresponds to the contractor-specified dig point on the prioritized dig list, and the maximum achievable P_d is based on the highest point on the pseudo-ROC curve.

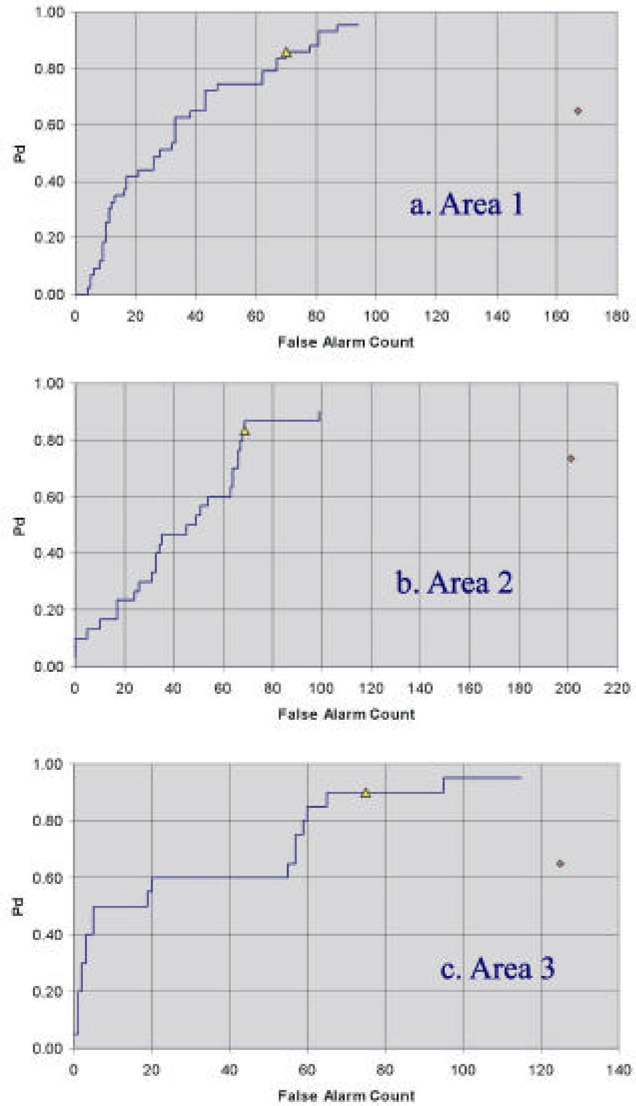


Figure 19. Pseudo-ROC Curves for EMMS Surveys of Areas 1 Through 3 and Analysis That Includes 20-mm Projectiles but Excludes MTADS Mag Data.

These performance metrics are presented in Figure 19, Figure 20, Figure 21, and Figure 22. The single-point P_d/FAR rate is shown as a yellow triangle on the pseudo-ROC curve. The red diamond corresponds to the single-point P_d/FAR performance point of the mag-and-flag survey.

Several points must be kept in mind when interpreting these plots. The abscissa in the pseudo-ROC curves is not the probability of a false alarm (P_{fa}), but rather total number of false alarms. As a result, the absolute slope of the curve has no intrinsic meaning but is nevertheless useful for comparing relative performance among different systems. These curves combine detection and discrimination of ordnance from nonordnance. Thus, the initial pseudo-ROC curve's slope represents the anomalies that the demonstrator has declared as UXO with the highest confidence. A flat slope in this area indicates poor discrimination capability. The final slope of the pseudo-ROC curve represents anomalies that the demonstrator declared as clutter with high confidence. A positive slope indicates there are UXO targets that the demonstrator would leave unexcavated.

In Figure 19, the steep early slopes of the pseudo-ROC curves indicate significant discrimination capability. The EMMS outperformed the mag-and-flag system at all three test areas, and the single-point performance points met the Kaho'olawe Tier II requirements. Based on the maximum of the pseudo-ROC curves, the EMMS did not achieve 100% detection at any of the three sites.

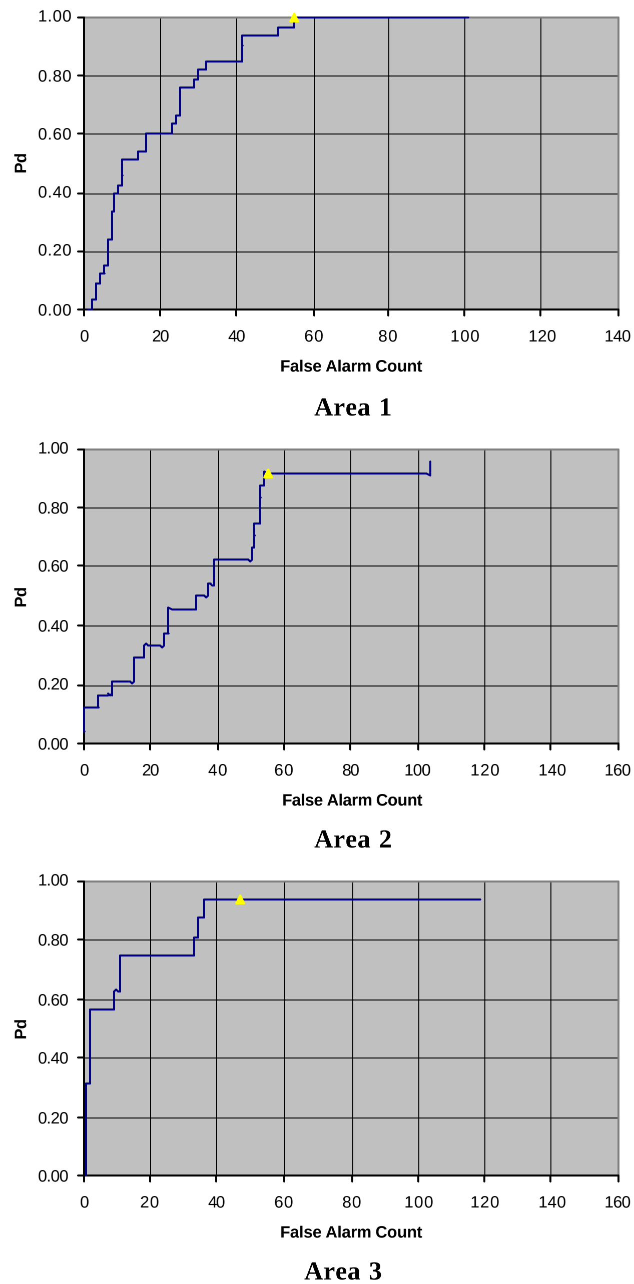


Figure 20. Pseudo-ROC Curves for EMMS Surveys of Areas 1 Through 3 and Analysis That Excludes Both 20 mm Projectiles and MTADS Mag Data.

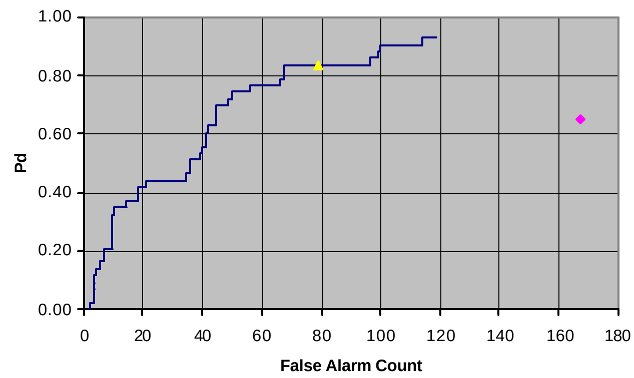
The naturally occurring geologic magnetic noise and the emplaced magnetic rocks presented no problems to the EMMS. All false alarms included in the submitted dig lists were attributable to metallic clutter, and analyses of the georeferenced maps showed no discernible anomaly over any of the emplaced magnetic rocks.

Figure 20 shows the detection performance of the EMMS based on the results of the off-site analyses that excluded objects estimated to be the size of 20-mm projectiles or smaller. The objective of this analysis was to determine system performance based on the more commonly encountered mid-sized (57-mm and larger) UXO targets. No comparisons with mag-and-flag results are included in these figures because analog magnetometers lack the capability to record the sensor data for reanalysis.

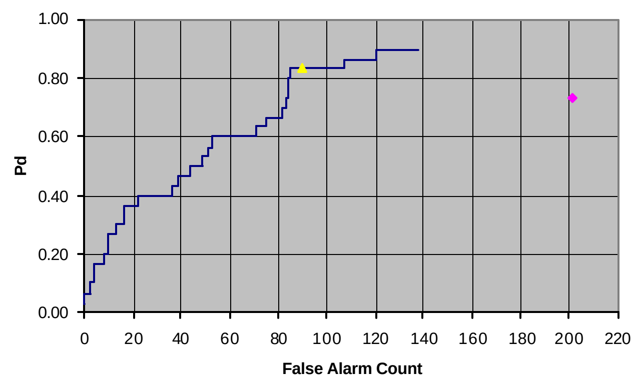
In Figure 20, comparison of these results with those provided on-site indicates significant improvement in pseudo-ROC curve-based performance. In addition, the EMMS operating P_d/FAR points improved substantially, particularly in Area 1 where 100% P_d was obtained with only 55 false alarms. Maximum P_d also increased slightly in the other two areas and exceeded the Tier II requirements. Excluding the small targets resulted in significant performance improvements for the EMMS.

Figure 21 shows the performance of the EMMS when the MTADS mag data were added to the analysis and all targets were considered. Overall, EMMS P_d detection performance actually decreased with the addition of the mag data. Comparison of these results with those in Figure 19 shows that, for all three areas, the pseudo-ROC curve performance was lowered when the mag data were included in the analysis. The maximum P_d was also slightly lower in all three areas.

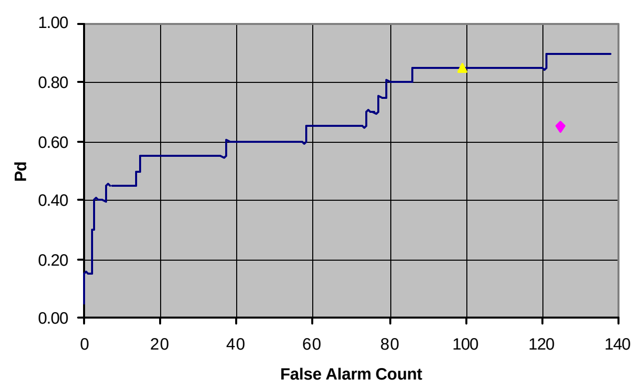
Figure 22 shows the detection performance of the EMMS systems against 57-mm and larger targets after integrating magnetometer data into the analysis. The purpose of this analysis was to quantify performance improvements in midsized UXO detection from magnetometer data under varying clutter conditions.



Area 1



Area 2



Area 3

Figure 21. Pseudo-ROC Curves for EMMS Surveys of Areas 1-3 and Analysis That Includes Both 20-mm Projectiles and MTADS Mag Data.

Overall performance improved very slightly from the EM-only analysis presented in Figure 20. The pseudo-ROC curve performance for all three areas was only slightly better than the EMI-only performance. The operating P_d performance was worse for the mag-EMI case because, for all three areas, the operating P_ds were slightly lower, and they occurred with higher false alarm counts. Though lower, operating P_ds still met or exceeded Tier II requirements in all three areas. The maximum achievable P_d was slightly lower for Areas 1 and 3 and unchanged for Area 2.

In general, the addition of mag data had very little effect on the early part of the pseudo-ROC curve (i.e., discrimination ability). The effect on the operating P_ds was minor. The primary impact on EMMS results was an increase in the number of anomalies included in the dig lists, most of which are correctly classified as clutter.

The discrimination and identification capabilities of UXO systems greatly affect the cost and residual risks associated with any UXO cleanup operation. Discrimination and identification performance is based on UXO versus clutter and UXO type declarations included in each of the required prioritized dig lists. The results presented in this section have been adjusted to account for UXO-related items that remained in Areas 1 and 2 from previous JPG demonstrations.

To facilitate the evaluation of detection, discrimination, and identification performance of the EMMS, as well as comparisons with mag-and-flag results where appropriate, dig list information is summarized in Table 7. It should be noted that, in this table, dig list declarations were interpreted to accept the correct choice of the first two choices listed. For example, if the dig list specified 57-mm projectile/60-mm mortar for an actual mortar target, credit was given in the mortar class.

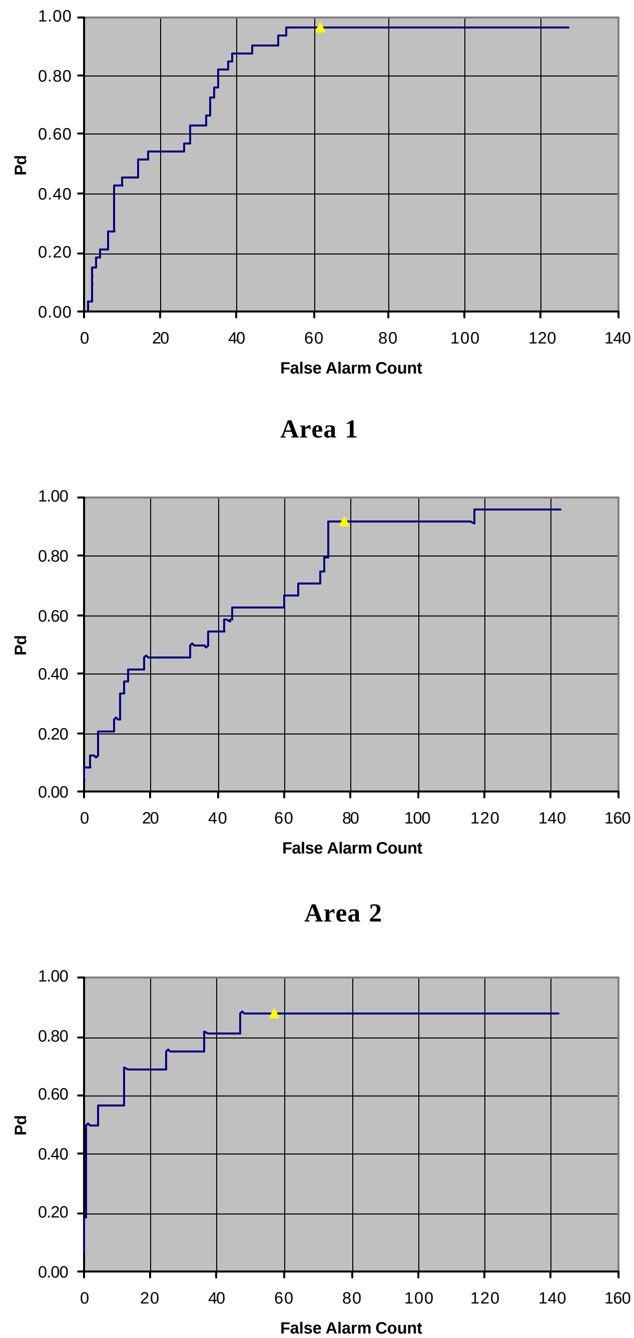


Figure 22. Pseudo-ROC Curves for EMMS Surveys of Areas 1 Through 3 and Analysis that Excludes 20-mm Projectiles and Includes MTADS Mag Data.

Table 7. Ability of EMMS to Detect and Discriminate Targets by Class.

System Class	Area 1			Area 2			Area 3			Total Score		
	Actual	Found	Match	Actual	Found	Match	Actual	Found	Match	Actual	Found	Match
On-site analysis (includes 20-mm and excludes MTADS mag data)												
EMMS P	27	25	13	16	13	07	10	10	05	53	48	25
M	12	12	08	12	12	06	09	08	05	33	32	19
R	04	04	02	02	02	01	01	01	01	07	07	04
Explosive	27	19	-	16	08	-	10	04	-	53	31	-
Ordnance	12	09	-	12	11	-	09	09	-	33	29	-
Detection	04	03	-	02	02	-	01	0	-	07	05	-
Technologies,												
Inc. (EODT)												
P												
M												
R												
Off-site analysis (excludes 20-mm and MTADS mag data)												
EMMS/Mag												
P	17	17	10	10	09	04	06	06	05	33	32	19
M	12	12	09	12	12	06	09	08	05	33	32	18
R	04	04	02	02	02	01	01	01	01	07	07	04
Off-site analysis (includes 20-mm and MTADS mag data)												
EMMS/Mag												
P	27	25	15	16	13	06	10	09	03	53	47	24
M	12	11	07	12	12	05	09	08	06	33	31	18
R	04	04	0	02	02	00	01	01	01	07	07	01
Off-site analysis (excludes 20-mm and includes MTADS mag data)												
EMMS P	17	17	12	10	10	04	06	05	03	33	32	19
M	12	11	07	12	12	05	09	08	06	33	31	18
R	04	04	0	02	02	0	01	01	01	07	07	01

Note: P = Projectile, M = Mortar, R = Rocket

Each demonstration area included three UXO targets that had clutter items in proximity so that their magnetic and EMI signatures would overlap. The purpose of these closely spaced targets was to evaluate the spatial resolution of the EMI sensor and to determine the robustness of the discrimination, classification, and identification techniques employed. Table 8 summarizes the ability of the EMMS to discriminate, classify, and identify UXO targets in proximity to clutter.

Table 8. EMMS Discrimination Capability Against Overlapping Targets.

Area	Ground truth	Found	Declared
1	2 – Clutter 113 – 105-mm projectile	113	P
	18 – Clutter 117 – 152-mm projectile	18	P
	184 – Clutter 121 – 155-mm projectile	121	P
2	16 – Clutter 131 – 81-mm mortar	131	M
	88 – Clutter 120 – 60-mm mortar	120	M
	76 – Clutter 166 – 2.75-in rocket	166	C-M
3	6 – Clutter 68 – 60-mm mortar	6	C-H
	50 – Clutter 76 – 60-mm mortar	50	C-M
	62 – Clutter 80 – 81-mm mortar	80	M

Note: P = Projectile, M = Mortar, R = Rocket, C-L = Clutter-Low, C-M = Clutter-Medium, C-H = Clutter-High

In Area 1, the EMMS correctly located two of the three UXO targets and correctly identified all three as projectiles. In Area 2, the EMMS correctly located all three UXO targets. The two mortar rounds were correctly classified as such, whereas the 2.75-in rocket was classified as clutter with medium confidence. In Area 3, the EMMS correctly located, discriminated, and identified only one of three overlapping targets.

The (x,y) location performance of the EMMS was evaluated by comparing each item in the onsite dig list with the ground truth, determining the closest item (within 1 m) to an emplaced UXO target location, and computing the error. Overall, the EMMS system demonstrated an average position error of 22.1 cm. Most of the targets detected by the EMMS were well within the 0.5-m error radius required by Kaho'olawe cleanup criteria.

The ability of the EMMS to estimate the depth of the UXO targets is summarized in Table 9. These results indicate that, although the performance varied significantly among test areas, the mean depth estimation errors were within the 0.5-m allowable error.

Table 9. UXO Target Depth Estimation Performance.

Area	Minimum Error (m)	Maximum Error (m)	Mean Error (m)	Standard Deviation
1	0.01	0.65	0.23	0.17
2	0.00	0.86	0.27	0.24
3	0.01	0.37	0.16	0.10

7.2 JPG-V ASSESSMENT

Surveys of Areas 1 and 2 included regions with significant geological activity. The motion-induced noise in the EM image of Area 3 (Figure 18) resulted from surveying across shallow furrows dating from when the area was in cultivation before its use as a target range. The magnetic soil deposits distributed across much of Area 2, and in the ravines in Area 3 did not significantly interfere with the EM survey data. Their effect on the magnetometry data was more pronounced. Target analysis of magnetometry data in these areas is much more tedious, requiring display of small areas with constant resetting of offsets and detrending during the fitting of individual targets. In general, with very careful analysis, 10 nT anomalies could be fit in regions with geological magnetic soil offsets of 200 nT. Small targets, such as 20-mm projectiles or 60-mm mortars, at depth, had a higher probability of going undetected in these areas.

7.2.1 Detection Sensitivity

Detection probability statistics for Area 3 are summarized for all three sites in Table 10, which shows a comparison among the three demonstrators using data taken from the presentation of Dr. Ernesto Cespedes at an ESTCP workshop. NRL data were turned in on-site, and assumed 20-mm projectiles were not UXO. The absolute detection sensitivities of the EMMS and MMS systems were similar. The EM sensors had a greater sensitivity for small shallow objects whereas the magnetometer array was more sensitive for large, more deeply buried objects. The EM sensors also detected small shallow objects more efficiently because, using the overlapping 1-m coils, surface coverage approached 100%. It was possible for small objects, such as 20-mm projectiles, to pass between the magnetometers undetected, even with a 25-cm separation. To some extent, the detection sensitivity was also a function of target picking. Saturation picking detected more metal objects, but without an efficient discrimination tool for analysis, many more objects would have to be dug using this approach. All three demonstrators appeared to have sufficient detection sensitivity to detect the full range of UXO items buried at the depths of this demonstration. The differences in detection efficiency of Surveyors B and C, relative to the MTADS, was largely a matter of the number of targets chosen for declaration.

Table 10. Surveyor Performance at the JPG-V Demonstration.*

Probability of UXO Detection

	NRL	Surveyor B	Surveyor C
Area 1	95.3%	100.0%	90.7%
Area 2	96.7%	100.0%	93.3%
Area 3	100.0%	100.0%	90.0%
Overall	96.8%	100.0%	91.3%

Objects Declared

	Total objects in dig sheet		
	NRL	Surveyor B	Surveyor C
Area 1	149	177	144
Area 2	147	236	206
Area 3	142	202	105

* This table was adapted from Dr. Ernesto Cespedes from an ESTCP workshop presentation.

7.2.2 Missed Targets

Assuming the sensors have sufficient sensitivity to detect these UXO challenges, the number of missed targets reflects three factors: the signal-to-noise and spatial resolution in the data, the number of targets chosen for declaration, and experience in extracting target signatures from geological and scrap/clutter interferences in the data. While the EM sensors are much less subject to geological interferences from magnetic soils, the spatial resolution of the magnetometer sensors is significantly higher, allowing better unclustering of adjacent or nearby targets. This unclustering (or cleanup of complex target signatures) is a time-consuming data processing step that does not readily lend itself to software automation. The time expended in this data cleanup is in part responsible for the accuracy of the MTADS in precisely locating and estimating sizes of UXO targets and in detecting deep targets in complex fields with nearby clustered targets. The relatively low EM coil sensitivity of the EMMS system used in the L-Range surveys led to missed targets and relatively poor location accuracy. This was overcome by the redesigned EMMS system. The data from this man-portable unit is at least as high fidelity as the MTADS vehicular EM survey data.

7.2.3 Target Locations

As described above, precision in location of targets is a strong function of data cleanup during analysis. However, use of carefully time-stamped data, the highest precision GPS navigation systems, and high data sampling rates are equally critical in obtaining target data fits with sufficient information to precisely describe the target. In general, the location accuracy of the target fitting routines from a vehicular MTADS magnetometer survey is about 10-15 cm whereas the EM array typically produces fits that are accurate to 15-25 cm. The lower accuracy is, in part, a result of the larger coil size of the EM array and the lower data density relative to the magnetometer data. The accuracy of the magnetometer fitting routines in predicting target depths is typically in the range of 20-30% of the absolute depth. Very shallow targets often have higher errors and deep targets are often fit to within 10% of their depth. The MTADS baseline EM-fitting routine typically gives much poorer depth fitting accuracy than the magnetometer-fitting algorithm. The 3-ß fitting algorithm applied to EM data typically provides depth estimates that are more accurate than the baseline point-dipole EM fit, though they remain less accurate than the magnetometer depth predictions.

Table 11 compares, performance predictions of the vehicular MTADS magnetometer array, the MMS, and EMMS surveys with the JPG ground truth (provided by Dr. Ernesto Cespedes for Area 3). To provide a greater range of information, the position and depth predictions of the MMS and EMMS surveys were compared with the predictions resulting from the MTADS vehicular survey. The latter comparisons might reveal any systematic bias or significant random errors in the location accuracy of the provided ground truth.

Table 11. Position and Depth Discrepancies in the Magnetometer and EM Surveys Compared with JPG Ground Truth.*

	DX-Y (m) Relative to JPG Ground Truth		DDepth (m) Relative to JPG Ground Truth		DX-Y (m) Relative to MTADS Mag		DDepth(m) Relative to MTADS Mag	
	Ave.	**Median**	**Ave.**	**Median**	**Ave.**	**Median**	**Ave.**	**Median**
EMMS	0.18	0.18	0.16	0.12	0.21	0.16	0.21	0.16
MMS	0.16	0.11	0.15	0.11	0.13	0.09	0.09	0.05
MTADS Vehicle Mag	0.16	0.09	0.13	0.08	-	-	-	-

* Both UXO and clutter targets are included in this analysis.

The location and depth predictions of the vehicular MTADS survey compare favorably with the provided ground truth and fall within the expected accuracies of the system. There was no detectible systematic position bias nor any significant single target location discrepancy. Likewise, the location accuracies and depth predictions of the MMS and EMMS surveys and analyses were within the expected accuracies of the systems. The performance of the MMS and the vehicular MTADS magnetometer array were statistically indistinguishable.

7.2.4 Classification Performance

Differentiating UXO from OE scrap and metallic clutter has been the primary objective of every MTADS development program for the past 3 years (except for the development of the man-portable MTADS adjuncts).

The test at JPG was the most stringent and comprehensive evaluation of the latest analysis tool for the EM system, the 3-ß analysis algorithm [23]. The approach was originally developed for the MTADS EM array with the overlapping 1-m coil systems. It was adapted for this development and this demonstration with the single unit 0.5-m coil system. With the vehicular array, two orthogonal surveys of the same area are typically conducted to get the maximum possible shape information for the processor. In the present instance, the smaller coil provides higher resolution data and, because of its 0.5 m^2 total area, effectively radiates each object with a much wider range of incidence radiation vectors on each survey lane. Using the EMMS, data are taken on closely spaced lanes to assure overlap and high data density. Under these circumstances, the three areas were surveyed only once, and the processor was used to extract classification information. Classification results are shown in Table 12. Level 1 targets were most confidently assigned as UXO. Level 2 targets are less confidently assigned. Level 3 targets are doubtful, but are more likely UXO than not. Level 4 targets are declared as more likely not UXO. Level 6 targets are most likely not UXO, and it was recommended that those targets not be dug. Confidence in Level 5 targets, although not likely to be UXO, was not high enough to risk leaving them in the ground.

Table 12. Classification of the Targets from the JPG Surveys.*

Classification Confidence Level	AREA 3			
	3-b Analysis		Joint Analysis	
	20-mm	No 20-mm	20-mm	No 20-mm
1	22	18	20	17
2	17	6	15	9
3	14	11	25	14
4	12	8	13	8
5	28	19	42	21
6	41	72	39	85
Total declarations	134	134	154	154
Dig/don't dig	93/41	62/72	115/39	69/85

*Ground truth data were not available for Area 1 and 2 when this document was completed.

In this demonstration, the 3-ß classifier's performance was a limited success. The pseudo-ROC curves show that Area 3 was the easier site on which to classify targets. Reaching 90% correct UXO declarations on Area 3 required picking only about 60 non-UXO targets. Area 1 required more than 80 targets and Area 2 more than 90 targets to recover 90% of the seeded UXO.

A more stringent test of a target classifier is its ability to recognize OE scrap and metal clutter as metallic targets that can be left in the field. As shown in Table 13, using the 3-ß classifier at the relatively benign Site 3, 11 of 29 (assuming 20-mm projectiles present) or 21 of 34 (assuming 20-mm projectiles not present) OE scrap targets were correctly classified. Only 4 of 29 (assuming 20-mm projectiles present) or 14 of 30 (assuming 20-mm projectiles not present) OE scrap targets in the field were correctly not recommended for digging. In the ordnance column, 13 of 19 (assuming 20-mm projectiles present) or 12 of 15 (assuming 20-mm projectiles not present) anomalies were correctly classified as UXO. The 20-mm projectiles were the most difficult UXO targets to classify correctly.

Combining the EM and magnetometer survey data in a joint analysis improved both the classification and dig decisions by a factor of about two, while simultaneously decreasing the number of ordnance items that would be left in the field after digging. The correct classification of UXO objects in the joint classification was similar to that using the EM data alone because these classifications were still primarily based on the 3-ß analysis. Most improvement in classification in the joint analysis was based on the improved spatial resolution in the magnetometer data and the ability of the magnetic dipole analysis to recognize strong remnant moments.

Table 13. EMMS Performance Summary for Area 3.

Targets Declared	Targets Buried	UXO Detected	UXO Not Detected	Correct UXO Classification	UXO Misclassified	UXO Correct Type Assignment	Incorrect UXO Type Assignments	OE Scrap Correct Classification	OE Scrap Correctly Not Dug
3-b classification assuming 20-mm projectiles are present									
134	55 20 UXO 35 OE	19	1 (81-mm)	13 of 19	4 (20-mm) 1 (60-mm) 1 (155-mm)	7 of 13	81mm as 105mm/4.2in 81mm as 2.75in 76mm as 57/60mm 105mm as 76/81mm 152mm as 105mm/4.2in 60mm as 76/81mm	11 of 29	4 of 29
3-b classification assuming 20-mm projectiles are not present									
134	55 16 UXO 39 OE	15	1 (60-mm)	12 of 15	1 (60-mm) 1 (81-mm) 1 (155-mm)	7 of 12	81mm as 105mm/4.2in 81mm as 2.75in 76mm as 57/60mm 105mm as 76/81mm 152mm as 105mm/4.2in	21 of 34	14 of 30
1.1.1.1.1 Joint analysis of magnetometer and EM surveys assuming 20-mm projectiles are present									
154	55 20 UXO 35 OE	20	0	15 of 20	4 (20-mm) 1 (60-mm)	13 of 17	81mm as 57/60mm 76mm as 2.75in/81mm 105mm as 2.75in 60m as 76/81mm	20 of 33	10 of 33
1.1.1.1.2 Joint analysis of magnetometer and EM surveys assuming 20-mm projectiles are not present									
154	55 16 UXO 39 OE	16	0	14 of 16	1 (60-mm) 1 (81-mm)	12 of 16	81mm as 57/60mm 76mm as 2.75in/81mm 105mm as 2.75in 60m as 76/81mm	28 of 37	21 of 37

Where time and resources will allow, using both sensor platforms and a joint target analysis will provide improved target detection and recovery. It is problematic whether it will lower digging costs overall. The improved classification capability in a joint analysis tends to be offset by the tendency to pick more targets using multiple survey data sets.

8.0 THE KAHO'OLAWE ISLAND, HAWAII, DEMONSTRATION DESIGN

ESTCP funded the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV), the U.S. Army Engineer Research and Development Center (ERDC), and the U.S. Army Environmental Center (AEC) to design and conduct controlled technology demonstrations on Kaho'olawe Island in Hawaii [7].

The entire island was used for many years as an air-to-ground practice range for a wide range of ordnance. At the time of this demonstration, an active clearance had been underway on the island for some time. More than 60,000 anomalies had been dug following geophysical UXO surveys using EM61 sensors. On average >35 nonhazardous objects were dug for each recovered intact UXO. In addition, many areas were resurveyed a second (or third) time with continued recoveries of substantial additional ordnance. Efficient detection of UXO is difficult, primarily because the volcanic nature of the soils, the presence of copious amounts of shrapnel (of all sizes), the difficult terrain, limited access to the island, and the constant high winds further complicate the process. The ongoing UXO cleanup operations at Kaho'olawe have been described in earlier presentations [22].

The objective of these demonstrations was to evaluate the performance of a new generation of EMI sensor technologies for potential support of the ongoing cleanup efforts in the highly magnetic noise environment [22]. Three of the demonstrators had previously used the same or similar systems during the summer and fall of 2000 to conduct UXO surveys at the JPG on prepared sites containing a combination of UXO and OE clutter targets.

Participating in the Kaho'olawe demonstration were:

- NAEVA (employing a new Geonics instrument, the EM63 on a wheeled man-portable platform)
- GTL (using a TM-5 EMU frequency-domain hand-held sensor)
- Geophex, Ltd (using a new large coil version of their GEM-3 frequency domain sensor on a wheeled man-portable platform)
- NRL (using a specially designed version of the EM61 on a wheeled man-portable platform)
- Parsons-UXB (using a standard wheeled EM61, as deployed on the island for QA studies)
- Parsons-UXB (using a standard wheeled EM61 in an EM-and-flag mode)

Each survey group, except the last, used an integrated GPS to create geo-located mapped data files for target reporting.

8.1 PERFORMANCE OBJECTIVES

The project managers [24] established evaluation objectives for these demonstrations, as stated below:

- To evaluate the demonstrators' detection and discrimination capabilities by means of surveys of ten 30-m X 30-m grids and one 1-ha area within the Kaho'olawe QA range under realistic target/geologic, clutter/man-made, clutter/topography scenarios and while operating as efficiently as possible (minimizing time, manpower, and costs)

- To evaluate the demonstrators' ability to analyze survey data in a timely manner and provide prioritized dig lists

- To collect manpower and time data required to produce their final products (prioritized dig sheets and georeferenced anomaly maps)

- To compare the performance of the advanced systems with the baseline technologies currently employed at Kaho'olawe

- To provide high quality, ground-truthed, georeferenced data for post-demonstration analysis

The project managers established the following factors influencing the cost and performance evaluation for the demonstrators:

- Equipment setup and calibration time and man-hour requirements

- Time and man-hour requirements to conduct surveys

- Downtime due to system malfunctions and maintenance requirements

- Re-acquisition/resurvey time and man-hour requirements

- Accuracy of georeferenced maps and prioritized dig lists with respect to

  - Probability of detection (P_d)
  - False alarm rates (Pfp, FAR, total FAR)
  - Discrimination capability (P_{disc})
  - Identification capability
  - Target location accuracy

8.2 SITE CHARACTERISTICS

The levels of both geological (soil) interference and OE clutter interference are much higher at Kaho'olawe than in the most difficult areas of the JPG survey. At the time these demonstrations were held, about 1,100 acres of the island had been remediated. Almost all of the geophysical survey work had been done using classical Geonics EM61 units operated in a mag-and-flag mode. Following the flagging of anomalies, more than 60,000 targets were dug. More than 37 holes have been dug for each UXO recovery. False alarms attributed to metallic objects (mostly shrapnel) are about three times more prevalent than those ascribed to geological returns. Many cleared areas have been resurveyed and dug up to three times, recovering more intact ordnance in each cycle. The overall fraction of the ordnance removed from or remaining in the completed areas remains undetermined.

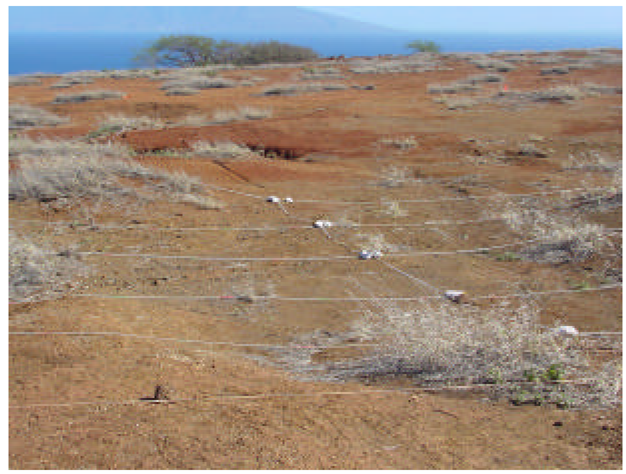


Figure 23. Calibration Area Within the QC Range. Tapes and Sandbags Were Placed by the Site Managers.

Site selection criteria, site description, and site preparation activities are described in detail in the Site Preparation Plan [24], but brief descriptions of the calibration and test sites and the emplaced targets are presented in this section. Kaho'olawe Island was used as a weapons range and military training area from 1941 until 1990. In preparation for the Kaho'olawe UXO remediation project, QC and QA ranges were established. These previously cleaned and seeded areas were chosen as the calibration and demonstration sites for this project. The QC and QA areas are scoured by the continual winds that are typical of high elevations on the island; because of the elevation and winds, no significant permanent soil layer has been created by sedimentation. Significant vegetation has been missing from this part of the island for more than 60 years. Precipitation is minimal, and vegetation on the QA and QC sites primarily consists of scattered small clumps of desert grass that collect blowing sand. There are isolated 1-2 foot high mounds of dirt, outcroppings of hardpan and/or lava, and occasional large rocks. Each of the sites has shallow gullies and depressions, most of which can be traversed by the wheeled survey platforms with some bumping and bouncing, Figure 23.

8.3 PHYSICAL SETUP AND OPERATION

8.3.1 Physical Setup

The Calibration Site. The calibration area consisted of three 30m X 30m grids (see Figure 24). The north and south grids were populated with previously existing UXO and frag targets. The ESTCP grid was populated with UXO and frag targets specifically for this project. The ground truth of all items emplaced in the calibration area was made available to each demonstrator prior to their access to the site. The seeded items are graphically indicated in Figure 24.

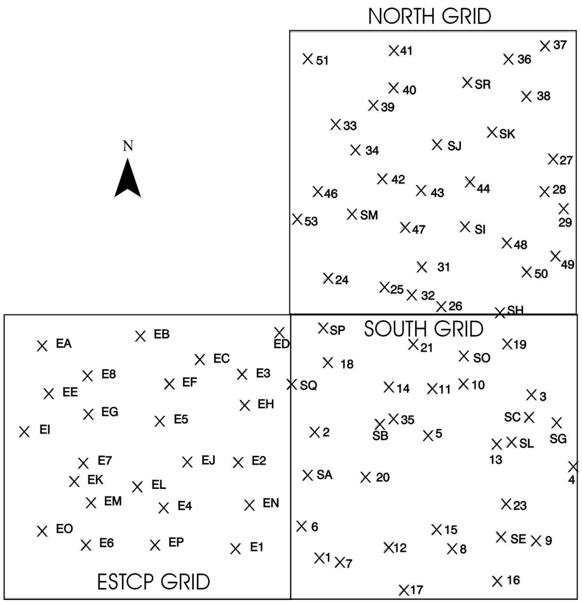


Figure 24. Layout of the Calibration Site Showing the Locations of the Calibration Targets.

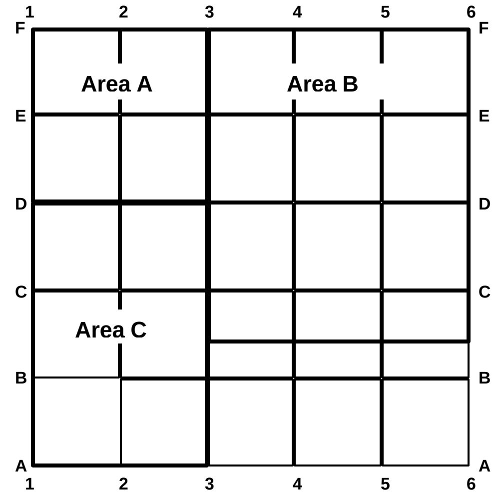


Figure 25. Layout of the QA Demonstration Area Superimposed on the 30-Meter Grid Structure.

The Demonstration Site. The QA Range was adapted to support this demonstration. The layout, shown in Figure 25, is based on a set of 30-m x 30-m grids. Area B was bounded to encompass an area of 1 hectare. Areas A and C include four and six of the 30-m x 30-m grids. Both pre-existing targets and frag and newly buried items were included in the demonstration area. Demonstrators were provided with UTM coordinates of the area corners and first-order survey control points near each site.

Emplaced Ordnance and OE Clutter. The list of possible inert ordnance items for burial was provided in the Demonstration Test Plan [24]. All ordnance was taken either from previously fired and recovered ordnance on Kaho'olawe or from inert stores managed by AEC. All ordnance was certified as inert; unfired ordnance was degaussed prior to burial. OE clutter items selected from scrap and shrapnel recovered on Kaho'olawe were considered typical of the ordnance expended on the site [22]. UXO challenge items included air-fired (20-40 mm) projectiles, (2.25 in and 2.75 in) rockets, (60- and 81-mm) ground-fired mortars and (3-in and 5-in) projectiles and practice bombs (bomb demonstration unit [BDU]-33 up to Mk-83).

8.3.2 Operations

Figure 26. Hotel Room on Maui Configured as a Data Processing Office.

All MTADS operations took place during the weeks of 15 and 23 October 2001. Survey data were typically taken in 1-hour increments, inspected in the field using notebook computers and saved to hard disk. All data processing and analysis took place on Maui in a hotel room set up as an office (see Figure 26). Data were downloaded from field notebook computers to PCs. One PC was used for data processing and algorithm development, the second primarily for target analysis. The MTADS survey log for the operation is shown in Table 14. The first week was devoted to survey work on the calibration grids. During this week and the following weekend, data processing, target analysis, and development of data treatment approaches were tested. Actual surveys of Areas A, B, and C took place during October 22-24. During the second week only four personnel were permitted to travel to the island; each day one person remained behind on Maui to process and analyze data.

Table 14. MTADS Kaho'olawe Survey Log.

October 15-16	MMS and EMMS surveys of the three 30m x 30m calibration grids (6 data files spanning 3.2 hrs were collected). An additional short test was performed with the EMMS to determine reproducibility of data by walking several round trips of the same line.
October 18	Testing of the EMMS with a Tilt-meter sensor incorporated for more accurate sensor positioning and attitude information. (3 data files spanning 1 hour were collected). Implementation of the Tilt-meter sensor ultimately failed due to unexpected demands on the data acquisition system.
October 22-23	EMMS survey of the ten 30m x 30m grids, areas A and C (11 data files spanning 4.78 hrs were collected). Note: Several breakdown problems were encountered with the wheel-platform attachment assembly, resulting from the rough terrain.
October 23-24	EMMS survey of the one hectare grid, Area B. (13 data files spanning 4.64 hrs were collected). Note: A severe breakdown occurred near the end of the survey that could not be repaired. As a result, two people carried the sensor platform in order to complete the final few lines of the survey.

The calibration site was gridded on 1.5-m spacing in a north/south direction using twine to define the survey lanes. Survey tracks were 0.5 m apart, and 80-d steel spikes were driven at 1.5-m intervals 1 m beyond the survey boundary, with twine stretched between spikes to define the survey grid. The site was surveyed first with the EM system, then with the magnetometer platform.

The 30-m grids and the 1-hectare areas were marked as a single site in a northeast/southwest direction using twine on 1.5-m spacing. Survey tracks were 0.5 m apart. The 30-m grids were completed in a single EM survey using survey tracks stretching the entire length of the site. The 1-hectare site was completed as a single EM survey, beginning at the northwest boundary.

8.4 SAMPLING AND MONITORING PROCEDURES

8.4.1 Production Information

Figure 27 shows a course-over-ground plot for the survey of the calibration area. This information is derived from the GPS data. A 25-point smooth filter has been applied to the data, which damps some of the side-to-side rocking motions of the cart. Similar plots are shown in Figure 28 for Area B, the 1-hectare survey and in Figure 29 for Areas A and C. As is apparent, the calibration area and Area B, the 1-hectare survey, are relatively smooth. Effectively, the entire calibration area was seamlessly surveyed. A relatively small area in Area C near the border of sections E4 and E5 was missed because of a 6-ft deep hole. Areas A and C were considerably more rugged with two gulleys and a line of trees stretching along the long dimensions of the survey. These obstacles, along with brief intermittent navigation dropouts (from trees) resulted in missed survey areas amounting to a small percentage of the targeted survey area.

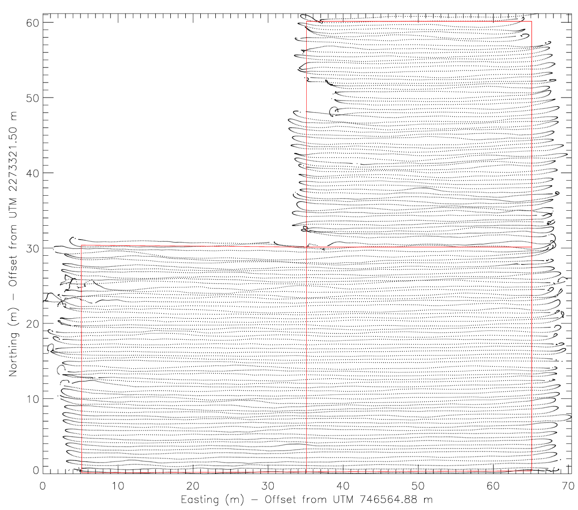


Figure 27. Course-Over-Ground Plot for the Calibration Area Survey.

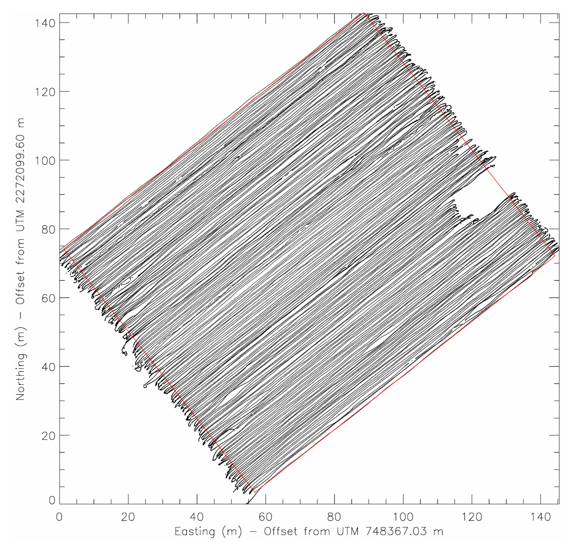


Figure 28. Course-Over-Ground Plot for the 1-Hectare Grid Survey, Area B.

Figure 30 shows a survey speed-over-ground plot for a 20-minute segment of the 1-hectare survey. Twelve consecutive survey lines are shown. For this area, the average survey speed was about 1.5 m/sec. This plot is also derived from GPS data.

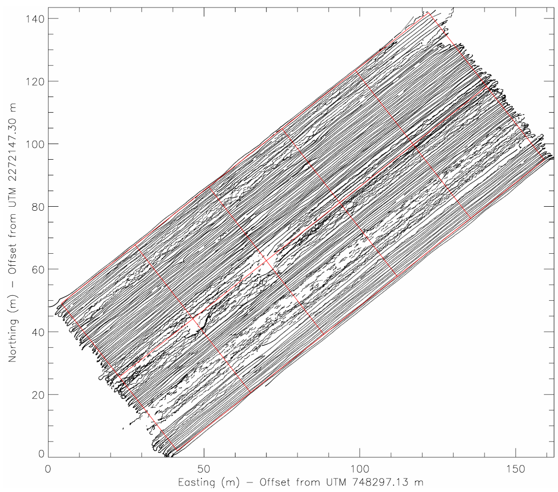


Figure 29. Course-Over-Ground Plot for the 30-Meter Grids Survey, Areas A and C.

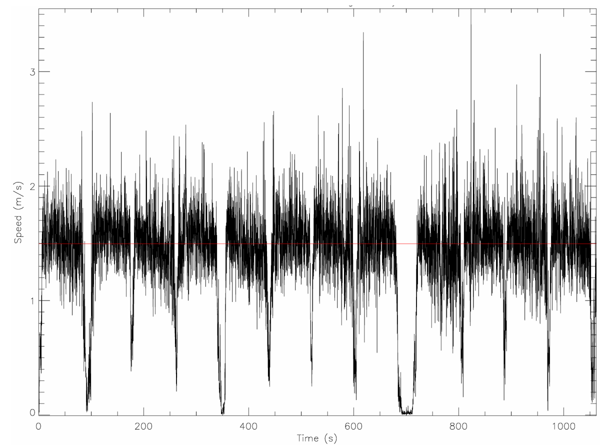


Figure 30. Plot of the Survey Speed for 12 Consecutive Lanes in the 1-Hectare Survey.

8.4.2 Data Acquisition

Figure 31 and Figure 32 show the EMMS and MMS surveying on the calibration site. The calibration site and the 30-m grids and 1-hectare grid on the QA range were surveyed with the EMMS; only the calibration site was also surveyed with the MMS.

Figure 31. The EMMS Surveying on the Calibration Site.

Figure 32. The MMS Surveying on the Calibration Site.

8.5 ANALYTICAL PROCEDURES

The EM anomaly map for the calibration site is shown in Figure 33. It is presented as an interpolated image on a 175-mv scale. The bright features stretching along the west and east boundaries are returns from 80-d steel spikes that were used to stake the twine. These nails also served as timing fiduciary markers to calibrate the timing offsets for the EM system.

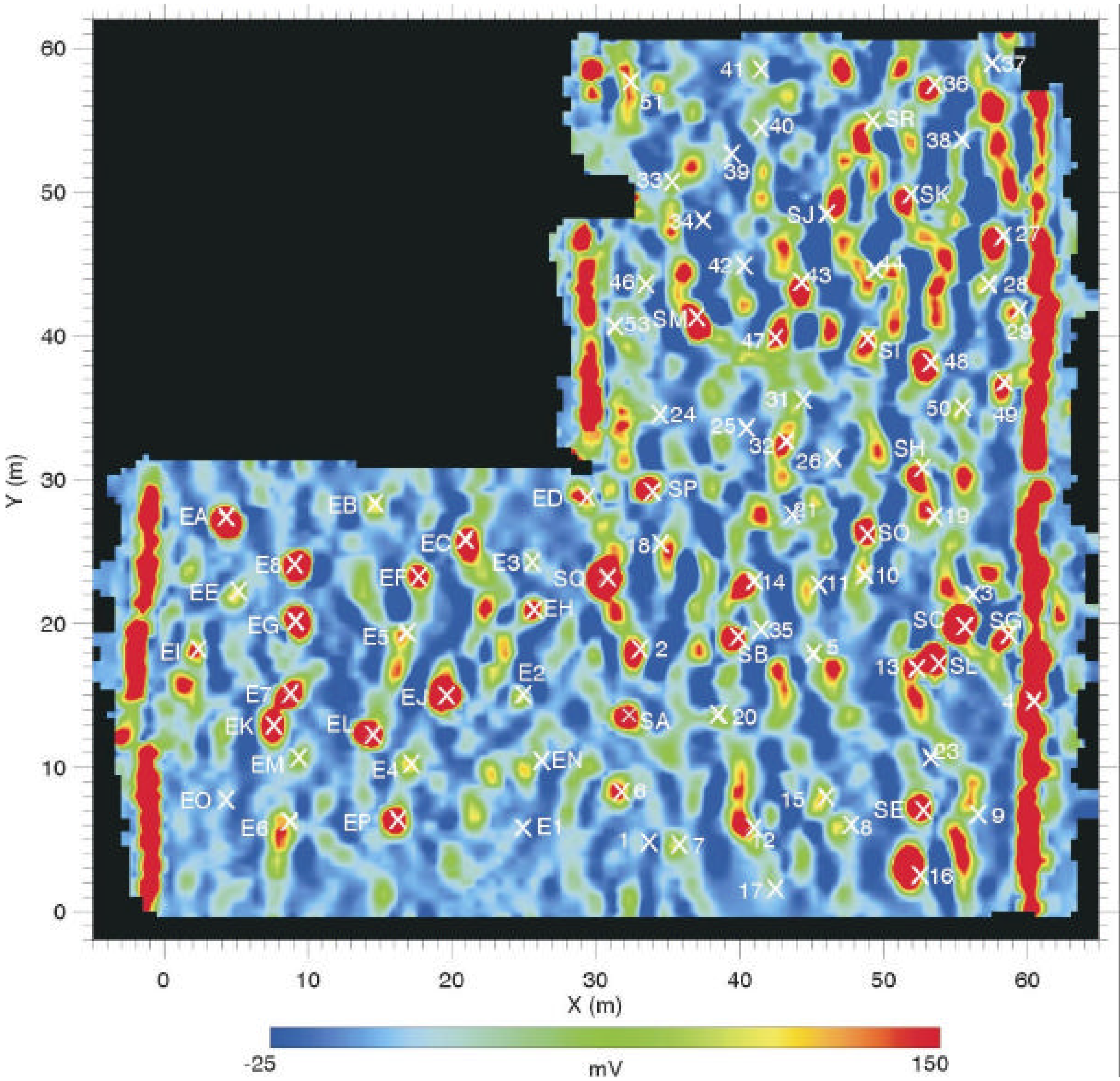


Figure 33. EM Survey of the Kaho'olawe Calibration Grid Using a 20-Point Demedian Filter in an Interpolated Image. (The seed target locations are marked with an "x.")

Figure 34 shows the EM anomaly site map for the QA site, including both the 30-m grids and the 1-hectare area. This interpolated image is presented on a 1,000-mv scale. Approximately 50 of the brightest targets are readily apparent on this scale, as are the 80-d steel spikes at the ends of the survey lines.

In all the EM presentations in this document, and for our analysis, the EM data were smoothed with a 20-point "down-the-track" demedian filter. The GPS navigation data were smoothed with a 25-point filter, and the EM data contains a timing correction of 3 ms. The demedian filter suppressed the larger-scale geological features without affecting the presentation or fitting, for most UXO targets. During the EM analysis, a data set was also displayed that was smoothed with a 1,000-point down-the-track filter. This data set was used when fitting larger UXO targets whose signatures were distorted by the much shorter scale 20-point filter.

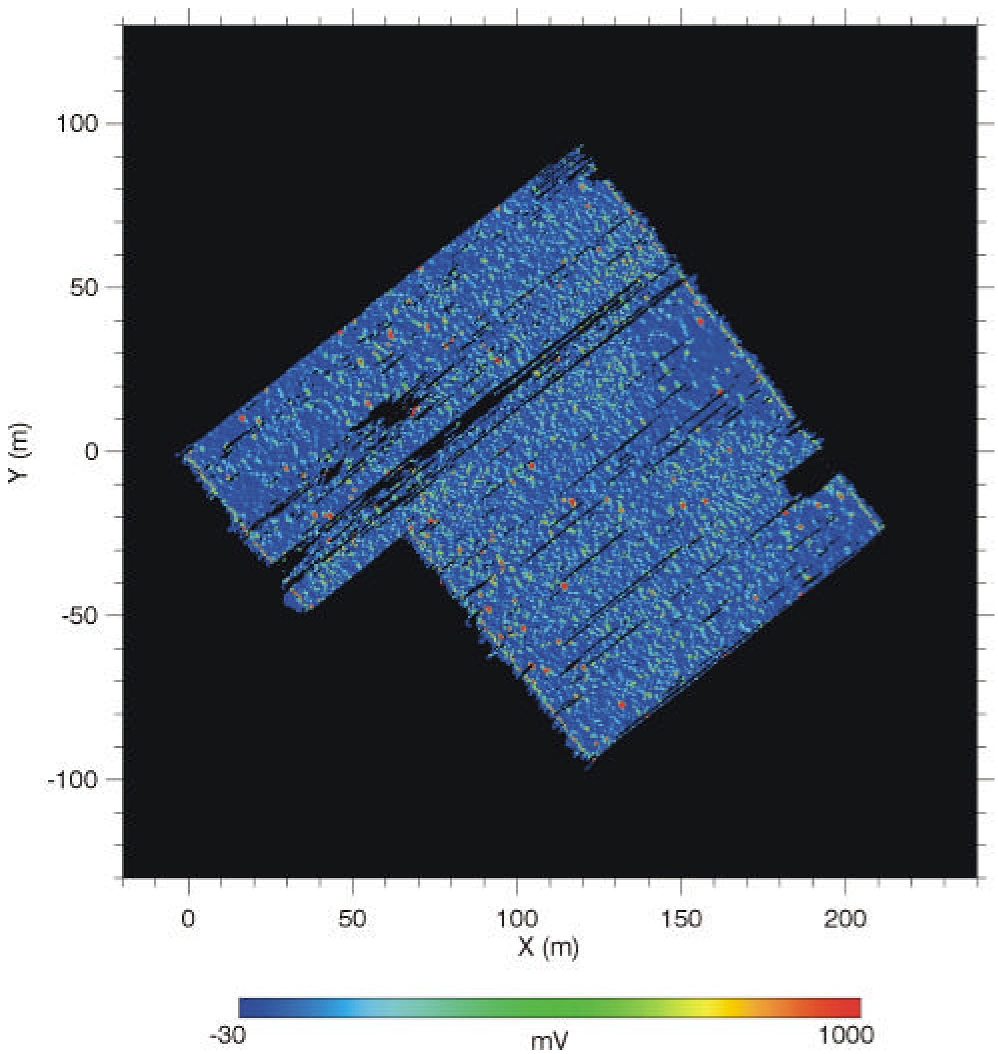


Figure 34. EM Survey of the QA Site at Kaho'olawe Using a 20-Point Demedian Filter in an Interpolated Image. (Note the different sensitivity scale from Figure 33.)

This page left blank intentionally.

9.0 KAHO'OLAWE PERFORMANCE ASSESSMENT

9.1 THE CALIBRATION SITE

Figure 35 shows the EM survey of the southwest third of the calibration site, both as an interpolated image and as a pixel plot. Individual data points are sometimes apparent in the pixel plot. The overlay of the target locations and identities shows that most, but not all, targets are apparent in either presentation. In the calibration site, the 20-point demedian filter effectively suppressed much of the interfering geological return. Table 15 shows a summary of our target analysis of the calibration site, along with the ground truth information provided by ERDC. The targets in the ESTCP (southwest 30-m X 30-m) grid are much more easily detected than the targets on the remainder of the calibration site. Overall, in the calibration site we concluded that 43 of the 87 (~50%) targets would likely not have been detected without prior knowledge of the ground truth. The targets that would likely be missed in a blind EM survey are highlighted in yellow in the right column in Table 15. The smaller targets, up to and including many of the 60- and 81-mm mortars, would not be detected in a blind survey, primarily because of geological interference. Most of the large, deep targets (projectiles or bombs) are buried below the detection limit of our EMI instrument. The deepest targets would probably be beyond our EMI detection limit, even without the geological interference.

Figure 36 shows a presentation on a similar area scale of an anomaly map from the magnetometer survey. The geological interference is, of course, much worse in the magnetometry data than in the EM data. The data shown in Figure 36 is highly filtered (15 point, down-the-track demedian filter). Unfortunately, we did not have access to more sophisticated data processing filters (or the time to incorporate them) to improve the magnetometer analysis. Many of the targets are detectable in the magnetometer data; however, only the deepest large targets were detectible in the magnetometer data, but not in the EM data. In Figure 36, we have circled dipole signatures that are probably associated with the identified target assignments. The targets circled in Figure 36 were declared as not detectable in the EM data analysis. Because of time constraints to complete the surveys, and because there was insufficient time to develop new data processing tools, we decided not to conduct magnetometry surveys of the QA site.

9.2 THE QA DEMONSTRATION SITE

The QA site, shown in Figure 34, is much more highly disturbed than the calibration site. Figure 37 shows a pixel presentation of part of the 1E 30-m grid on about the same scale as the pixel plot in Figure 35. The remainder of the QA site looks similar when viewed on this presentation scale. There are 3 factors affecting the QA site that make analysis more difficult for us than analysis of the calibration site. The density of small and intermediate sized shrapnel chunks is much higher on the QA site. In most cases, these present as 0.5-m to 1-m single-track signals, such as those that dominate the image in Figure 37. The surface of the QA site is also physically much rougher than the calibration site. Our EM sensors, unfortunately, generate

Table 15. MTADS Target Report (edited), Kaho'olawe Calibration Site, 20-Point Smooth.

MTADS ID	Local X (m)	Local Y (m)	UTM X (m)	UTM Y (m)	Depth (m)	Goodness of Fit	SIZE (m)	Analyst Comments	RESULT
1	4.21	8.43	746574.24	2273330.39	0.73	0.364	0.032	EO, no real signal	20MM, Missed TARGET
2	8.42	6.57	746578.45	2273328.53	0.67	0.704	0.058	E6, 20mm, better pixel target	20MM, OK
3	9.39	10.85	746579.42	2273332.81	0.75	0.382	0.046	EM, IPO fit, large frag	LARGE FRAG, OK
4	7.76	12.59	746577.79	2273334.55	0.72	0.795	0.086	EK, IPO fit, large frag	LARGE FRAG, OK
5	8.71	14.94	746578.74	2273336.91	0.90	0.715	0.097	E7, IPO fit, 81mm	81MM, OK
6	2.25	18.03	746572.28	2273339.99	0.72	0.796	0.049	E1, pixel fit,	20MM, NOT FIT THE TARGET
7	9.38	20.13	746579.41	2273342.09	0.55	0.788	0.063	EG, IPO fit, medium frag	MED FRAG, OK
8	5.11	22.25	746575.14	2273344.22	1.03	0.463	0.080	EE, IPO fit, medium frag	MED FRAG, OK
9	9.27	24.15	746579.30	2273346.11	0.74	0.909	0.088	E8, pixel fit, 2.75in WH	2.75", OK
10	16.13	6.37	746586.16	2273328.34	0.38	0.888	0.048	EP, IPO fit, medium frag	MED FRAG, OK
11	14.30	12.74	746584.33	2273334.70	0.59	0.828	0.070	EL, IPO fit, medium frag	MED FRAG, OK
12	17.27	10.61	746587.30	2273332.58	0.82	0.672	0.073	E4, IPO fit, 40mm proj	40MM, OK
13	19.77	14.98	746589.81	2273336.94	0.64	0.661	0.091	EJ IPO fit, medium frag	MED FRAG, OK
14	16.62	18.54	746586.65	2273340.50	0.87	0.704	0.087	E5, IPO fit, 105mm HEAT	105 HEAT, OK
15	25.81	21.15	746595.84	2273343.11	0.72	0.743	0.053	EH, IPO fit, large frag	LARGE FRAG, OK
16	24.59	14.72	746594.62	2273336.68	1.23	0.369	0.096	E2, IPO fit, 40mm proj	40MM, OK
17	25.42	11.14	746595.45	2273333.11	0.87	0.467	0.105	EN, pixel fit, no real signal	SMALL FRAG, Mised TARGET
18	31.93	-0.86	746601.97	2273321.11	-2.38	0.003	0.414	E1, pixel fit, no real signal	20MM, Missed TARGET
19	18.09	23.56	746588.12	2273345.53	0.71	0.657	0.068	EF, IPO fit, medium frag	MED FRAG, OK
20	27.30	25.55	746597.33	2273347.51	7.93	0.056	1.939	E3, wont fit IPO, 60mm mortar	60MM, Missed TARGET
21	30.83	23.28	746600.87	2273345.24	0.33	0.967	0.067	SQ, IPO fit, undefined frag	FRAG, OK
22	32.92	18.04	746602.95	2273340.00	0.65	0.772	0.062	2, IPO fit, undefined pipe	PIPE, OK
23	32.20	13.79	746602.23	2273335.75	0.49	0.651	0.057	SA, IPO fit, undefined frag	FRAG, OK
24	31.71	8.24	746601.75	2273330.20	0.34	0.48	0.036	6, IPO fit, 60mm mortar	60MM OK
25	29.40	3.38	746599.43	2273325.34	-1.83	0.013	0.489	1, IPO wont fit, 20mm, no signal	20MM, Missed TARGET
26	35.65	4.77	746605.68	2273326.74	0.35	0.592	0.031	7, IPO fit, 3in proj	3", OK
27	32.50	0.70	746602.53	2273322.67	0.33	0.595	0.029	18, IPO fit, Mk81@1.8m, weak signal	MK81, FIT GEOLOGY
28	42.72	3.49	746612.75	2273325.45	0.70	0.485	0.258	17, pixel fit, Mk81@1,5m, no signal	MK81, FIT GEOLOGY
29	40.37	6.20	746610.40	2273328.16	0.56	0.665	0.058	12, IPO fit, 5in proj @1m	5', DOUBTFUL FIT
30	52.18	2.95	746622.21	2273324.91	0.86	0.892	0.124	16, IPO fit, 500lb bomb @1.2m	500LB, OK
31	47.12	5.83	746617.15	2273327.79	0.34	0.43	0.029	8, IPO fit, 3in pipe	3' PIPE, DOUBTFUL FIT
32	45.97	7.62	746616.00	2273329.58	0.60	0.533	0.053	15, IPO fit, 3in pipe	3' PIPE, DOUBTFUL FIT
33	52.95	7.18	746622.98	2273329.15	0.76	0.572	0.086	SE, IPO fit, undefined frag	FRAG, OK
34	52.29	10.64	746622.32	2273332.60	0.51	0.756	0.041	23, pixel pick, no real signal	4 LB BOMB, Missed TARGET
35	38.53	14.51	746608.56	2273336.47	0.40	0.466	0.133	20, wont fit IPO, Mk82, no see	MK82, Missed TARGET
36	45.80	18.28	746615.84	2273340.25	0.50	0.757	0.033	5, IPO wont fit, 5in frag	FRAG, Missed TARGET
37	40.49	22.50	746610.52	2273344.47	0.70	0.555	0.082	14, IPO fit, 2.25in rocket	2.25" OK
38	44.96	22.49	746614.99	2273344.45	0.60	0.543	0.058	11, IPO fit, 2.25in rocket	2.25", Missed TARGET
39	48.68	23.53	746618.71	2273345.49	0.84	0.481	0.077	10, IPO fit, 81mm mortar	81MM, OK
40	56.22	7.86	746626.25	2273329.82	0.43	0.845	0.037	9, pixel fit, IPO sees geology, 2.25in rocket	2.25", Missed TARGET
41	60.90	15.15	746630.93	2273337.12	0.88	0.28	0.103	4, target lost in border nails	5" FRAG, Missed TARGET
42	58.67	19.02	746628.70	2273340.99	0.72	0.565	0.070	SG, IPO fit, undefined frag	FRAG, Missed TARGET
43	52.44	17.01	746622.47	2273338.97	0.56	0.844	0.057	13 IPO fit, 3in pipe	3", OK
44	53.87	17.30	746623.90	2273339.27	0.29	0.905	0.045	SL, IPO fit, undefined frag	FRAG, OK
45	55.75	20.05	746625.78	2273342.01	0.46	0.784	0.081	SC, IPO fit, undefined frag	FRAG, OK
46	55.73	21.95	746625.76	2273343.91	0.67	0.711	0.052	3, pixel pick, no see in IPO, rocket motor	rocket motor, MissedTARGET
47	53.43	27.65	746623.46	2273349.62	0.47	0.433	0.052	19, IPO fit, Mk 82 bomb, doubtful signature	MK82, Missed TARGET
48	52.91	30.62	746622.94	2273352.59	0.70	0.556	0.087	SH, IPO fit, undefined frag	FRAG, OK
49	49.02	26.46	746619.06	2273348.42	0.42	0.672	0.050	SO, IPO fit, undefined frag	FRAG, OK
50	42.99	16.97	746613.02	2273338.93	15.21	0.001	0.267	21, pixel fit, no IPO signal, 4lb bomb	4LB, Missed TARGET
51	46.90	31.70	746616.93	2273353.66	0.72	0.523	0.039	20, pixel fit, no IPO signal, Mk82	MK82, Missed TARGET
52	43.46	33.08	746613.49	2273355.04	0.67	0.633	0.078	32, IPO fit, 40mm	40MM, OK
53	2544.08	291.76	749114.11	2273613.72	#####	0.003	21.402	25, pixel pick, no signal, 5in proj	5", Missed TARGET
54	44.25	35.58	746614.28	2273357.54	0.64	0.769	0.041	31, pixel pick no IPO signal, 40mm	40MM, Missed TARGET
55	55.32	34.54	746625.36	2273356.50	0.78	0.551	0.065	50 pixel pick, no IPO signal, 81mm tail	81MM TAIL, Missed TARGET
56	58.84	36.54	746628.87	2273358.50	0.85	0.395	0.085	49, IPO fit, 81mm tail	81MM TAIL, OK
57	53.26	38.21	746623.29	2273360.17	0.60	0.73	0.071	48, IPO fit, 81mm tail	81MM TAIL, OK
58	59.47	41.79	746629.50	2273363.75	0.66	0.736	0.052	29, IPO fit, 60mm mortar	60MM, OK
59	57.42	43.60	746627.45	2273365.56	0.85	0.475	0.080	28, pixel fit, IPO no fit, 60mm mortat	60MM, Missed TARGET

Table 15. MTADS Target Report (edited), Kaho'olawe Calibration 20-Point Smooth.
(continued)

MTADS ID	Local X (m)	Local Y (m)	UTM X (m)	UTM Y (m)	Depth (m)	Goodness of Fit	SIZE (m)	Aqnalyst Comments	RESULT
60	60.69	45.61	746630.72	2273367.57	4.96	0.077	1.500	27, IPO fit, 60mm mortar	60MM, LOST IN GEOLOGY
61	49.27	39.42	746619.30	2273361.38	0.65	0.554	0.074	SI, IPO fit, undefined frag	FRAG, OK
62	**********	**********	************	**************	*********	0.021	#######	44, IPO, no signal, 2.75in rocket	2.75", Missed TARGET
63	44.52	43.66	746614.55	2273365.62	0.44	0.705	0.061	43, IPO fit, 2.75in rocket	2.75", OK
64	43.04	40.44	746613.07	2273362.41	0.31	0.37	0.038	47, IPO fit, nose fuze	FUZE, OK
65	39.62	48.52	746609.65	2273370.48	-2.43	0.008	0.756	42, pixel pick no signal, 2.75in WH	2.75", Missed TARGET
66	37.44	41.00	746607.47	2273362.96	0.61	0.515	0.069	SM, IPO fit, undefined frag	FRAG, OK
67	41.20	55.67	746611.24	2273377.64	10.84	0.009	1.009	24, pixel pick, no signal, 5in proj	5", Missed TARGET
68	33.43	44.53	746603.47	2273366.49	0.92	0.029	0.080	46, pixel pick, no signal, nose fuze	FUZE, Missed TARGET
69	32.24	43.12	746602.27	2273365.08	0.37	0.074	0.368	53, pixel pick, no signal, 60mm can	60MM, Missed TARGET
70	21.37	25.66	746591.40	2273347.62	0.56	0.679	0.070	EC, IPO fit, large frag	FRAG, OK
71	14.93	28.27	746584.96	2273350.23	0.68	0.509	0.050	EB, IPO fit, medium frag	FRAG, OK
72	4.43	27.30	746574.46	2273349.26	0.72	0.791	0.095	EA, IPO fit, large frag	FRAG, OK
73	35.32	24.79	746605.35	2273346.75	0.59	0.577	0.059	18, pixel pick, IPO no fit, Mk81@1.8m	MK81, Missed TARGET
74	33.94	29.70	746603.98	2273351.66	0.51	0.776	0.071	SP, IPO fit, undefined frag	FRAG, OK
75	29.20	28.98	746599.23	2273350.94	0.67	0.885	0.066	ED. IPO fit, medium frag	FRAG, Missed TARGET
76	58.64	57.79	746628.67	2273379.76	-4.62	0.205	2.176	37, pixel pick, no IPO signal, 81mm	81MM, Missed TARGET
77	53.53	57.66	746623.56	2273379.62	0.81	0.714	0.078	36, IPO fit, 81mm can	81MM, Missed TARGET
78	55.36	52.95	746625.39	2273374.91	0.68	0.331	0.046	38, pixel pick, no IPO signal, 81mm	81MM, Missed TARGET
79	51.42	50.34	746621.45	2273372.30	1.40	0.521	0.205	SK, IPO fit, undefined frag	FRAG, Missed TARGET
80	**********	**********	************	**************	*********	NaN	************	SJ, pixel pick, no signal, undefined frag	FRAG, Missed TARGET
81	49.35	55.27	746619.38	2273377.24	1.08	0.389	0.159	SR, pixel geology pick, undefined frag	FRAG, Missed TARGET
82	41.47	58.69	746611.50	2273380.65	0.85	0.458	0.068	41, IPO fit, 2.25in rocket	2.25", Missed TARGET
83	41.54	54.49	746611.57	2273376.45	0.58	0.371	0.040	40, IPO fit, 2.25in rocket	2.25", Missed TARGET
84	39.12	52.91	746609.15	2273374.88	0.76	0.439	0.045	39, IPO, no signal, 2.25in rocket	2.25", Missed TARGET
85	######	#######	************	**************	*********	0.011	#######	34, IPO, no signal, 20mm	20MM, Missed TARGET
86	35.64	51.02	746605.67	2273372.98	0.80	0.73	0.050	33, IPO, no signal, 20mm	20MM, Missed TARGET
87	32.70	57.28	746602.73	2273379.25	0.50	0.284	0.048	51, IPO, sees geology, 60mm can	60MM, Missed TARGET

* The designation "IPO" in the Comments column signals that the target data were selected from the interpolated image presentation. All target fitting algorithms are applied to the uninterpolated sensor data as shown in the pixel plots

sensor spikes when the system bumps hard over a surface feature. These signals, which one might expect to be sensor data spikes that could be edited out, unfortunately damp out over a period of a few tenths of a second, making them almost undistinguishable from the shrapnel clutter signal returns. Together, these two effects are responsible for most of the red signal return shown in Figure 37. This noise-dominated data required that we carry out analysis at much less sensitive scales and give up even more of the small targets than in the calibration site analysis. The third effect, referred to above, is the more intense geological interference on this site. The geological returns effectively dictated that we analyze data with the visual guidance of the pixel presentations rather than the combination of pixel and interpolated image presentations used at the calibration site.

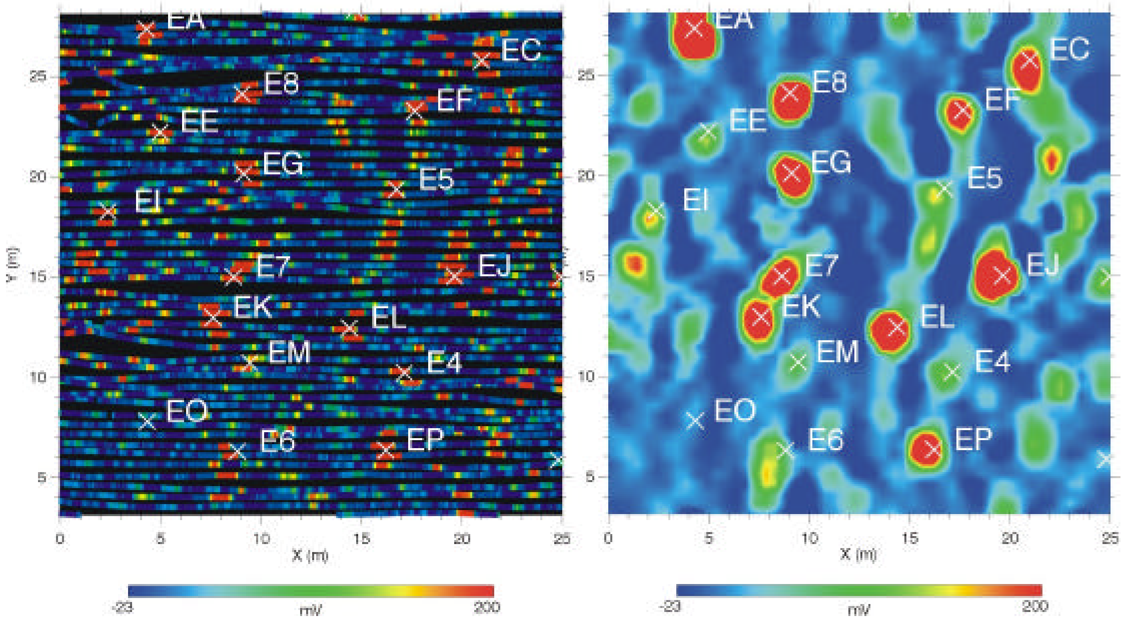


Figure 35. Southwest Quadrant of the Calibration Site. A Comparison of Pixel (left) and Interpolated Image Presentations of the EM Survey.

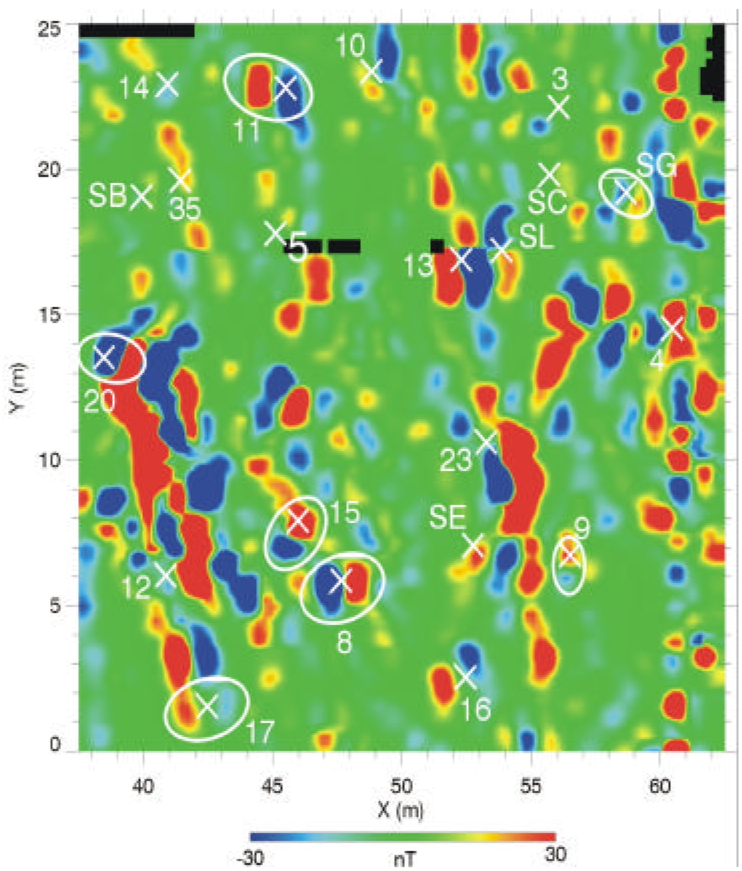


Figure 36. Calibration Site. Interpolated Image from the Magnetometry Survey Using a 15-Point Demedian Filter.

The EM data analysis graphical user interface (GUI) in use at the time of this demonstration employed what we call the 3-ß analysis algorithm. This provides an analysis that generates three parameters that presumably correlate with size along the primary orthogonal axes of the target. These ß parameters are used as clues to target shape information for use in classification decisions. The geological interferences and the noise signals from the shrapnel clutter and sensor bouncing rendered the 3-ß parameters effectively useless as an analysis tool. Figure 38 shows that the ordnance on the calibration site is indistinguishable from clutter, based on the 3-ß analysis. Therefore, our analysis used the previously developed baseline EM analysis approach in which the important analysis parameters are location, depth, and size. Shape information, to the extent that it is available, is gleaned from the detrend presentation in the model fit analysis window. The goodness-of-fit parameter is used primarily as an evaluation tool to guide boxing the data chip for analysis and as a guide in editing the data selected for target fitting.

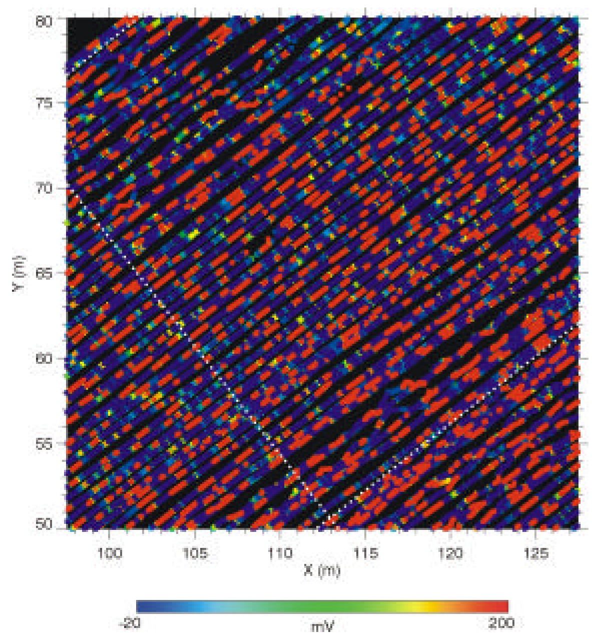


Figure 37. Pixel Presentation of Part of Grid 1E in the QA Site from the EM Survey. (The pixel presentation uses the same settings as the calibration site presentation in Figure 35.)

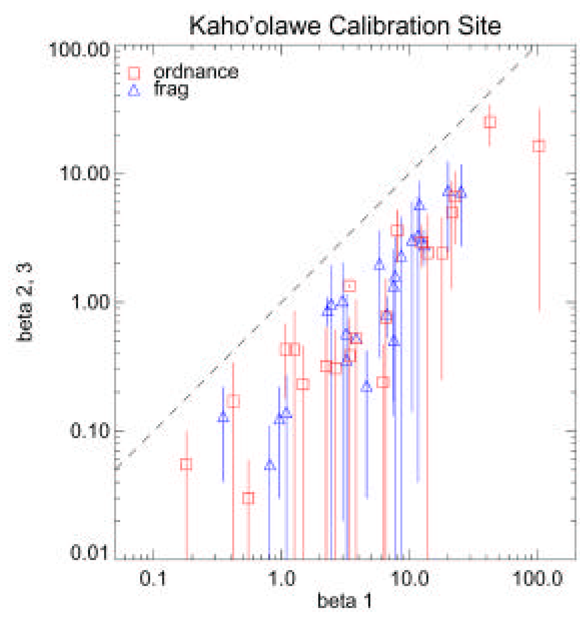


Figure 38. Three-Beta Plot from the Analysis of the Ordnance and Clutter Targets on the Calibration Site.

Presentations such as the one shown in Figure 39 were used to guide the analysis. This presentation shows the targets boxed for analysis in Grid 1C of Area A. Target numbers were deleted so the sensor data could be more easily visualized. To reduce the signal dominance of shrapnel returns, we were guided by the upper coil data. We particularly sought out targets with returns in adjacent tracks on the assumption that larger targets would appear on multiple tracks. Some single-track targets were still reported. During analysis of individual targets, we typically rescaled the presentation many times to seek out smaller targets and to try to evaluate geological returns. However, because of the noisy returns we were limited to working with fairly high intensity signals. We were aware that this mitigated against our detection of both the small targets and the deep targets with smaller intensity signal returns.

9.3 REPORTS

Data were analyzed from the hotel/office site in Maui, and the required target tables were submitted to the program representative. On October 24, preliminary data containing a target analysis of Area A were submitted to the program manager, Scott Steward. The analysis was graded immediately (as described in the Test Plan) [22], and results were returned to NRL to guide the remaining analysis. The spreadsheet in Table 16 was the provided grading. We were informed that we had correctly declared ~40% of the seeded targets in our preliminary report. Missed items were not identified and further ground truth was not provided until the final report [25]. The list included 9 UXO items and 11 items of frag. These results were consistent with our expectations based on our analysis of calibration site data and the relative greater geological and shrapnel interferences on the QA site. On October 25, we delivered to Mr. Steward the completed analysis and the remainder of the deliverables specified in the Demonstration Test Plan. The target tables were submitted separately for the 1-hectare site, and an analysis of combined Areas A and C was submitted.

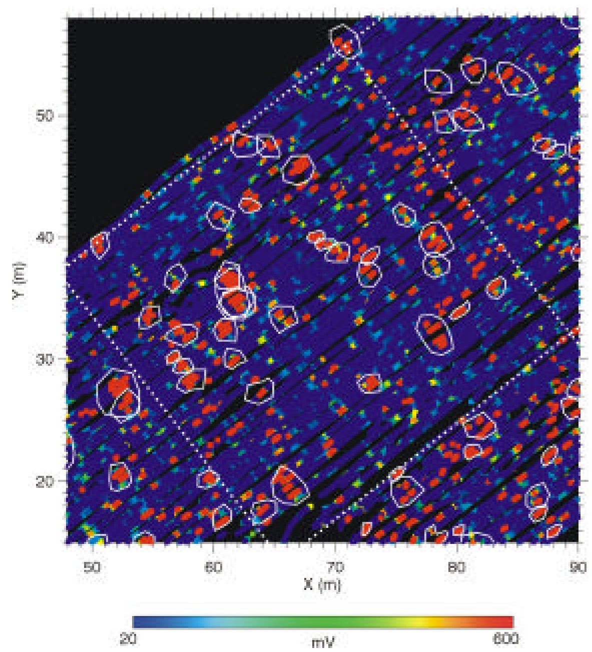


Figure 39. QA Site, Grid 1C. Pixel Presentation of the EM Survey Showing Targets Selected for Analysis.

Table 16. Grading from Submission of Preliminary Analysis of Targets from Area A.

	UTM Coordinates							
NRL Target ID	Northing	Easting	Elev(msl)	Description	Depth (m)	Az (deg)	Incl (deg)	Nose U/D
51	2272256.419	748397.026	253.451	Med Frag	0.3	90	45	
49	2272250.367	748393.534	252.521	Large Frag	0.65	135	60	
41	2272247.050	748382.421	252.332	Large Frag	0.35	0	60	
56	2272244.694	748404.410	252.861	Med Frag	0.25	315	0	
50	2272254.966	748391.016	252.964	Med Frag	0.25	270	0	
65	2272254.143	748415.915	253.774	5" HE PRACTICE	0.9144	180	0	
65	2272254.728	748415.651	253.706					
82	2272258.247	748426.907	254.370	MK 76 P.B. (BDU 33-(NOSE)	0.2286	0	0	
82	2272258.102	748426.634	254.372					
1	2272284.586	748418.571	255.406	LAAW	0.127	0	0	
1	2272284.661	748418.333	255.404					
8	2272271.238	748423.191	254.656	2.75" ROCKET WH	0.381	270	45	D
8	2272271.667	748423.305	254.584					
14	2272265.901	748413.695	253.946	20 mm Projectile	0.25	90	0	
4,5	2272277.843	748421.755	254.518	Large Frag	0.55	0	90	
13	2272264.487	748425.991	254.555	Med Frag	0.35	90	45	
18	2272266.476	748408.781	253.920	Small Frag	0.15	45	0	
228	2272227.670	748421.220		MK 76 P.B. (BDU 33)	0.7112	270	45	D
226	2272225.120	748413.860		MK-3 PRAC BOMB	0.2286	0	45	D
224,225	2272220.170	748407.530		MK-81 P. B. W/S.E. FINS	1.016	130	0	
229	2272223.595	748423.136	252.701	Small Frag	0.1	270	0	
94	2272258.720	748439.050		MK 76 P.B. (BDU 33-(NOSE)	0.2286	0	0	
231	2272243.420	748440.679	254.520	Med Frag	0.2	0	0	
232	2272250.539	748441.520	254.598	Large Frag	0.55	0	0	

At the ESTCP Partners Symposium in December 2001 a preliminary analysis of the results from all demonstrators for the 1-hectare site was presented in the form of ROC curves showing relative probability of UXO detection as a function of the false alarm count [26]. A summary of the results, presented at the meeting, is shown in Figure 40. NRL was Demonstrator B. The ESTCP Program Office felt that NRL should have picked more targets in our analysis because our ROC curve (Demonstrator B) was similar in shape to the other demonstrators, but our analysis was terminated well before the other demonstrators had ceased picking targets that continued to increase their performance in identifying UXO targets.

It was further agreed between the ESTCP Program Office and the Kaho'olawe demonstration support organizations that in the final analysis the demonstrator's results would be regraded following deletion of the 20- and 40-mm targets from the database. This presumed that the demonstrators would resubmit analyses based on this assumption. NRL analyzed and resubmitted new target lists for evaluation. In the reanalysis a few small targets were deleted (or moved to lower confidence levels) and, as requested, many additional targets were chosen. The total targets reported for Area B increased from 141 to 305 over the analysis submitted in Maui. Similarly, the final count of targets in the combined Areas A + C increased from 246 to 312.

In the final demonstration report [25], the ground truth for all sites was released and the performances of the demonstrators was presented and analyzed. Table 17 extracts information from this report relative to the NRL performance following reanalysis and submission of the target tables.

Table 17. Evaluation of the NRL Performance from the Reanalyzed Data Assuming the 20- and 40-mm Ordnance Were Not Present.*

		Area A	Area B	Area C	Total
	Number of Targets (without 20/40-mm)	19	55	28	102
NRL (without 20/40-mm)	Targets Detected	8	19	8	35
	P_d	0.421	0.345	0.286	0.343

*Adapted from Table 3 of Reference 24

The ROC curves showing NRL's performance in each of the areas are shown in Figure 41. These data reflect the deletion of the 20- and 40-mm ordnance from the database and are based on our target analyses after picking additional targets. These expanded analyses were submitted to ESTCP and ERDC on December 14, 2001. The information in Figure 41 was adapted from Figures 40-42 in the final report [25].

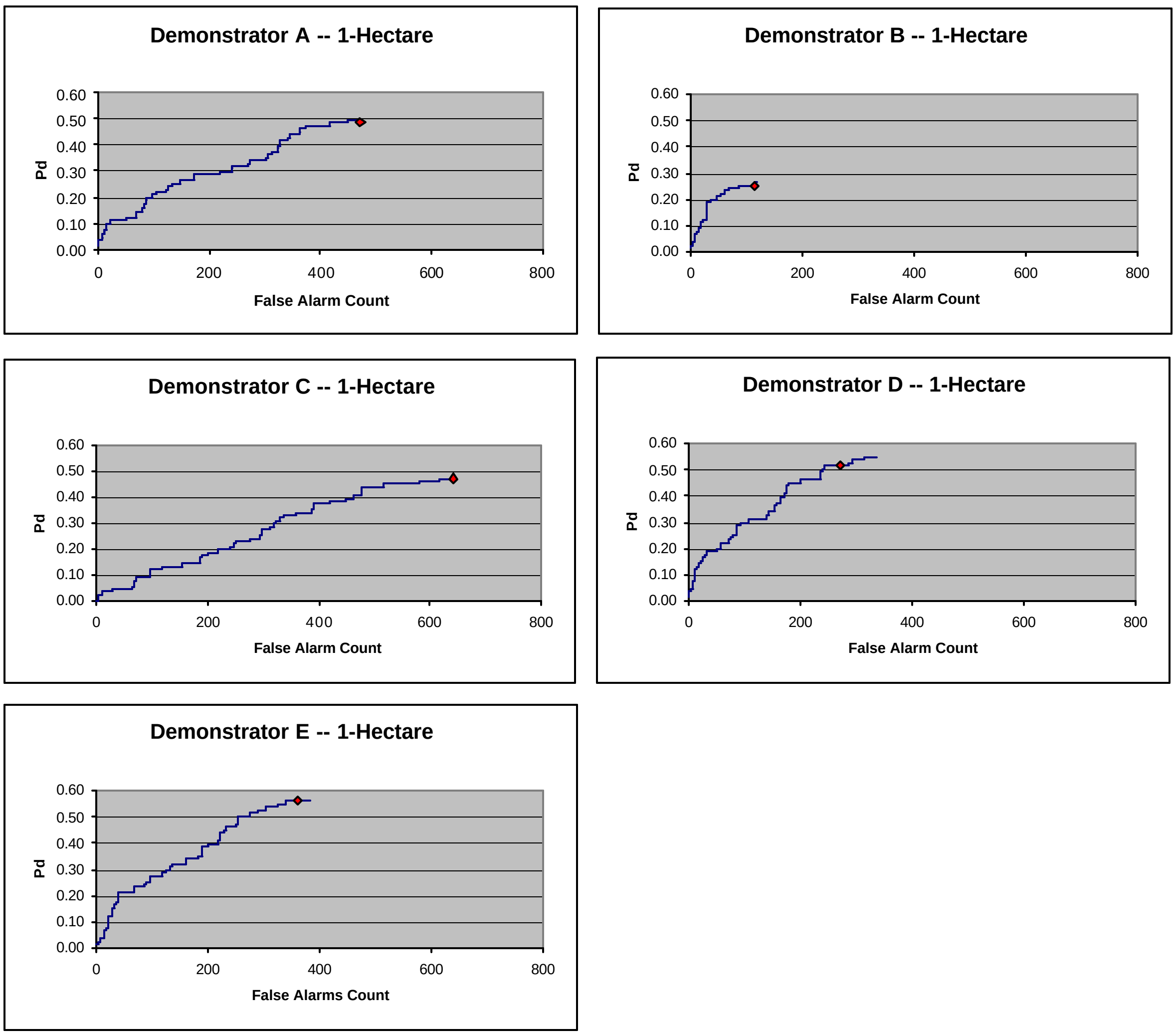


Figure 40. ROC Curves for the Five Demonstrators' Analyses of Area A, the 1-Hectare Site.

9.4 RESULTS

Based on the P_d, (Tables 2 and 3 of Reference 25, and Figures 40 and 41), it appears that in Area B, the MTADS ordnance detection efficiency rose substantially as the result of the reanalysis of the data, i.e., from 21% to 34.5%. A closer inspection of all the information, however, shows that almost the entire increase was based on the deletion of twenty-six 20-mm and 40-mm targets from the database. In our original submission (on Maui) we did not detect any of the 20- or 40-mm targets in Area B. By adding 164 targets to our original Area B dig list of 141 targets, we detected only two additional targets (a 60-mm and a Mk-3). Similarly, by expanding the number

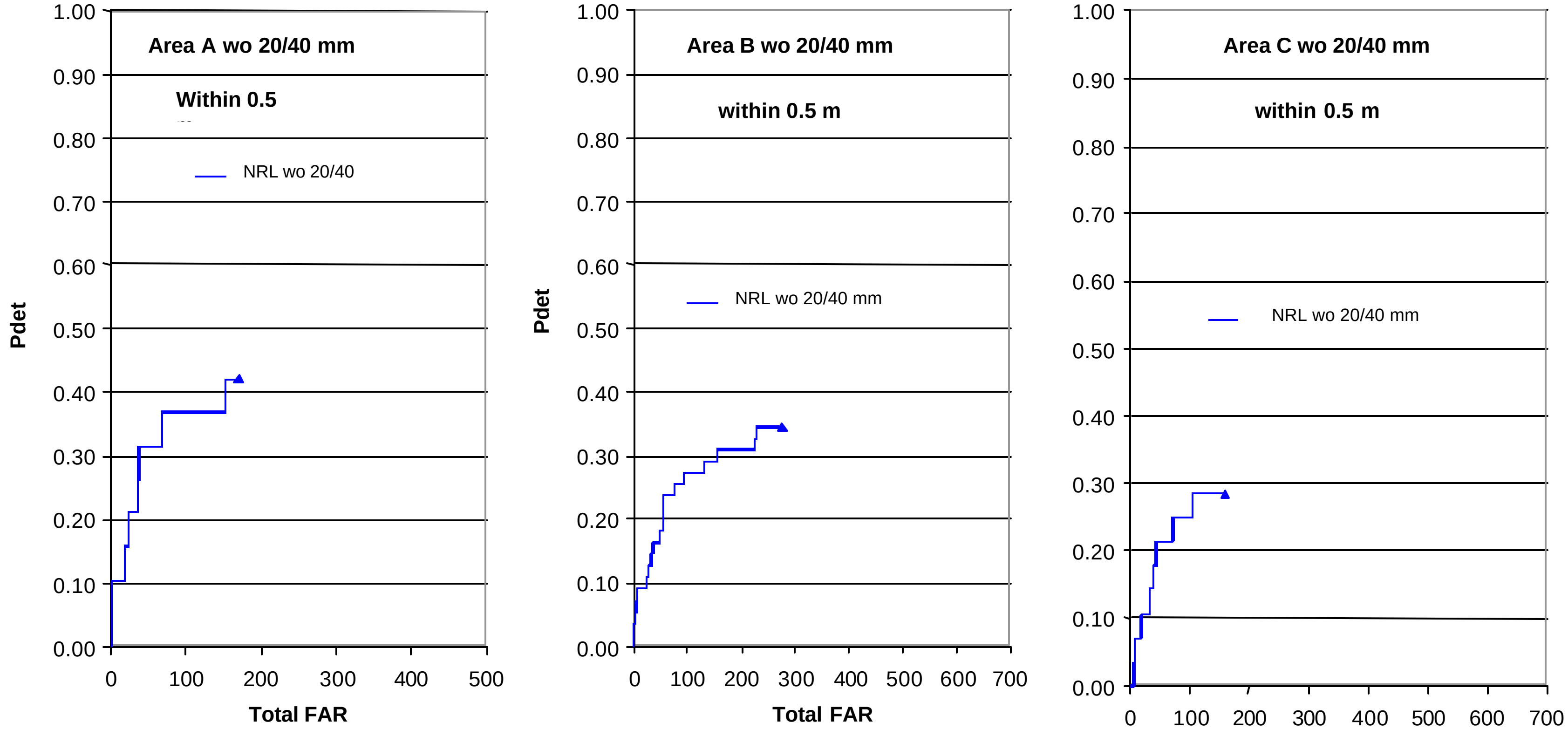


Figure 41. ROC Curves from the Reanalysis and Resubmission of NRL's Kaho'olawe Data. (Graphics are adapted from Figures 40-42 of Reference 25.)

of target picks in Areas A + C by 27%, we detected only three additional targets. In each case, at least some of these additional "detected" targets may have been coincidences. On the basis of either the detection efficiency or ultimate costs to remediate targets on the dig list, our original target analysis as submitted on Maui was the better of the two work products.

The important questions that must be addressed, however, are:

- Why was the MTADS EMMS performance much poorer on an absolute scale on Kaho'olawe than had been previously demonstrated on other sites?

- Why did the MTADS EMMS detect a much smaller fraction of the Kaho'olawe targets than the other better performing demonstrators?

First, consider the performance of the three systems that used virtually the same sensor—the MTADS EMMS, the Parsons EM-and-flag, and the Parsons EM digital. All use variants of the EM61. The EM61 has excellent sensitivity for very small shallow ordnance, good detection efficiency for intermediate sized objects, and diminishing detection efficiency for more deeply buried objects. The ROC curves, Figures 37-45 of Reference 25, show that the two Parsons EM61 approaches performed similarly; overall, the EM & Flag approach may have been the slightly superior of the two. The EMMS ROC curves parallel the other two EM61 performance curves, but terminate at a detection limit well below the other two systems. Picking extra targets from the EMMS data did not drive the performance in parallel to the other two EM61 systems. One of the historical advantages of the EMMS (Figure 31) is that we have located the coils closer to the ground than the traditional Geonics wheeled carts. In retrospect, at Kaho'olawe, this was a disadvantage because survey data were overwhelmed by returns from tiny shrapnel fragments (Figure 37). Locating the sensors higher above the ground would provide a relative discrimination against this very small clutter.

A substantial impediment to detection of either small objects or weak signals by the EMMS was the overwhelming noise generated by bouncing the cart over rough terrain. Our reanalysis of the data demonstrated that there were effectively no further gains to be made from additional analysis of our data. Using the EM61 in an EM-and-flag mode allowed the cart to be maneuvered back and forth to reacquire signals several times from different directions and while moving at different speeds. These differences provided enough of a detection edge that the Parsons EM61 systems could continue successful detection further up the ROC curve than the EMMS. Neither of the Parsons systems could detect 20-mm ordnance; however, the EM & Flag system was fairly efficient in finding the 40-mm ordnance.

It is likely that the setup of the control electronics on the EMMS (higher transmit power, earlier time gates, and reduced time constants imposed during the data acquisition step) may also have worked to a relative disadvantage for the EMMS. It is also possible that the experience that Parsons had while using these systems specifically on Kaho'olawe for more than a year before this demonstration (in conjunction with instant feedback from digging targets) worked to the relative advantage for their system.

The other two consistently better performing systems were the Geophex GEM, and the Geonics EM63, operated by NAEVA. The EM63 performance was similar to that of the two Parsons EM61 systems, except in Area C where it performed relatively less well. The EM63 has many time gates. It is not clear that these provided any significant operational advantage. The EM63 also has relatively lower detection sensitivity than the EM61. This may have been responsible, in part, for the relatively poorer performance in Area C where the EM63 failed to detect seven of the eight large/deep bombs. The EM63 demonstrated a consistently better detection capability than the EMMS. Each followed similar ROC curves, but, apparently better signal-to-noise levels allowed the EM63 to ultimately detect ~20% more ordnance than the EMMS.

The Geophex GEM performed outstandingly well in Area A compared to all other systems and about equivalently to the Parsons EM61 surveys in Areas B and C. As with the EM63, the GEM and the EMMS initially followed generally the same ROC curve, but the GEM ultimately detected 10-20% more ordnance than the EMMS. See Figures 40-42 in Reference 25.

9.5 LESSONS LEARNED

The relatively poor performance of the EMMS was effectively entirely the result of signal-to-noise limitations on our ability to analyze data. This was true on an absolute scale relative to the EMMS performance at other sites and in a relative sense in comparison to other systems performing at Kaho'olawe. There are three primary contributing factors, all of which involve noise contributions (rather than limits on the signal). On an absolute sensitivity basis, the EMMS is almost certainly the most sensitive instrument among those demonstrated at Kaho'olawe.

None of the participants demonstrated the ability to detect 20-mm ordnance. The Parsons EM-and-flag (but not the Parsons digital EM), the GEM, and the EM63 detected ~half of the 40-mm ordnance. For the EMMS to achieve this level of performance, the signals generated from shrapnel and from cart bouncing would have to be substantially reduced.

Two significant alterations would have to be taken to approach this goal. Each is, to a large extent, unique to this site. The first would require raising the coils higher above the ground, perhaps even higher than the Parsons systems. Most of the frag pieces are very small, and their signals would disappear if the coils were raised. The second "fix" would be to hand carry the EM coils, much as was done on Adak, Alaska, because of the rugged terrain. This would require two operators for the EMMS, one to carry the coils and the second to carry the support instrumentation in a backpack. Implementing both of these changes might improve the EMMS performance to the level of (or perhaps marginally better than) the GEM, the EM63, or the EM-and-flag EM61. It seems unlikely that any fieldable system will ever be able to detect significantly more than 50% of *this* distribution of ordnance on *this* site. This implies that it is unlikely that even three repeated surveys and digs on the same area could achieve a 90% clearance.

At a minimum, it is now well-documented that none of the newer technologies demonstrated in this effort offer the potential for substantial improvements over the use of a standard EM61 for detection of UXO. This conclusion holds only for this site; however, this site is very unique.

Many sites are rugged and difficult to survey, and many sites, to a greater or lesser degree, are characterized by magnetically active soils. However, this site has magnetic interferences that are as difficult as any naturally occurring soil geology anywhere in the world. The site is contaminated by UXO widely ranging in size and depths, and it has been used so extensively that the surface is nearly saturated with small, medium, and large shrapnel.

The Parsons EM-and-flag survey that was done as part of this demonstration showed a similar performance to the better of the other systems demonstrated. It would be logical to conclude that EM-and-flag provides an efficient and economical approach for cleaning this site. Such a conclusion should not be based on the results of this demonstration, however. The performance in a Parsons EM-and-flag survey is completely dependent on the skill of and consistent performance by the equipment operator. Parsons, no doubt, put one of their best operators on this job. His performance is very unlikely to be the same as that of the dozens of other operators, particularly when the other operators work very long days under very difficult conditions. It has been generally understood for many years in the UXO community that the performance of mag-and-flag operators is highly variable from operator to operator and that achieving consistent performance by a single operator requires that he work continuously only for relatively short periods of time.

It is much more feasible to achieve a consistent UXO survey product when the data are taken using georeferenced positioning, routine and standardized survey data collection techniques, and analysis and target decisions that are not made in the field but by a data analyst working in a controlled environment.

This demonstration took place under very realistic conditions on an extremely challenging site. The developers of the Technology Demonstration Plan, the site preparation effort, the demonstration support staff, and the performance analysis efforts were all extremely professional and fair to all participants. The fact remains, however, that the demonstrators brought their best equipment and their best people and that the operation was of only a few days duration. While the results demonstrate how well each of the techniques could perform under these specific limited circumstances, they do not directly address the performance any of these technologies in a large-scale clearance, using many operators over an extended time frame such as that taking place on Kaho'olawe. The results are likely to be very different.

This demonstration did prove, however, what is likely the maximum achievable result for the extended operation taking place on Kaho'olawe. It should be concluded that one cannot expect to consistently achieve an efficiency of 50% UXO recovery on this site in a single pass survey and dig operation. The QA approach that is being used on the island takes more precisely-positioned data than the EM-and-flag survey but is likely less sensitive because of signal-to-noise limitations from taking data using a cart bumping along at constant speed. The results of this demonstration should be accepted as the ultimate benchmark of maximum expected performance for EM61 systems in this environment.

10.0 COST ASSESSMENT

All discussions relating to cost and production rates are based on the JPG-V demonstration at the Jefferson Proving Ground as described in Sections 6 and 7 of this document. Careful tracking of onsite costs was maintained also for the Kaho'olawe demonstration (Sections 8 and 9). However, both costs and production rates for the latter demonstration are unrealistic because of the transportation costs of all people and materials by air to Hawaii, the lodging on Maui in resort hotels, the difficult and limited logistical access to the work site, and the 2-week extended operation to complete effectively only 3-hectares of survey work.

Operations and maintenance costs for the JPG-V demonstration include labor costs associated with setup, calibration, survey, analysis, and maintenance as well as any required support equipment, consumables, and supplies. Labor was monitored by on-site representatives of the government and converted to costs by the application of the same labor rates for all demonstrators. The following labor rates were used:

- Supervisor—$95/hour
- Data Analyst—$57/hour
- Logistics/field support—$28.50/hour

In addition to the costs listed above, the government analyzed the dig sheets provided by each demonstrator, and cost penalties associated with false positives and with UXOs misclassified as clutter were assigned as described in Section 6.5.

The evaluation factors related to production rate performance are listed in Section 6.5 of this report. Because of a variety of problems experienced in the field by some of the demonstrators (e.g., the need to collect a new target signature library on site and the inability to perform on-site analysis), direct comparison of all production rate factors is not possible. Because survey times are important production factors, and accurate information from all the demonstrators (including mag-and-flag) is available, it was decided to use this factor for production rate performance evaluation and comparison. A summary of the time and man-hours required by the EMMS to survey each site is presented in Table 18.

Table 18. EMMS Production and Man-Hours.

Area	Number of People	Time On-Site (Hr:Min)	Actual Man-Hours (Hr:Min)
1	1-4	5:49	19:13
2	3-4	7:55	25:20
3	3	5:56	17:50

The standard mag-and-flag approach achieved an average production rate of 1 hectare per 5.97 hr and required a three-person survey crew. The best performer among the demonstrators was the EMMS, which achieved an average of 1 hectare per 6.56 hr and required a field survey crew ranging from one to four persons.

The costs associated with each field task are detailed in Table 19 for the EMMS and summarized for all the demonstrators in Table 20. Field costs of the three demonstrators were fairly close, but the EMMS demonstrated the lowest costs. The baseline mag-and-flag field work conducted by EODT was considerably lower than all three demonstrators, but it should be noted that EODT was not required (nor capable) of providing georeferenced sensor maps, prioritized dig lists, and target discrimination/classification. Mag-and-flag also failed to reach 80% P_d at any of the three test areas, had significantly higher false alarms at the high magnetic background areas, and did not meet the Kaho'olawe clearance requirements.

Table 19. Breakdown of Field Costs.

Area	Categories	Cost	Time (hr:min)	Job Cost
1	Supervisor	$95.00	13:56	$1,232.66
	Data Analysis	$57.00	12:05	$688.75
	Logistic/Field Setup	$28.50	6:58	$198.55
	Logistic/Field Survey	$28.50	25:28	$697.30
	Logistic/Field Resurvey	$28.50	5:09	$146.78
	Total			**$3,055.04**
2	Supervisor	$95.00	18:32	$1,760.66
	Data Analysis	$57.00	26:16	$1,497.20
	Logistic/Field Setup	$28.50	11:22	$323.95
	Logistic/Field Survey	$28.50	25:20	$722.00
	Logistic/Field Resurvey	$28.50	0:00	$0.00
	Total			**$4,303.81**
3	Supervisor	$95.00	9:15	$878.75
	Data Analysis	$57.00	21:03	$1,200.35
	Logistic/Field Setup	$28.50	35:18	$1,006.05
	Logistic/Field Survey	$28.50	42:57	$1,224.08
	Logistic/Field Resurvey	$28.50	1:42	$48.45
	Total			**$4,357.68**

Table 20. Total Cost for All JPG-V Test Areas.

Demonstrator	Total Cost of Field Work	Total Cost of Field Work Excluding Data Analysis
NRL	$11,183.24	$7,854.44
GEOPHEX	$13,507.27	$9,972.32
NAEVA	$10,940.68	$10,783.93
EODT	$2,669.51	$2,669.51

Table 21 summarizes the operational costs of the demonstrator systems after the cost penalties described in Section 6.5 were applied. These penalties consisted of $200 for each false alarm (clutter item selected for digging by the demonstrator) and the cost of a complete resurvey for one or more UXO targets missed or erroneously classified as clutter with high confidence. This table highlights the fact that false alarms have (by a large margin) the greatest impact on the cost performance of each system. Table 21 indicates that all three demonstrators were penalized with the cost of a resurvey at each of the three test areas because UXO had been left in the ground as a result of misclassified or missed targets. The EMMS demonstrated significantly lower overall costs at all three areas. Comparison with the baseline mag-and-flag costs indicates that the best performing EMI technologies, including the EMMS, were considerably more cost-effective. Even though EMI system costs include the cost of analysis in both the survey and resurvey cost factors, they are consistently lower than EODT's. As expected, the EMI advantage is more significant in Areas 1 and 2, which have significant levels of magnetic noise from geologic sources.

Table 21. Demonstrator Costs, Including Penalties for False Alarms and Leaving UXO Targets in the Ground.

		Demonstrator			
Area	**Parameter**	**NRL**	**Geophex**	**NAEVA**	**EODT**
1	Cost of survey	$3,055	$5,255	$3,968	$960
	Cost of resurvey	$3,055	$5,255	$3,968	$960
	Cost of false alarms	$14,200	$18,200	$15,000	$26,900
	Total cost	$20,310	$28,710	$22,936	$28,820
2	Cost of survey	$4,304	$5,094	$2,247	$912
	Cost of resurvey	$4,304	$5,094	$2,247	$912
	Cost of false alarms	$12,600	$32,800	$24,600	$34,000
	Total cost	$21,208	$42,988	$29,094	$35,824
3	Cost of survey	$4,358	$3,111	$4,683	$798
	Cost of resurvey	$4,358	$3,111	$4,683	$798
	Cost of false alarms	$13,000	$31,000	$15,800	$20,600
	Total cost	$21,716	$37,222	$25,166	$22,196

Assuming deployments similar to those at JPG-V, the MTADS deployment costs are about $10,000 per day, on site. The production rate of the MMS and EMMS system is about 1.5-hectares per day in open areas using GPS navigation. The MMS can be used with less labor costs as it is much less labor-intensive to operate. Production rates would likely decrease and costs would likely increase by a factor of 2 to 4 in difficult terrain or in a wooded environment. Production rates with the vehicular MTADS system are 7-10 hectares per day on areas with terrain typical of JPG. Vehicular production efficiencies are higher on larger sites because it is possible to use deployment strategies to more efficiently survey and analyze data. Daily, on-site, deployment costs are similar for the two systems. Mobilization costs are typically higher for the vehicular system because it requires leasing of a trailer truck and fuel and labor costs associated with transportation. In addition, in a commercial application, amortization or depreciation costs associated with the vehicular systems will be significantly higher for the vehicular system than for the man-portable adjuncts.

Without consideration of other complicating issues, deployment of the vehicular system to sites where it can be used is probably more efficient if the sites are larger than 5 or 10 acres. For sites larger than 20 acres, it would be difficult to rationalize use of the man-portable systems unless issues of availability arise, or if their use is required because of site logistics. Both the vehicular and the man-portable systems can be transported in the same trailer and could likely be used simultaneously, assuming availability of the GPS equipment and the required labor to support simultaneous operations.

This page was left blank intentionally.

11.0 REFERENCES

1. “Multisensor Towed Array Detection System (MTADS).” http://www/estcp/org/projects/uxo/199526v.htm.

2. Cost and Performance Report, September 1999. http://www.estcp.org/projects/uxo/9526.pdf.

3. Blackhawk GeoServices, Inc. Web Site. http://www/blackhawkgeo.com.

4. “Portable UXO Detection System, Adjunct to MTADS.” http://www.estcp.org/projects/uxo/199811o.htm.

5. “Navy Tri-Service Environmental Quality Research Development, Test and Evaluation Strategic Plan,” October 1994, p. Cleanup-21.

6. “Advanced UXO Detection/Discrimination Technology Demonstration U.S. Army Jefferson Proving Ground, Madison, Indiana,” Technology Demonstration Plan Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV), Research and Development Department, Indian Head, MD, 30 June 2000.

7. “Advanced UXO Detection/Discrimination Technology Demonstration, Kaho’olawe Island, HI,” Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) Indian Head, ME, 31 August 2001.

8. “MTADS TECHEVAL Demonstration,” October 1996, H.H. Nelson, J.R. McDonald and Richard Robertson, NRL/PU/6110-97-348.

9. “Results of the MTADS Technology Demonstration #2, Magnetic Test Range, Marine Ground Air Combat Center,” Twentynine Palms, CA, December 1996, J.R. McDonald, H.H. Nelson, R.A. Jefferies and Richard Robertson, NRL/PU/6110-97-349.

10. “Results of the MTADS Technology Demonstration #3, Jefferson Proving Ground,” January 1997, J.R. McDonald, H.H. Nelson, R.A. Jeffries and Richard Robertson, NRL/PU/6110-99-375.

11. “MTADS Unexploded Ordnance Operations at the Badlands Bombing Rang,” Pine Ridge Reservation, Cuny Table, SD, July 1997, J.R. McDonald, H.H. Nelson, J. Neese, R. Robertson and R.A. Jeffries.

12. “MTADS Demonstration at the Former Fort Pierce Amphibious Base,” Vero Beach, FL, March 1998, J.R. McDonald, H.H. Nelson, R. Robertson, R.A. Jeffries and Karl Blankenship. NRLPU/6110-98-372.

13. “MTADS Live Site Survey, Bombing Target #2 at the Former Buckley Field,” Arapahoe County, CO, August 1998, J.R. McDonald, H.H. Nelson, R. Robertson and R.A. Jeffries, NRL/PU/6110–99-379.

14. “MTADS Live Site Survey and Remediation at Bombing Targets N-9 and N-10 on the Laguna Pueblo Reservation,” Laguna, NM, August 1998, J.R. McDonald, H.H. Nelson, R. Robertson and R.A. Jeffries. NRL/PU/6110–00-398.

15. “MTADS Geophysical Survey of the Jamaica Island and Topeka Pier Landfills at the Portsmouth Naval Shipyard,” October 1998, J.R. McDonald, H.H. Nelson, Bernard Puc, NRL/P6110-99-381.

16. JPG-IV.

17. “MTADS Demonstration at the Walker River Paiute Reservation, Schurz, NV,” J.R. McDonald, H.H. Nelson, R.A. Jeffries, NRL/PU/6110–00-406.

18. “Technology Demonstration Plan—MTADS Man-Portable Demonstration at the L-Range, Army Research Laboratory, Blossom Point, MD,” NRL, August 1999.

19. “Advanced UXO Detection/Discrimination Technology Demonstration - U.S. Army Jefferson Proving Ground, Madison Indiana,” Ernesto R. Cespedes, September 2001.

20. “Man-Portable Adjuncts for the MTADS,” J.R. McDonald, H.H. Nelson, Thomas H. Bell, and Bernard Puc, Naval Research Laboratory, NRL/PU/6110-01-434.

21. “Site Preparation Plan—Advanced UXO Detection/Discrimination Technology Demonstration,” U.S. Army Jefferson Proving Ground, Madison, February 2000.

22. “Technology and Innovation Partnerships for Success, The Kaho’olawe UXO Clearances,” James D. Putnam, SERDP/ESTCP Partners in Environmental Technology Symposium and Workshop, Washington, DC, 28 November 2001.

23. “Electromagnetic Induction and Magnetic Sensor Fusion for Enhanced UXO Target Classification,” http://www.estcp.org/projects/uxo/1998120.html.

24. “Advanced UXO Detection/Discrimination Technology Demonstration, Kaho’olawe Island, HI,” Site Preparation Plan, 31 August 2001.

25. “Advanced UXO Detection/Discrimination Technology Demonstration – Kaho’olawe, Hawaii,” Diane M. Cargile, Hollis H. Jay Bennett, Ricky A. Goodson, Tere’ A. DeMoss and Ernesto R. Cespedes, Final Report – DRAFT ERDC/EL TR-02-XX, May, 2002.

26. “Demonstration of Advanced Unexploded Ordnance (UXO) Detection and Discrimination Technologies at Kaho’olawe, Hawaii,” E. R. Cespedes, D. M. Cargile, H. Bennett, T. Berry, R. Goodson, H. Q. Dinh, S. Steward, and G. E. Robitaille, Presented in Technical Session 2A, SERDP/ESTCP Partners in Environmental Technology Symposium and Workshop, Washington, DC, 28 November 2001.

APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone/Fax/E-mail	Role in Project
Dr. Jeffrey Marqusee	ESTCP	(703) 696-2120 (703) 696-2114 jeffrey.marqusee@osd.mil	ESTCP Director
Dr. Anne Andrews	ESTCP	(703) 696-3826 (703) 696-2114 anne.andrews@osd.mil	UXO Program Manager
Dr. J. R. McDonald	AETC, Inc. Cary, NC 27513	(919) 653-0215 Ext 103 jmcdonald@nc.aetc.com	Principal Investigator
Dr. Herbert Nelson	Naval Research Laboratory Washington, DC 20375	(202) 767-3686 (202) 404-8119 herb.nelson@nrl.navy.mil	Principal Investigator
Mr. Jack Kaiser	Army Research Laboratory, Blossom Point	(301) 870-2329 (301) 870-3130 jkaiser@arl.mil	Blossom Point Site Manager
Mr. Bill Davis	Army Research Laboratory, Blossom Point	(301) 394-2434 (301) 394-2514 wdavis@arl.mil	Explosives Safety Officer
Mr. Richard Robertson	Hughes Associates, Inc.	(202) 767-3556 (202) 404-8119 roberts5@ccf.nrl.navy.mil	Program Manager
Mr. Larry Koppe	GeoCenters, Inc.	(301) 753-1690 (301) 870-3130 LarryEOD@aol.com	Site Safety Officer
Dr. Tom Bell	AETC, Inc. Arlington, VA 22202	(703) 413-0500 (703) 413-0505 tbell@va.aetc.com	Project Manager
Dr. Bruce Barrow	AETC, Inc. Arlington, VA 22202	(703) 413-0500 (703) 413-0505 bjb@va.aetc.com	Project Scientist

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

e-mail: estcp@estcp.org
www.estcp.org