Survey of Munitions Response Technologies

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CONTENTS

Executive Summary

The Strategic Environmental Research and Development Program (SERDP), Environmental Security Technology Certification Program (ESTCP), and the Interstate Technology Regulatory Council (ITRC) jointly developed this Munitions Response Technology document. Our goal with this document is to provide an overview of the current status of technologies used for munitions response (MR) actions and, where possible, evaluate and quantify their performance capabilities. This study provides project managers and regulators an understanding of the performance capabilities of available technologies under real-world site conditions. Detailed observations and critical considerations in the application of munitions technologies are discussed, with particular emphasis on detection technologies.

Detection Technology Evaluation

A large volume of data has been collected over the past several years to document the application and performance of MR technologies. This is particularly true of munitions detection technology. In this study, a significant effort has also been made to develop a database documenting the performance of munitions detection technologies on the Standardized Test Sites and in recent MR actions. The analysis and interpretation of this database has revealed significant insights into current use and performance of munitions detection technologies.

A description of currently used munitions detection technology, as well as findings on the current state-of-the-practice, can be found in Chapter 3. The methodology for the analysis of the performance of detection technology is presented in Chapter 4, and the results of the analysis detailed in Chapter 5.

The interpretation and application of the results to MR projects are discussed in Chapter 6, which may be most useful to the novice reader. There is no single best technology that can be recommended for all applications: rather, the selection of appropriate technology will be dependent on site conditions, munitions of concern, and specific project objectives. This chapter provides hypothetical scenarios that illustrate how the detailed information and metrics in Chapter 5 may be used in evaluating and selecting technologies based on these considerations.

Major Findings

The results of the analysis indicate that currently available magnetometer and electromagnetic induction (EMI) technologies are capable of detecting most munitions under typical site conditions. However, there are large variations in the performance of munitions detection technology across demonstrators, even when using systems based around the same basic sensors. The ability of a system to achieve optimum performance is a function of both the capabilities of the detection technology and the quality of its implementation. Real-world challenges such as terrain, geologic noise, overlapping signatures, surface clutter, variances in operator technique, target selection, and data processing all degrade from and affect optimum performance. Quality-control and quality-assurance programs are critical to achieving successful results with any munitions detection technology.

Some of the major findings in this report include the following:

- System noise does not generally limit detection ability. This is a strong indication that implementation is a key component in the ability of a technology to achieve project objectives.
- Magnetometers and EMI sensors both have individual strengths in detecting all types of munitions at varying depths. Munitions type and response action objectives must be evaluated.
- Attempts to employ alternative sensor technologies to munitions detection have not resulted in robust performance that is comparable to that achieved by magnetometers and EMI sensors.
- Digital geophysical mapping (DGM) generally achieved a higher probability of detection and lower false-alarm rate than mag and flag. Site conditions may limit the application of DGM.
- All sensors have trouble detecting smaller items. Where these items are of concern, data quality objectives must be tailored with these items in mind.

The objective of the analysis presented in this document is to evaluate currently available MR technologies and their performance drivers. From this analysis we have documented major findings that will provide common understanding to guide regulators and project managers as they set project objectives and determine the appropriate technology for a given site.

1.0 INTRODUCTION

1.1 Objective

The Strategic Environmental Research and Development Program (SERDP), Environmental Security Technology Certification Program (ESTCP), and the Interstate Technology Regulatory Council (ITRC) jointly developed this Munitions Response Technology document. Our goal with this document is to provide an overview of the current status of technologies used for munitions response (MR) actions and, where possible, evaluate and quantify their performance capabilities. The analysis presented here is designed to help regulators, implementers, and researchers understand the current capabilities, applications, and limitations of munitions response technology. In turn, this information will help facilitate communication within the MR community regarding technology application to specific site conditions.

The ultimate success or failure of MR actions will hinge on the proper selection, application, and evaluation of technologies throughout the project. As MR technology continues to evolve and mature, there is a growing need to establish a common and widely accepted understanding of performance capabilities and limitations, as well as the conditions that affect them. Since the selection of appropriate technology will be dependent on site conditions, munitions of concern, and specific project objectives, there is no single best technology that can be recommended for all applications. This report provides information relevant to evaluating and selecting technologies throughout a cleanup process. It is not designed or intended to predetermine cleanup decisions. The document walks through performance metrics at a level that will assist a project team in selecting the most appropriate technology for the application.

The technologies discussed in this document address site preparation, munitions detection and discrimination, filler material identification, munitions removal, and treatment. Because this report is an overview of the current state of the practice, it is limited in scope mainly to commercially available technologies. Detection technologies concentrate on those deployed from ground-based platforms for production geophysics. Recent advances in wide-area assessment and underwater technologies, as well as ongoing research and development efforts, are summarized. To monitor and track emerging technologies from the research programs, the reader is urged to utilize the numerous resources and program offices referenced in this document. (http://www.serdp.org; http://www.estcp.org; http://aec.army.mil/usace/technology/eqt00.html).

MR technologies have evolved significantly over the past decade. Planning software has been created, geolocation and navigation tools are becoming more accurate and reliable, sensor and platform design and performance are continuing to evolve, and our overall understanding of how to deploy MR technologies in the field is increasing. With these advances, the ability of a response action to successfully detect and remove munitions items in the field has increased significantly. In this document, we attempt to capture these improvements by documenting specific tools and technologies and analyzing their capabilities in controlled test sites and actual field performance. In particular, we have conducted a significant in-depth analysis of the performance capabilities and limitations of detection technologies and their deployment by users because of the importance to the overall effectiveness of MR actions. We have also looked at discrimination technologies to the extent possible, although their use has been largely limited to simple sites with large cost drivers. More extensive analysis on discrimination technologies is the subject of future work.

The importance of understanding the strengths and limitations of the MR technologies as they exist today cannot be overstated. Their effectiveness has an impact on all aspects of the MR process, from site inspections to response actions, and it will determine the amount of munitions contamination removed, the productivity, the cost of a project, and ultimately the degree of confidence in the response action. According to joint guidance from the Department of Defense (DOD) and the Environmental Protection Agency (EPA), “Rapid employment of the better performing, demonstrated technologies needs to occur.” (DOD and EPA 2000).

1.2 Document Structure

The chapters of this document are structured by technology and application, presented in roughly the order in which the technologies would be applied. Since many of the technologies could be used in multiple steps of the regulatory process, no attempt is made to tie the chapter structure to the process. Instead, the intent of the chapters is to provide information on various technologies as needed. Readers are encouraged to select the appropriate level of detail needed to meet their needs and to use the references for additional information as appropriate.

Chapter 2 describes the technologies utilized in the site-preparation phase. The goal of site preparation is to allow safe access to the site and ensure that MR technologies can perform to their optimum ability.

Chapter 3 describes detection technologies. Included are the components that make up detection systems, among them the sensor, the survey platform, navigation/positioning technologies, and data acquisition and analytical tools. Various configurations and applications as they are employed for different conditions and objectives are discussed. Current trends in equipment use by contractors in the field are documented.

Chapter 4 describes how performance data collected from the standardized test sites and recent geophysical case studies were analyzed for this document.

Chapter 5 documents the performance of detection technologies. This section also presents a failure analysis and discusses how conclusions drawn from that analysis that can affect the selection and use of these technologies.

Chapter 6 highlights the major conclusions drawn from the analysis of the test sites and GPO data. This section also discusses real-world implementation considerations that can affect technology performance.

Chapter 7 provides information on emerging advanced detection and discrimination technologies. This section outlines current research and development priorities and looks at the ability of systems to differentiate between munitions and metallic clutter or geology. Advances in underwater and wide-area assessment technologies are summarized.

Chapter 8 summarizes technologies to identify the fill material in munitions. The ability to identify live high-explosive rounds from inert training rounds may be applicable to some projects.

Chapter 9 discusses the general categories of technologies currently in use to remove and recover munitions that are safe to move. These include manual, mechanized, and remote-control technologies.

Chapter 10 describes detonation and decontamination technologies used to treat the recovered munitions.

The following topics are not covered in this document:

- Regulatory process or policy
- Explosive safety issues
- Chemical warfare materials
- Munitions constituents

Finally, this document is not intended to prescribe or endorse specific technology solutions.

2.0 SITE PREPARATION TECHNOLOGIES

Not surprisingly, MR technologies work best in areas that are dry, level, without vegetation, and free of surface debris. Site-preparation activities typically consist of evaluating safety hazards, clearing at least some vegetation, and removing surface munitions and surface metallic clutter. Vegetation removal and surface clearance help to ensure that an MR project can be safely and effectively conducted. Clearing the site of as much vegetation and surface debris as possible allows a better view of the area being worked, improves access, and removes metallic clutter so geophysical instruments can perform to their optimum ability in a given environment. While vegetation removal and surface clearance cannot alter terrain, they can improve access to even topographically challenging sites.

The objective of this chapter is to provide the reader with a better understanding of the various vegetation-removal and surface-clearance methods currently being used in the field, including technical considerations relevant to technology selection. Site condition and the effectiveness of site preparation will influence the technologies that can be used during all phases of the cleanup. The implications for site ecology of some vegetation-removal methods and the limits they impose on instrument selection will also be discussed. This chapter will not, however, address specific regulatory or permitting requirements for habitat management applicable to certain vegetation-removal techniques.

2.1 Vegetation Removal

The most common site-preparation activity is vegetation removal. This process allows physical access to heavily vegetated sites and eliminates the vegetation that hinders movement for either physical site inspection or the operation of geophysical mapping equipment. Figure 2-1 shows a site before and after vegetation removal.

MR sites are found in all types of terrain, including flat and sparsely vegetated, densely tropical, and mountainous or heavily forested. Vegetation removal can consist of cutting or burning brush and undergrowth and removing trees and larger brush. Sites with light vegetation can normally be cleared using hand tools such as machetes, hedging tools, trimmers, chain saws, and mechanized mowers and tractors. Where vegetation is heavier and denser and trees must be removed, larger mechanized equipment is required. Table 2.1 groups types of vegetation and terrain into four easily identifiable classes.


(a) (b)

Figure 2-1. Site (a) before and (b) after vegetation removal (pictures courtesy of Franklin Equipment Company, Franklin, Va.).

Table 2-1. Site difficulty levels used in vegetation removal.

Class	Vegetation	Terrain	Obstacles
Class 1 (easy)	Light grass and vegetation up to 2 feet high.	Fairly level terrain.	Minimal debris and obstacles.
Class 2 (moderate)	Moderate vegetation with sparse brush 2 to 4 feet high.	Level to light rolling terrain with some ruts.	Some debris and obstacles.
Class 3 (difficult)	Moderate vegetation with brush, saplings, and trees 4 to 6 feet high.	Primarily rolling terrain with lots of ruts.	Moderate debris and obstacles.
Class 4 (very difficult)	Heavy vegetation with dense brush, saplings, and trees 6 feet and higher.	Steep hills with lots of ruts and ravines; very rugged terrain.	Heavy debris and obstacles.

A site may have habitat constraints that limit vegetation removal. For example, at Fort Ord, coastal oak trees cannot be removed, and as a result, vegetation removal in affected areas consists of clearing underbrush and trimming branches to allow access under and around the trees. Some MR sites may require multiple removal methods. Habitat restrictions and clean air concerns may determine whether controlled burns are permissible in certain areas; mowing may be necessary in others. Areas with class 3 or class 4 vegetation and terrain that cannot be burned will require the use of heavier mechanized equipment.

Large-scale mechanized equipment can be used to remove vegetation where site conditions permit. Mechanized equipment for vegetation removal can include armored, unarmored, or remote-controlled technology. Table 2-2 lists mechanized equipment that can be used for removing vegetation. Although much of this equipment was originally developed for demining applications, it may be equally useful for MR sites.

Table 2-2. Mechanized technology for vegetation removal.

Technology	Description	Capability
Armored Mechanized Technology		
Tractor Assisted Zerriest	A tracked Caterpillar 325B excavator with specialized vegetation-cutting attachment. Can remove dense brush and all sizes of trees in large areas. Works well in hard-to-reach areas such as berms, ravines, and ditches. Allows for clearance and re-seeding.	Class 1–4 vegetation Most effective on class 3.
Aardvark Mark IV Joint Services Flail Unit	New Holland tractor and flail unit with vegetation-cutting capability. Unable to clear vegetation without ground penetration.	Class 2–4 vegetation.
Uni-Disk	A 40-ton tracked Caterpillar Excavator with Shinn Cutter Systems SC4 forestry cutter. Can access and clear heavily vegetated, wooded, and hard-to-reach areas. Size requires significant logistic support.	Class 3–4 vegetation.
Severe Duty Vegetation Shredder	D7R crawler tractor with knife-shredding unit capable of shredding bushes; tall, dense grass; and small trees. Can be used to clear ditches and embankments along roadways. Wide range of movement and flexibility	Class 1–4 vegetation.
Improved Backhoe	A modified JCB 215s (backhoe) with a medium-sized vegetation cutting attachment, it removes ferrous metal and minimizes debris.	Class 1–3 vegetation.
Rotar Mk2	Commercial-off-the-shelf backhoe with 80 hp Caterpillar 428C backhoe tractor. Mulching unit is a SIGMA brand model TS/TS-P 155 brush shredder. Has soil-sifting capabilities.	Class 1–3 vegetation.
Survivable Demining Tractor and Tools	Armored commercial farm tractor with multiple functions. Attachments include slasher, forestry topper (bush hog), hedge trimmer (boom mower), large and small grabs, and light and heavy tree pullers. Attachments mechanically clear brush and prepare surface for field work	Class 2–4 vegetation

Technology	Description	Capability
Non-Armored Mechanized Technology		
Heavy Vegetation Cutter	A 30-ton Leibherr Model 904 wheeled excavator with a Shinn Cutter Systems Uni-Disk attachment capable of performing multiple tasks. Clears densely vegetated and wooded areas, removes ferrous metal, and minimizes surface debris.	Class 3–4 vegetation.
Specialty Forestry and Land Clearing Equipment	Variety of backhoe and tractor-mounted mulchers designed for vegetation removal operations.	Class 3 vegetation
Agricultural Tractors with Hedge Cutters and Mowers	Commercial tractors, cutters, and mowers capable of covering large areas.	Class 1–2 vegetation
Residential and Commercial Use Vegetation Clearing Equipment	Weed-wackers, trimmers, etc.	Class 1 vegetation
Remote-Controlled Mechanized Technology		
All-Purpose Remote Transport System	Applied Research Associates Posi-Track MD70 tractor fitted with brush-cutter mower attachment. Cuts and shreds vegetation; lifts and moves heavy and large objects; can move and excavate earth.	Class 1–3 vegetation.
Tempest Mk 5	Low-cost, multipurpose steel wheels; cutting flail with integrated magnet. Slasher component can cut through fibrous vegetation.	Class 1–2 vegetation.
MAXX v1	Modified commercial tracked backhoe with shredding and mowing attachments.	Class 1–3 vegetation

2.1.1 Controlled Burns

Under some circumstances, vegetation removal can be performed using controlled burns. In areas that can be burned, this is often the preferred method, since controlled burns may also be beneficial for habitat management. Controlled burns must be done carefully to ensure that the size of the area being burned will achieve the desired results, but does not grow so large that the burn gets out of control. Consideration must also be given to the potential for unintended explosions. Fire breaks, air monitoring, specific weather conditions, and, in many cases, permitting are required for this type of removal to be successful. If burning does not achieve the desired result, it may be necessary to perform a second burn or employ an additional method of brush removal such as cutting or mowing. Further details can be found in DOD's burn policy (DoD 2004).

Figure 2-2. Ranges 43-48 at Fort Ord, Calif., before and after a controlled burn (picture courtesy of Fort Ord Army BRAC office; photo credit: Bill Collins).

2.1.2 Implementation Considerations

Although the technical aspects of vegetation removal are relatively simple and straightforward, there are explosives safety concerns and the tasks are often controversial because the ultimate effect on the landscape can be severe. Landowners or land managers may value the habitat that vegetation provides and may prefer that it not be removed. Some vegetation is protected, and its removal may be regulated. Similarly, the presence of threatened and endangered species may significantly influence the types of vegetation-removal methods to be deployed. Permits or some type of evaluation process may be necessary before removal can take place. (Fort Ord BRAC Office 2004)

In many instances, trees and heavy brush are reduced to splinters that can then cover the MEC meant to be exposed. If root systems are also removed, some form of erosion control may need to be considered. Final land use may be a determining factor in selecting a vegetation-removal method. If a cleared area is to be extensively developed, then removing all vegetation and sifting soil for any munitions remnants may be the preferred option. If a site is to remain a habitat reserve, however, stripping the land of all vegetation will not be the preferred option. Depending on the future use of the land, re-seeding or repopulating the area may be necessary.

Ultimately, vegetation removal and surface clearance will influence the types of technologies that can be deployed at an MR site. Many removal and clearance techniques are dictated by the terrain of the site and the regulatory requirements. Each site must be evaluated separately, taking into consideration vegetation, terrain, regulatory, technology, and end-use requirements.

2.2 Surface Clearance

The primary objective of surface clearance is to remove surface munitions and other metallic objects. For some sites, removal of surface munitions hazards is the only objective. For sites where the subsurface must be investigated, the surface clearance will render the site safe for field activity and to ensure that surface debris does not impede the subsurface geophysical investigation of the area. Metallic surface debris such as fence wire and munitions fragments can mask subsurface anomalies and interfere with effective geophysics. Surface clearance helps to ensure that the geophysical data collected provide as accurate a picture as possible of subsurface munitions contamination. The extent of surface clearance required will be based on the hazards presented by the munitions present, as well as the detection system that will be used to investigate the site. In areas where geophysical instruments will be utilized, removing nonhazardous metallic scrap is essential in areas of high density; otherwise, the quality of the geophysical data will be compromised.

Detection and removal of surface items is performed by sweep teams under the supervision of personnel trained in munitions removal. Visual surface clearance can be done at sites with sparse or short vegetation. Instrument-aided surface clearance will assist in detecting items that penetrate the surface or are hidden by tall grasses or brush. Some sites that contain thousands of surface munitions under dense brush may require a controlled burn before it is safe for an operator to clear the area.

Mechanical Surface Clearance

This method of clearing sites was developed primarily for humanitarian demining, in which landmines, left in place during wars and other conflicts, were removed. However, there have been occasional attempts to utilize various kinds of mechanized and electromagnetic equipment to perform MEC cleanup work at domestic sites.

One such mechanized surface clearance was conducted at the Honey Lake Site on Sierra Army Depot, Herlong, Calif., in 2002. Honey Lake is a dry lake that was used for munitions disposal by Sierra Army Depot (Air Force Research Lab 2003). The main tool used during cleanup activities was the Barber Surf Rake with the All-Purpose Robotic Transport System (ARTS) (Figure 2-3), which removed the majority of scrap items from the surface of the lake bed. ARTS is remotely controlled from a mobile command center. The surf rake, towed behind the ARTS, uses a rotating belt with tines to scrape the ground surface. It picks up items larger than the tine-to-tine spacing (1.5–2 in.). The material taken off the ground is moved up the tine belt and put into a rear hopper.

Figure 2-3. ARTS with a Barber Surf Rake (photo courtesy of U.S. Army Corps of Engineers).

There have been occasions where electromagnets were used to remove metal clutter and debris. In two instances (Fort Ord, Calif., and Pueblo Chemical Depot, Colo.) anecdotal reports suggest that their use resulted in the magnetization of soil or unremoved metallic debris, which interfered with later use of geophysical sensor technologies (Parsons 2006).

3.0 MUNITIONS RESPONSE DETECTION TECHNOLOGIES

Technology selection plays a critical role in military munitions responses. In this chapter we focus on evaluating and selecting detection systems and how the specific operation influences the technology approach. By asking the question, “What munitions cleanup technologies are currently being utilized in the field?” we examine how technologies are being deployed and identify, for each type of operation, current trends in equipment usage. To better understand technology selection in the field, we have documented the results of a recent state of the practice survey designed to analyze munitions technology selection during various phases of a cleanup project. In so doing, our goal is to reinforce the importance of considering all available technologies and determining the most appropriate for each specific project, taking into account site conditions, cleanup objectives, and final land use. To help the evaluation process, we review the basic concepts behind each type of sensor technology and provide descriptions of technology platforms, navigation and positioning, and data-processing systems. Performance and metrics will be discussed and evaluated in detail in later chapters.

Munitions detection technology performs three distinct types of operations:

- *Munitions-Sweep Operations*—systematic real-time search of an area to locate surface or subsurface anomalies. Surface clearance and mag-and-flag subsurface clearance are two examples of munitions-sweep operations. Munitions-sweep operations typically use hand-held instruments, but may use carts or other configurations of instruments to detect and locate subsurface anomalies.
- *Munitions-Mapping Operations*—collecting geo-referenced digital geophysical mapping data over a specific area and processing that data to identify and report the locations of subsurface anomalies for later action.
- *Munitions-Reacquisition Operations*—locating subsurface anomalies previously detected through sweep or mapping operations in support of excavation and removal.

Current sensor technology is available in a broad range of commercially available instruments and, depending on the type of operation, is deployed in many different configurations, ranging from manually operated hand-held systems to complex multisensor towed arrays. The technologies are presented by type of detection operation.

3.1 Overview of Munitions Technology

Two main sensor technologies are currently being used for munitions detection:

- *Electromagnetic Induction (EMI)*—an active sensor that induces electrical currents in nearby conductive objects. The electrical currents generate a secondary magnetic field in both ferrous and nonferrous items that is measured to detect the item. EMI detectors are operated in either time domain (TD) or frequency domain (FD). A common example of a hand-held EMI sensor is the metal detector used to locate coins buried on a beach. A detailed review of EMI sensor technology is presented in Section 3.3.

- *Magnetometer (Mag)*—a passive sensor that measures a magnetic field. Ferrous items create irregularities in the Earth's magnetic field and may contain remnant magnetic fields of their own that are detected by magnetometers. Magnetometers currently used for munitions detection are the flux-gate magnetometer and cesium vapor (CV) magnetometer. Detailed reviews of both types of magnetometers are in Section 3.3. Magnetometers can detect ferrous metal items but not other metals, such as aluminum or brass.

Overall, the time-domain EMI sensor (i.e., EM61-MK2) and flux-gate magnetometer (i.e., Schonstedt) are by far the most commonly used munitions-detection technology in the field today (see Figure 3-1). EMI and magnetometer-based sensors can be operated in either an analog or digital recording mode, and most sensors can be configured in several different platforms.

Figure 3-1. Schonstedt magnetometer (left) and Geonics EM61-MK2 EMI (right).

The most common sensor for munitions-mapping operations is the EM61-MK2, followed by the G-858 cesium-vapor magnetometer. The Schonstedt magnetometer is most common for munitions-sweep and munitions-reacquisition operations. A large variety of EMI instruments are also used for munitions-reacquisition operations.

Several other instruments using the same basic sensor technology are also being used for munitions detection operations. The next section reviews the current state of the practice of munitions detection by type of operation, including a list of available instruments, current field usage, and strengths and limitations.

3.2 Current State of the Practice—What is used in the field?

To determine the current state of the practice and understand which instrument technologies dominate in actual field applications, 66 instrument evaluation studies at 44 munitions response sites from 2000–2005 were studied. Figure 3-2 shows the locations of the 44 munitions response sites included in this survey, which are listed in Table 3-1. Figure 3-3 gives the distribution of studies by regulatory response phase. The survey is equally weighted between the investigation phase (53% EECA and SI/RI) and cleanup phase (47% RA and TCRA).[1] The investigation phase is dominated by EECA studies (23 EECA, 6 RI, 5 SI). There is no obvious correlation between the regulatory cleanup phase and munitions technology selected; rather, munitions technology selection cuts across the regulatory process and is driven by site-specific conditions, data quality objectives, and the desired goal of the work. Detailed tabulations of survey results are presented in Appendix C. These studies were chosen based on availability of needed data and documentation and may not be representative of all current munitions-response actions.

The approach used in this evaluation was to catalog the geophysical instruments that were considered and tested in a geophysical prove-out (GPO) or equivalent evaluation and subsequently selected or recommended for production survey use. After action reports were also used to identify geophysical equipment used when a GPO was not available. The results are organized and presented by type of munitions operation. Figure 3-4 and Table 3-2 give a summary of the classes of sensors selected by type of munitions operation.

The survey led to the following general observations regarding the state of the practice for munitions detection:

- Munitions-mapping operations are dominated by time-domain EMI and cesium-vapor magnetometer technology.
- Munitions-mapping operations (digital geophysical mapping) are utilized on a strong majority of munitions response actions surveyed (89%), either as the sole detection method (54%) or in combination with sweep operations (35%) (mag and flag).
- Mag-and-flag-based munitions response actions are also being conducted, with 11% of the munitions response actions surveyed utilizing only sweep (mag and flag) operations. Munitions-sweep operations are dominated by flux-gate magnetometer technology.
- Munitions-reacquisition operations surveyed are dominated by magnetometers (87%), either as the sole reacquisition instrument (41%) or in combination with EMI instruments (46%). EMI and cesium-vapor magnetometer technologies are also widely used for munitions-reacquisition operations.
- Reacquisition operations commonly utilized different technology than mapping operations. Reacquisition of EMI-based mapping operations used magnetometer technology exclusively for reacquisition in 22% of the actions, 46% used magnetometer and EMI technology, and 13% used EMI exclusively.

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[1] EECA = engineering evaluation and cost analysis, RI = remedial investigation, SI = site inspection, and TCRA = time critical removal action.

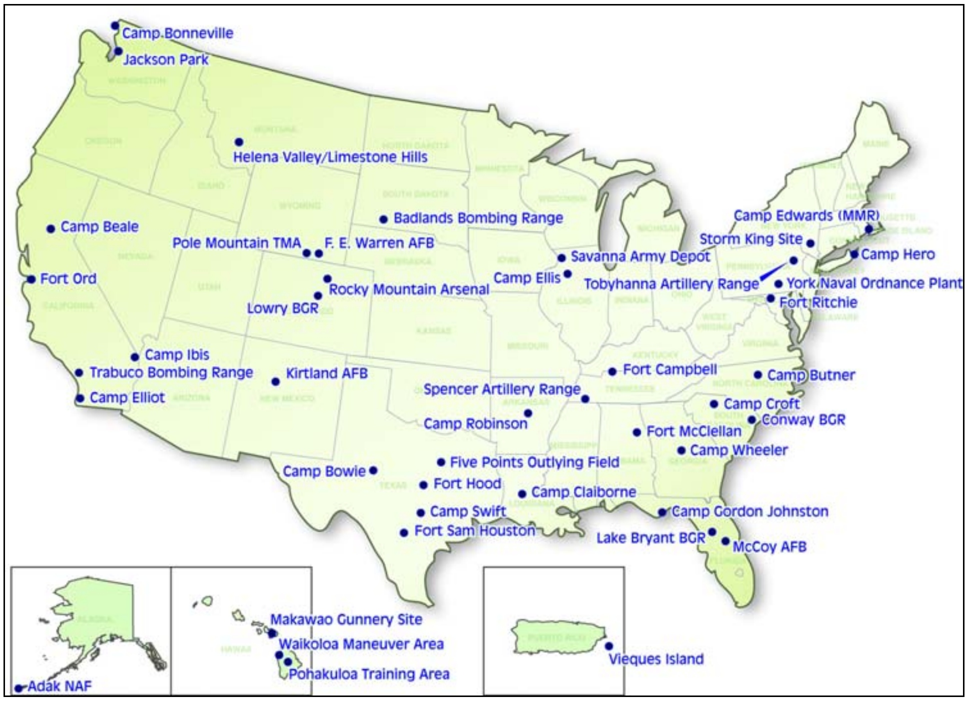

Figure 3-2. Locations of 44 munitions response sites evaluated in state of the practice survey to evaluate munitions technology use in the field today.

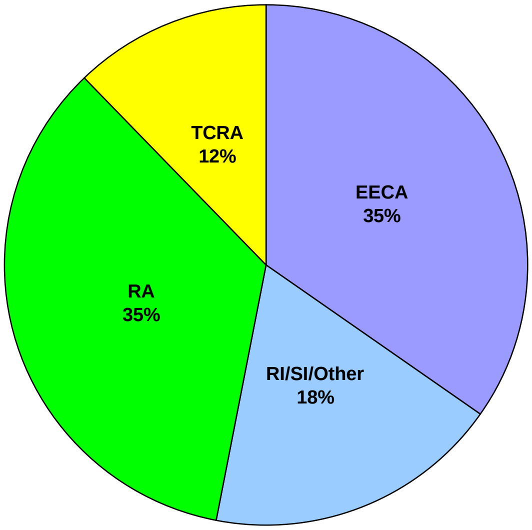

Figure 3-3. Distribution of munitions response actions evaluated in state of the practice survey by response phase.

Table 3-1. Munitions response actions evaluated in state-of-the-practice survey.

Site	Action/Year	Site	Action/Year
1. Adak NAF, AK	RI / 2000	34. Fort Ord, CA	RA / 2000
2. Adak NAF, AK	RA / 2001	35. Fort Ord, CA	SI / 2002
3. Adak NAF, AK	RA / 2002	36. Fort Ord, CA	TCRA / 2002-2003
4. Badlands Bombing Range, SD	EECA / 1999-2000	37. Fort Ord, CA	RA / 2003
5. Badlands Bombing Range, SD	EECA / 2003	38. Fort Ord, CA	RA / 2005
6. Camp Beale, CA	EECA / 2002	39. Fort Ritchie, MD	RA / 1999-2002
7. Camp Beale, CA	SI / 2004*	40. Fort Sam Houston, TX	EECA / 2000
8. Camp Bonneville, WA	RA / 2004*	41. Helena Valley, MT	SI / 2004
9. Camp Bowie, TX	TCRA / 2000	42. Jackson Park, WA	RI / 2005
10. Camp Butner, NC	EECA / 2001-2002	43. Kirtland AFB, NM	EECA / 2005
11. Camp Butner, NC	TCRA / 2002-2003	44. Lake Bryant Bombing and Gunnery Range, FL	EECA / 2002*
12. Camp Claiborne, LA	RA / 2001	45. Lowry Bombing and Gunnery Range, CO	RI / 2002
13. Camp Croft, SC	RA / 1999-2000	46. Lowry Bombing and Gunnery Range, CO	RA / 2002-2003a
14. Camp Croft, SC	RA / 2001-2002	47. Lowry Bombing and Gunnery Range, CO	RA / 2002-2003b
15. Camp Croft, SC	RA / 2004	48. Lowry Bombing and Gunnery Range, CO	RA / 2003*
16. Camp Edwards - MMR, MA	OTHER / 1999-2001	49. Lowry Bombing and Gunnery Range, CO	RA / 2004
17. Camp Edwards - MMR, MA	EECA / 2002	50. Lowry Bombing and Gunnery Range, CO	RI / 2005
18. Camp Elliott, CA	RA / 2003	51. Lowry Bombing and Gunnery Range, CO	RA / 2005a
19. Camp Ellis, IL	EECA / 1999-2000	52. Lowry Bombing and Gunnery Range, CO	RA / 2005b
20. Camp Gordon Johnson, FL	EECA / 1999-2000	53. Makawao Gunnery Site, HI	EECA / 2003
21. Camp Hero, NY	EECA / 2001	54. McCoy AFB, FL	RA / 1999-2000
22. Camp Ibis, CA	EECA / 2002*	55. Pohakuloa Training Area, HI	SI / 2004
23. Camp Robinson, AR	EECA / 2001	56. Pole Mountain Target and Maneuver Area, WY	EECA / 2000
24. Camp Swift, TX	EECA / 2002	57. Pole Mountain Target and Maneuver Area, WY	EECA / 2005
25. Camp Swift, TX	TCRA / 2003	58. Rocky Mountain Arsenal, MT	RI / 2002
26. Camp Wheeler, GA	EECA / 2004	59. Savanna Army Depot, IL	EECA / 2004*
27. Conway Bombing and Gunnery Range, SC	EECA / 2000	60. Spencer Artillery Range, TN	EECA / 2003*
28. Conway Bombing and Gunnery Range, SC	TCRA / 2000	61. Storm King Site, NY	EECA / 2001
29. F.E. Warren AFB, WY	RI / 2004	62. Tobyhanna Artillery Ranges, PA	TCRA / 2002
30. Five Points Outlying Field, TX	RA / 2005	63. Trabuco Bombing Range, CA	TCRA / 2004

Site	Action/Year	Site	Action/Year
31. Fort Campbell, KY	RA / 2003*	64. Vieques Naval Training Range, PR	SI / 2000
32. Fort Hood, TX	RA / 2003*	65. Waikoloa Manuever Area, HI	EECA / 2003*
33. Fort McClellan, AL	RA / 2004*	66. York Naval Ord. Plant, PA	TCRA / 2004*

* Action phase based on Work Plan or GPO document. Date is the year the Work Plan was published or the year the GPO was conducted.

Notes:

EECA = Engineering Evaluation and Cost Analysis
RA = Remedial Action
RI = Remedial Investigation
SI = Site Inspection
TCRA = Time Critical Removal Action
Other = Special Investigations
MMR = Massachusetts Military Reservation

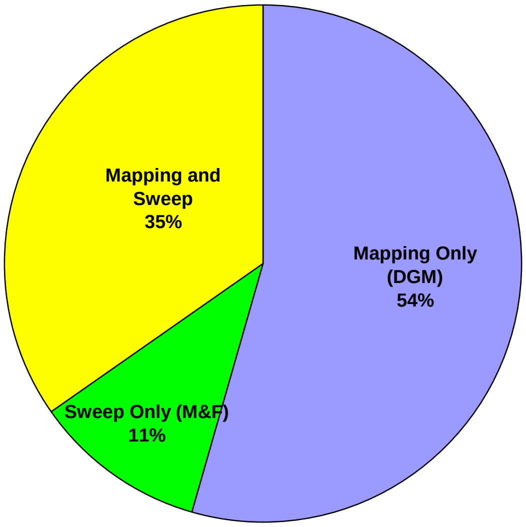

Figure 3-4. Distribution of MR actions evaluated in state-of-the-practice survey by type of munitions detection operation.

Table 3-2. Summary of munitions-detection instruments selected for field operations by type of operation and sensor technology in state of the practice survey

	Magnetometer		**Electromagnetic Induction**		
Type of MEC Detection Operation	**Flux Gate**	**Cesium Vapor**	**Time Domain**	**Frequency Domain**	**Total**
Mapping (digital geophysical mapping)	3	17	57	3	80
Sweep (mag and flag)	28	1	0	8	37
Reacquisition operations	42	8	22	12	84
Total count	73	26	79	23	201

Notes: Several sites selected multiple instruments for each type of operation.

The following subsections presents the current state of the practice survey findings for each type of munitions response operation.

3.2.1 Munitions Sweep Technology

Most munitions response removal actions include some degree of sweep operations. Munitions-sweep technology ranges from being the primary method of removal, to being a pre-mapping operation, to being limited to areas not accessible by mapping technology. Munitions-sweep operations are typically conducted in areas where munitions-mapping operations are not effective or are cost prohibitive.

For munitions-sweep operations, the operator holding the sensor serves as the survey platform, positioning system, and data-processing system. Technology selection is normally limited to the type of hand-held sensor and the method of coverage used to navigate the sweep area. The navigation system is typically a systematic grid using ropes and tapes to mark specific sweep lanes. Munitions-sweep operations can deploy analog or digital instruments and use EMI or magnetometer sensors.

In munitions-sweep operation, UXO personnel survey the area with geophysical sensors and identify anomalies and mark them for excavation. The exception is surface-sweep operations, where instruments may or may not be utilized, depending on the site and the objectives of the surface sweep. A summary of the excavation results (often referred to as a dig list) is produced for the area.

Table 3-3 presents the currently available technologies for munitions-sweep operations. The most common sweep operation is the analog mag-and-flag survey (Figure 3-5), and the most common sweep instrument is the Schonstedt magnetometer. Although commonly referred to as a “mag” survey, in a mag-and-flag munitions-sweep operation where nonferrous items are of concern, EMI instruments are typically deployed sequentially with magnetometers on the same project site. Several models of EMI detectors are commonly used for munitions-sweep operations, with no preference shown for any.

Table 3-4 summarizes the general strengths and limitations of munitions-sweep technology. Munitions sweeps are used in a number of munitions response operations in some areas, especially where high density of metallic clutter limits the munitions-mapping operations or where physical access issues such as vegetation or terrain limit mapping operations. Munitions-sweep operations can also be advantageous for very small munitions response sites because of the lower capital equipment costs.

Table 3-3. Munitions-sweep technologies.

Sensor	Technology	Instrument	Deployment Configurations	Output	Status*
Munitions Sweep Operations					
Magnetometer	Flux-gate	Schonstedt 52-Cx and 72 Cd	Hand-held	Analog	Established
		Vallon EL 1302D/A	Hand-held	Analog or digital	Established
		Foerester FEREX 4.032 API	Hand-held	Analog or digital	Established
		Ebinger MAGNEX 120 LW	Hand-held	Digital	Emerging
	Cesium Vapor	Geometrics G-858	Hand-held	Digital	Established
EMI	Time Domain	Geonics EM61 (MK2 HH)	Hand-held	Digital	Established
		G-tek TM5-EMU	Hand-held	Digital	Emerging
	Frequency Domain	Fisher 1266-X Metal Detector	Hand-held	Analog	Established
		Foerster MINEX 2FD 4.500	Hand-held	Analog	Established
		Minelab Explorer II	Hand-held	Analog	Established
		Vallon VMH3	Hand-held	Digital	Established
		White Spectrum XLT	Hand-held	Analog	Established
		Ebinger EBEX 420	Hand-held	Analog	Innovative
		Guartel MD8+	Hand-held	Analog	Innovative
		Schiebel AN-19/2 & ATMID	Hand-held	Analog	Innovative
		Shadow X5	Hand-held	Analog	Innovative
		Teroso Lobo	Hand-held	Analog	Emerging

* EPA defines technologies as follows (EPA 2005):

- *Emerging technology*—an innovative technology that is currently undergoing bench-scale testing in which a small version of the technology is tested in a laboratory.
- *Innovative technology*—a technology that has been field-tested but lacks a long history of full-scale use. Information about its cost and how well it works may be insufficient to support prediction of its performance under a wide variety of operating conditions.
- *Established technology*—a technology for which cost and performance information are readily available. Only after a technology has been used at many different sites and the results have been fully documented is that technology considered to be established.

There are several limitations in munitions-sweep operations:

- Probability of detection is generally lower and false alarms higher than munitions-mapping operations.
- Quality control of the process is difficult (i.e., it is hard to measure the ability of the technician to interpret the geophysical instrument’s signal).

- The tools most commonly used are significantly less sensitive to the physical parameters being measured than most digital geophysical equipment.[2]
- It is impossible to verify that the entire search area was covered by the geophysical sensor operators.
- The sensitivity of flux-gates is selectable, and the operators do not always use the most appropriate setting.
- There is no direct record of geophysical data.

Figure 3-5. Mag-and-flag survey (left) and flags placed following a mag-and-flag survey (right) (Photos courtesy of Tetra Tech EC, Inc.).

Of the 66 actions studied in the survey, 30 actions included munitions-sweep operations. A total of 37 instruments were selected:

- 24 Schonstedt (52Cx and 72Cd).
- 2 Foerester FEREX.
- 3 White Spectrum XLT.
- 1 Geometrics G-858.
- 1 Fisher 1266-X.
- 2 Vallon VMH3.
- 2 MineLab Explorer II.
- 2 Shadow X5.

The majority of actions studied (24 of 30) used a single munitions-sweep instrument; however, five actions used two instruments, and one action used three. Figure 3-6 shows the distribution of instruments selected for munitions-sweep technology by type of sensor technology. Note that this survey may not be representative of all munitions-sweep operations.

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[2] Sensor noise of the flux-gate magnetometer is about 10 times the noise of a cesium-vapor magnetometer. In addition, small-coil hand-held systems have significantly less transmit and receive moment, and therefore lower sensitivity, than the larger coil cart-based systems.

Table 3-4. Munitions-sweep technology—applications, strengths, and limitations.

Typical munitions-sweep applications: Sensor-aided surface clearance; anomaly avoidance sweep, and mag-and-flag sweep.		
Technology	**Strengths**	**Limitations**
All munitions-sweep technology	• Useful for initial removal operations in areas with high density of metallic clutter prior to munitions-mapping operations. • Usable in rough terrain and areas that other systems can not access. • Low capital cost.	• Quality control of process is difficult. • Sensors most commonly used are significantly less sensitive to the physical parameters being measured than most digital geophysical equipment. • Difficult to verify search area coverage by the geophysical sensor operators.
Hand-held magnetometer	• Low power, lightweight, passive. • Ignores nonferrous items. • Can locate relatively deeper ferrous items than EMI.	• Not sensitive to nonferrous munitions. • Effectiveness reduced by magnetic geology or other ferrous clutter.
Hand-held EMI (time domain and frequency domain)	• Capable of detecting ferrous and nonferrous munitions. • Can be effective in geology that challenges magnetometers. • Better sensitivity against small, near-surface items than magnetometers.	• Detection depth limited by coil size and transmit power. • Detection depth typically limited to only shallow items (i.e., less than 1 foot). Limited sensitivity against deep objects. • Higher power required, particularly if recording data, and device is heavy.

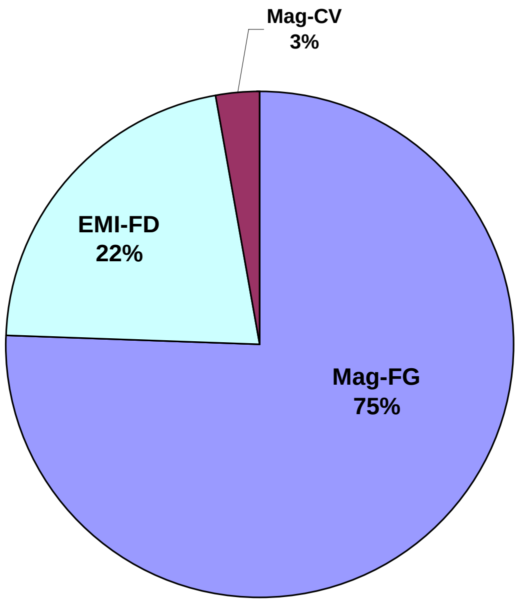


Figure 3-6. Breakout by instrument type of those selected for munitions-sweep operations. Mag-FG = flux-gate magnetometer; Mag-CV = cesium-vapor magnetometer; and EMI-FD = frequency-domain EMI.

The survey led to the following general observations regarding the state of the practice for munitions-sweep technology:

- Magnetometer technology was selected for use in all but five sweep actions studied. In only 3 of 30 actions were both EMI and magnetometer technology used.
- The most commonly used sweep technology is the Schonstedt flux-gate magnetometer, selected at 83% (25 of 30) of actions studied. The MineLab Explorer II, the Fisher 1266-X, and the White Spectrum XLT and Shadow X5 were used in the other actions.
- Multiple munitions-sweep instruments were selected at 20% (6 of 30) actions surveyed. Three of the actions selected EMI and magnetometers, and three selected multiple magnetometer instruments.

3.2.2 Munitions Mapping Technology

As a result of advances in geophysical sensors, field techniques, and advanced navigation systems, munitions-mapping operations using digital geophysical methods have become widespread for MR projects. In munitions-mapping operations, the ground is “mapped” by correlating sensor data points to spatial locations, which are often GPS coordinates. The survey data from the geophysical survey are processed and analyzed, and anomalies within the data are selected as potential targets. Figure 3-7 shows a map of digital geophysical mapping data for EMI and magnetometry data. A dig list that records the anomalies selected for excavation is compiled. After excavation, the dig lists are updated. The dig lists and the electronic records of geophysical and positioning data are archived and available for data-quality review.

For many munitions response sites, this methodology is an improvement over munitions-sweep operations (i.e., mag-and-flag methods) because it offers a greater ability to not only locate anomalies but to locate them to a greater depth and, in some limited circumstances, to characterize a buried item as a munition or nonmunition. Munitions-mapping operations also provide a digital record of the operation, ensure that complete coverage of the site is achieved, and allow for increased quality control and quality assurance. Target size and depth can be reliably estimated from high-quality magnetometer data for single items. On sites with only a few munitions types, with low to moderate densities where isolated signatures can be measured, cultural and munitions debris can be screened reliably from military munitions. Table 3-5 shows commonly used mapping sensors.

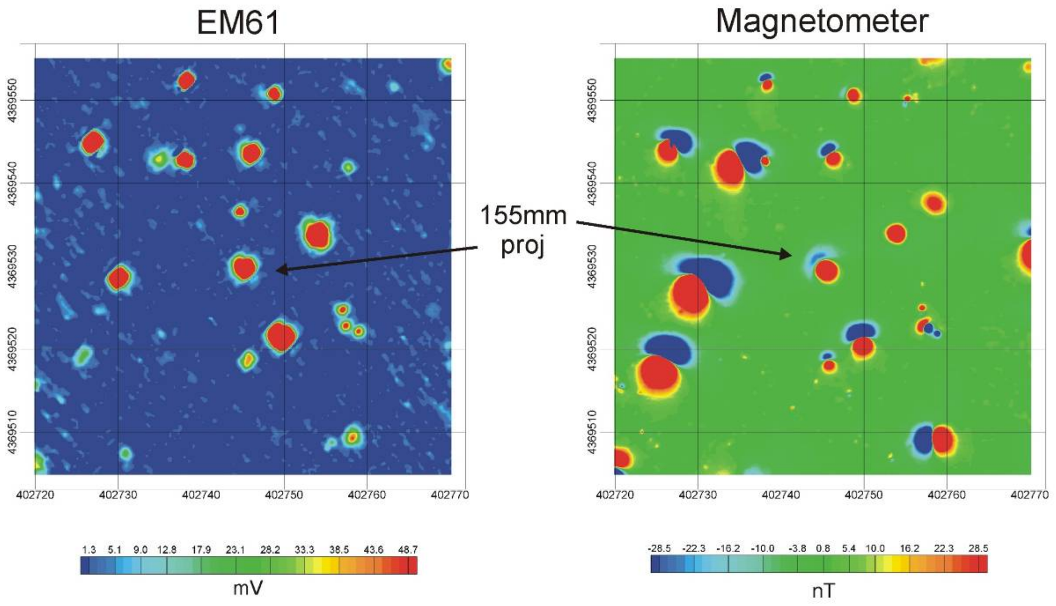


Figure 3-7. Examples of data from an EM61 MK2 (left) and cesium-vapor magnetometer (right) from the Multi-sensor Towed Array Detection System (MTADS) system. A 155 mm projectile is labeled in both data sets.

Of the 66 actions studied, 59 included munitions-mapping operations, including both transect and area mapping applications. The survey identified 12 munitions-mapping systems used. In several cases, more than one instrument was selected for production use at a site. A total of 80 systems were selected across the 44 sites:

- 51 EM61 (MK1/MK2).
- 12 G-858.
- 2 EM61–HH.
- 3 GX3/GX4 (EM61) Array.
- 2 Foerster FEREX.
- 1 Fisher 1266-X.
- 3 Airborne arrays (AIRMAG).
- 2 GEM3.
- 1 Scintrex Smartmag.
- 1 G-TEK TM-4 Mag Array.
- 1 G-TEK TM5 EMU.
- 1 Schonstedt Mag Array.

These totals include only those systems used in the primary geophysical survey to characterize the site, as opposed to those used for sweep operations, target reacquisition, or quality-assurance/quality-control actions. Figure 3-8 shows the distribution of munitions-mapping systems by type of sensor technology. Table 3-6 lists the strengths and limitations of each technology.

This section summarizes the technology used across a broad range of response actions. The most appropriate mapping technology for a specific munitions response action is determined based on a geophysical prove-out and can be influenced by such factors as the response action objectives, types of munitions, terrain, and geology. See Chapter 6 for more information on these and other munitions detection-performance considerations.

Table 3-5. Munitions mapping sensor technologies.

Sensor	Technology	Instrument	Deployment Configurations	Output	Status*
Munitions Mapping Operations					
Magnetometer	Cesium Vapor	Geometrics G-858	Hand-held, cart mounted, or towed array	Digital	Established
		Scintrex Smartmag	Hand-held	Digital or analog	Emerging
		AIRMAG	Airborne	Digital	Emerging
		G-TEK TM-4 Array	Hand-held, cart mounted, or towed array	Digital	Innovative
	Flux-gate	Foerester FEREX 4.032 DLG	Hand-held, cart mounted	Digital	Emerging
		Schonstedt Array	Towed Array	Digital	Emerging
		Ebinger MAGNEX 120 LW	Hand-held	Digital	Emerging
EMI	Time Domain	Geonics EM61 (MK1/MK2)	Cart mounted or towed array	Digital	Established
		G-tek TM5-EMU	Hand-held	Digital	Emerging
		GX3/GX4 (EM61) Array	Towed array	Digital	Emerging
		NanoTEM GDP-32	Cart mounted	Digital	Emerging
	Frequency Domain	Geophex GEM 3	Hand-held, cart mounted, or towed array	Digital	Established

* EPA defines technologies as follows (EPA 2005):

- *Emerging technology*—an innovative technology that is currently undergoing bench-scale testing in which a small version of the technology is tested in a laboratory.
- *Innovative technology*—a technology that has been field-tested but lacks a long history of full-scale use. Information about its cost and how well it works may be insufficient to support prediction of its performance under a wide variety of operating conditions.
- *Established technology*—a technology for which cost and performance information are readily available. Only after a technology has been used at many different sites and the results have been fully documented is that technology considered to be established.

The survey led to the following general observations regarding the state of the practice for munitions mapping technology:

- Time-domain EMI (TD-EMI) technology dominates munitions mapping. It was used in 81% (48 of 59) of the munitions-mapping operations surveyed, with 66% (39 of 59) using TD-EMI only, 10% (6 of 59) using both magnetometers and TD-EMI, and 5% (3 of 59) using both frequency-domain EMI (FD-EMI) and TD-EMI.
- The Geonics EM61 and its variants (MK1, MK2, HH) are the most common TD-EMI sensors, used in all TD-EMI actions surveyed. Multiple Geonics EM61

variants were used in some actions. The G-TEK TM5 EMU was also utilized at one action, along with the Geonics EM61 MK2.

- Magnetometers were utilized in 29% (17 of 59) of the munitions-mapping operations surveyed, with cesium-vapor magnetometers used in 14 actions and flux-gate magnetometers in 3 actions.
- The Geometrics G858 cesium-vapor magnetometer is the most common magnetometer sensor, used in 12 of 17 magnetometer-based mapping operations surveyed. The Foerster FEREX, Scintrex Smartmag, G-TEK TM-4, and Schonstedt Mag Array were used in the other actions.
- Frequency domain EMI (FD-EMI) was used in 5% (3 of 59) of the mapping operations surveyed. The GEM3 was used in two actions, and the Fisher 1266-X was used in the other action. FD-EMI was always used in combination with TD-EMI.

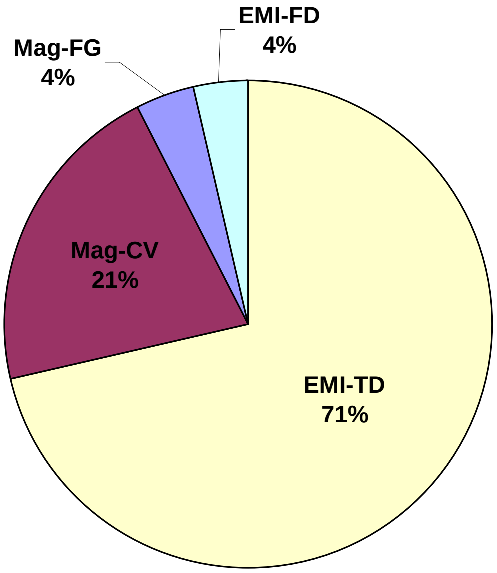


Figure 3-8. Distribution of munitions mapping systems by sensor technology. Mag-FG = flux-gate magnetometer; Mag-CV = cesium-vapor magnetometer; EMI-FD = frequency-domain EMI; and EMI-TD = time-domain EMI.

Table 3-6. Munitions mapping technology—applications, strengths and limitations.

<table>
<tr><td colspan="3">Typical Munitions Mapping Application: Digital geophysical mapping, integrating sensor and geolocation data to detect and characterize geophysical anomalies for detailed MR site characterization.</td></tr>
<tr><th>Technology</th><th>Strengths</th><th>Limitations</th></tr>
<tr><td>Magnetometer</td><td>• Can locate relatively deeper ferrous items.
• Data can be analyzed to estimate target size and depth.
• Can be arrayed, even in man-portable applications.</td><td>• Detects only ferrous materials.
• Effectiveness reduced by magnetic geology.
• Surveys typically result in high rate of false alarms (nonordnance items).
• Subject to interference from large ferrous or current-carrying objects such as power lines, fences, and vehicles.
• Can be influenced by high concentrations of surface munitions fragments.</td></tr>
<tr><td>EMI</td><td>• Detects ferrous and nonferrous metallic objects.
• Effective in detecting near-surface objects.
• Can be effective in geology that challenges magnetometers.
• Provides additional information that can be related to target shape and material properties.
• More advanced systems measure multiple frequency or time gates.
• Additional data can provide information on target shape, orientation, and material properties.</td><td>• Limited depth of investigation due to faster signal fall-off over distance than a magnetometer.
• Can be influenced by high concentrations of surface munitions fragments.
• Subject to interference from large metal objects such as power lines, fences, cables, and vehicles.</td></tr>
</table>

3.2.3 Munitions Reacquisition Technology

Reacquisition operations are similar to sweep operations, but instead of systematically searching an entire area for anomalies, the search is limited to finding anomalies detected during munitions-mapping operations. The process of anomaly reacquisition is currently not well defined or standardized within the industry. Several different approaches are currently being used in the field.

Munitions-reacquisition operations, as they are employed today, generally involve the following steps:

- The anomaly coordinates identified by munitions-mapping operations are located using land survey techniques.
- The area around the selected location is then searched to a predefined radius (search halo) with a geophysical sensor to confirm the presence of the anomaly and determine its precise location.

- Once the anomaly is reacquired, the reacquisition technician marks its location, and UXO technicians proceed with excavation.
- Finally, quality control and quality assurance are conducted to verify that the selected anomaly was excavated and that additional anomalies are not present.

Depending on the capabilities of the reacquisition sensor and the accuracy of the survey data, reacquisition may have the unintended consequence of reducing the location accuracy, requiring a larger search radius than would be needed for the mapping survey data. This operation can also be problematic if the reacquisition sensor is less sensitive than the mapping sensor, in which case anomalies may be missed. See Chapter 6 for more information on these and other munitions detection performance considerations.

As mapping technologies evolve, reacquisition may be more appropriately defined by its two main functions: returning to the location of a previously detected anomaly and ensuring that the anomaly is excavated safely and completely. The first of these is inherently a location activity and need not necessarily involve a geophysical sensor. It may be more efficient to simply navigate to an accurately positioned electronic flag using a high-accuracy survey technique. The second step has inherent sensing requirements both to guide the excavation and ensure that the appropriate objects have been removed.

Reacquisition, as it is currently practiced, can be done with either a hand-held or cart-mounted instrument. The majority of projects reacquire anomalies with a hand-held flux-gate magnetometer. Some projects require that anomaly reacquisition be done with the same technology used for mapping operations, while others use multiple reacquisition technologies. The rationale for different reacquisition approaches and technology requirements is not well understood. Table 3-7 lists the currently available instruments for munitions-reacquisition operations.

The majority of the removals studied included either mapping operations or sweep and mapping operations. The evaluation of reacquisition technology was limited to those instruments selected in connection with munitions-mapping operations. Sweep operations were not included—in all cases where sweep operations were conducted, the sweep instruments were used during anomaly excavation.

Table 3-7. Munitions reacquisition technologies.

Sensor	Technology	Instrument	Deployment Configurations	Output	Status*
Munitions Reacquisition Operations					
Magnetometer	Flux-gate	Schonstedt 52-Cx & 72 Cd	Hand-held	Analog	Established
		Ebinger MAGNEX 120 LW	Hand-held	Digital	Emerging
		Foerester FEREX 4.032 API	Hand-held	Digital or analog	Established
		Vallon EL 1302D/A	Hand-held	Digital or analog	Established
	Cesium Vapor	Geometrics G-858	Hand-held and cart mounted	Digital or analog	Established
		Scintrex Smartmag	Hand-held	Digital or analog	Emerging
EMI	Time Domain	Geonics EM61 (MK1/MK2)	Cart mounted	Digital	Established
		Geonics EM61 HH	Hand-held	Digital	Established
		G-tek TM5-EMU	Hand-held	Digital	Innovative
	Frequency Domain	Fisher1266-x Metal Detector	Hand-held	Digital or analog	Established
		Foerster MINEX 2FD 4.500	Hand-held	Analog	Established
		Vallon VMH3	Hand-held	Digital	Established
		White Spectrum XLT	Hand-held	Analog	Established
		Ebinger EBEX 420	Hand-held	Analog	Innovative
		Guartel MD8+	Hand-held	Analog	Innovative
		Schiebel AN-19/2 & ATMID	Hand-held	Analog	Innovative
		Teroso Lobo	Hand-held and cart mounted	Analog	Emerging
		Shadow X5	Hand-held	Analog	Innovative
		Geophex GEM 3	Hand-held and cart mounted	Digital	Established

* EPA defines technologies as follows (EPA 2005):

- *Emerging technology*—an innovative technology that is currently undergoing bench-scale testing in which a small version of the technology is tested in a laboratory.
- *Innovative technology*—a technology that has been field-tested but lacks a long history of full-scale use. Information about its cost and how well it works may be insufficient to support prediction of its performance under a wide variety of operating conditions.
- *Established technology*—a technology for which cost and performance information are readily available. Only after a technology has been used at many different sites and the results have been fully documented is that technology considered to be established.

Removals that included mapping operations used a variety of instruments and approaches for anomaly reacquisition. A total of 46 instrument evaluations included munitions mapping and reacquisition operations. In many cases, multiple hand-held instruments and technologies were selected for reacquisition. Multiple reacquisition sensors were used when required by site conditions and for quality control and quality assurance. Tables 3-8 and 3-9 give the primary reacquisition instruments selected for the 46 removal actions studied. Table 3-10 presents the strengths and limitations of each technology for reacquisition operations. Figure 3-9 shows distribution by sensor technology. The primary reacquisition instruments were the following:

- 35 Schonstedt (52Cx and 72Cd).
- 19 EM61 (MK1/MK2).
- 8 Geometrics G-858.
- 6 Vallon ferrous locator.
- 3 Fisher 1266-X.
- 1 Foerster FEREX.
- 1 G-TEK TM5 EMU.
- 1 MineLab Explorer II.
- 2 EM61–HH.
- 6 White Spectrum XLT.
- 1 GEM3.
- 1 Shadow X5.

Table 3-8. Mapping and reacquisition technology combinations.

Mapping Technology	Reacquisition Technology		
	Magnetometer	Electromagnetic Induction	Magnetometer and EMI
EMI	9	6	17
Magnetometer	9	0	0
Magnetometer and EMI	1	0	4

Table 3-9. Frequency of multiple instrument use in reacquisition operations.

Mapping Technology	Reacquisition Operation	
	Single Instruments	Multiple Instruments
EMI	10 (22%)	22 (48%)
Magnetometer	5 (11%)	4 (9%)
EMI and Magnetometer	1 (2%)	4 (9%)
Totals	16 (35%)	30 (65%)

Note: Percentages are rounded.

Table 3-10. Munitions reacquisition technology—applications, strengths and limitations.

Typical Munitions Reacquisition Application: Verify anomaly, locate anomaly, clear hole.		
Technology	**Strengths**	**Limitations**
Flux-gate Magnetometer	• Effective in rough terrain and areas other systems cannot access. • Low capital cost.	• Quality control of process is difficult. • Sensors most commonly used are significantly less sensitive to the physical parameters being measured than most digital geophysical equipment. • Difficult to verify search area coverage by the geophysical sensor operators.
EMI	• Can create a quality-control record by mapping small reacquisition area.	• Large coil of EM61 makes pinpointing location difficult. • Small-coil instruments are depth limited compared with typical mapping instruments.

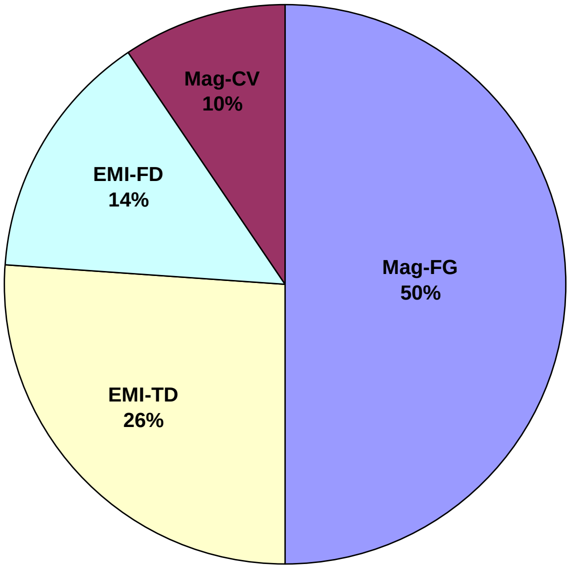


Figure 3-9. Distribution of munitions sensor technology used for reacquisition of target anomalies or clearance verification. Mag-FG = flux-gate magnetometer; Mag-CV = cesium-vapor magnetometer; EMI-FD = frequency-domain EMI; and EMI-TD = time-domain EMI.

The survey led to the following general observations regarding the current state of the practice for munitions-reacquisition technology:

- The most common reacquisition technology in the field today is the magnetometer. Of the munitions-reacquisition operations surveyed, 87% (40 of 46) utilized magnetometer technology, with 41% (19 of 46) using magnetometer only and 46% (21 of 46) using both magnetometer and EMI technology.

- Munitions-reacquisition operations at the surveyed sites are dominated by flux-gate magnetometers. The most common instrument for reacquisition operations is the Schonstedt magnetometer, which was used either by itself or in combination with other technology for reacquisition in 76% (35 of 46) of the mapping operations surveyed.
- Time-domain EMI and cesium-vapor magnetometer technologies are also commonly used. The EM61 (MK1/MK2) was used for reacquisition in 46% (21 of 46) of the mapping operations surveyed, the G858 magnetometer in 17% (8 of 46).
- EMI-based mapping operations used magnetometer or magnetometer and EMI instruments together for reacquisition operations at all but one site. All magnetometer-based mapping operations used magnetometers for reacquisition, with one site using magnetometers and EMI.
- Multiple instruments were used for reacquisition at 65% (30 of 46) of sites.

3.3 Munitions-Detection Tools and Equipment

This section reviews munitions-detection technology and how it works. This section is divided into munitions technology components or categories, not applications. We review each technology by component (i.e., sensors, platforms, positioning and navigation, data processing).

A munitions-detection system for either munitions sweep, munitions mapping, or munitions-reacquisition operations is composed of four main elements:

- Geophysical sensor.
- Survey platform.
- Positioning and navigation system.
- Data-processing system.

The technology tools and equipment for each element are discussed in detail below.

The geophysical sensor, with its central role in detecting anomalies, is generally the main focus in munitions-detection systems, but other elements are also critical to the success of the overall system. The survey platform deploys the geophysical sensor and not only governs the terrain in which the system can be operated, but is also a major factor in system and motion noise and thus sensor performance. The positioning equipment determines the geophysical sensor’s geographic location at each data point recorded during the survey. The navigation system ensures that the correct area is surveyed and complete coverage is achieved. The data-processing system ultimately determines how data are handled and how targets are selected and interpreted.

For munitions-sweep operations such as mag-and-flag surveys, many of these elements are inherent in the survey method—the operator holding the sensor is the survey platform, positioning system, and data-processing system. For mapping operations, the elements are usually more complex, and many are integrated into the mapping system.

3.3.1 Geophysical Sensors

Two classes of sensors are commonly used for munitions detection at most munitions response sites—magnetometers and EMI devices. Magnetometers and EMI sensors can be operated in either an analog (audible tone or visual meter) or digital recording mode and can be configured for field deployment in munitions sweep, mapping, or reacquisition applications.

3.3.1.1 Magnetometers

Magnetometers detect ferrous metal objects by measuring changes in the Earth's magnetic field caused by the object, as shown in Figure 3-10. Magnetometers are passive devices that respond to ferrous materials, such as iron or steel. Magnetometers will not respond to metals that are not ferromagnetic, such as copper, tin, and aluminum. These sensors typically perform better for large, deep, ferrous objects relative to other sensor technology. They may also detect small ferrous objects at or near the surface better than electromagnetic sensors with large sensor coils.

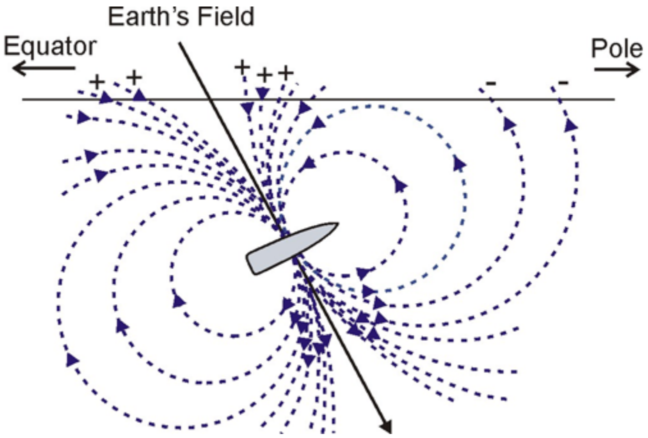


Figure 3-10. Perturbation of Earth's field by ferrous ordnance.

The two types of magnetometers commonly used in the UXO industry are the flux-gate magnetometer and the cesium-vapor magnetometer. A Schonstedt magnetometer is an example of a flux-gate magnetometer. The Geometrics G-858 is an example of a commonly used cesium-vapor magnetometer (see Figure 3-11).

Flux-gate Magnetometer. There are a number of different configurations of flux-gate magnetometers, but all are based on what is referred to as the magnetic saturation circuit. The system contains two sensor coil assemblies that are precisely spaced and electronically balanced to achieve a near magnetically balanced operating condition (see Figure 3-12). In a uniform magnetic field, such as Earth's, the two sensor coils maintain a magnetically balanced state because both coils experience the same magnetic lines of force. However, when a ferromagnetic object is nearby, the field strength and angle of the magnetic lines measured at each sensor are different. This difference, although minute, is enough to offset the critical balance and produce a signal, which indicates the magnitude and direction of the field. Although the signal is usually presented as an audio tone, it can also be digitized and recorded by the instrument.

Figure 3-11. Schonstedt used in mag-and-flag operation (left) and G858 used in a hand-held mapping operation (right) (Photograph courtesy of Geometrics).

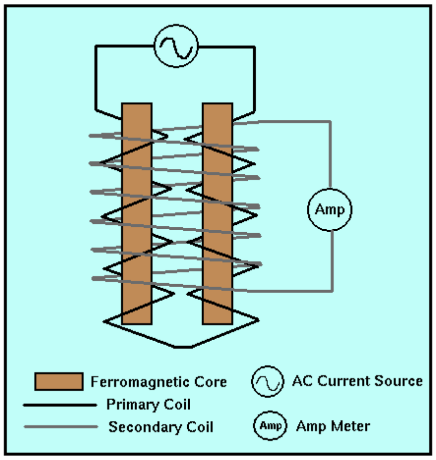


Figure 3-12. Diagram of a flux-gate magnetometer (Courtesy of T. Boyd, Colorado School of Mines)

Flux-gate magnetometers are typically used for mag-and-flag surveys, although a variety of hand-held digital and analog magnetometers could be used. Typically inexpensive and easy to operate, flux-gate magnetometers are also used for anomaly reacquisition. Although many flux-gate magnetometers do not digitally record data, data loggers can be adapted for use with them. One disadvantage of flux-gate magnetometers is that they typically have a higher noise floor than other instruments.

Cesium-Vapor Magnetometer. Cesium-vapor magnetometers (Figure 3-13) are used for munitions-sweep operations and munitions-mapping operations. Although lightweight and portable, the cesium-vapor magnetometer's principal advantage is its rapid data-collection capability. (One disadvantage is its insensitivity to the magnetic field in certain directions, so dropouts can occur where the magnetic field is not measured. This problem can be minimized with proper orientation of the sensors to Earth’s magnetic field.)

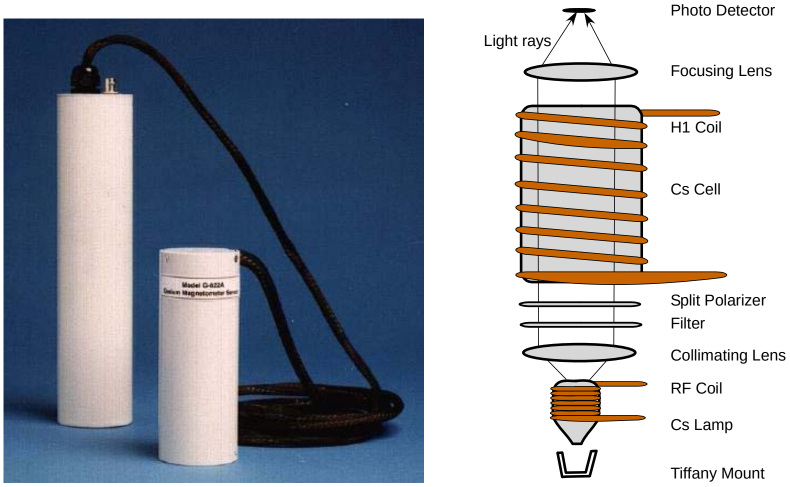


Figure 3-13. Photo and diagram of G-858 cesium-vapor magnetometers.

Cesium-vapor magnetometers make use of the Zeeman effect, in which an ambient magnetic field splits the fine energy levels of the valence electron in a cesium atom. The energy difference between the two levels, where the electron’s spin moment is either aligned with the magnetic field or opposes it, is proportional to the strength of the externally applied magnetic field. The cesium-vapor magnetometer measures the radio frequency required to pump the electron from the lower energy level to the higher, which will vary as the magnetometer encounters perturbations in Earth’s magnetic field. This frequency gives the difference in energy and hence the magnitude of the external field. The cesium-vapor magnetometer measures the total magnetic field, as opposed to the field in a specific direction.

3.3.1.2 Electromagnetic Induction

EMI is a geophysical technology used to transmit an electromagnetic field, which in turn induces a secondary magnetic field in objects that are conductive. When secondary magnetic fields of military munitions and other conductive items exceed background responses, they can be identified as potential anomalies requiring further investigation. Figure 3-14 shows the basic EMI physics schematically. EMI sensors can operate in either the time domain or the frequency domain. The two domains are capable of producing theoretically equivalent results, but practical implementation issues often result in performance differences.

Time-domain electromagnetic systems measure the response of the subsurface to a pulsed electromagnetic field as a function of time. Frequency-domain electromagnetic systems measure the secondary field response of the subsurface as a function of the transmitted frequency. In more advanced instruments, measurements can be made in multiple time gates (time-domain electromagnetic systems) and multiple frequencies (frequency-domain electromagnetic systems), which can increase the information obtained about the physical properties of the targets.

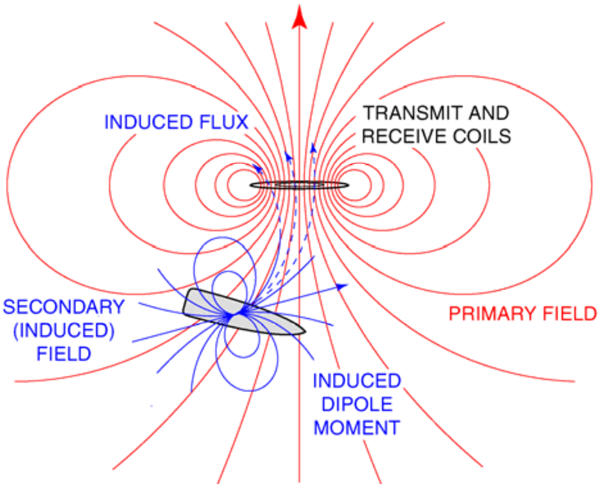


Figure 3-14. Schematic illustrating EMI physics. The primary field (red) is transmitted by the system, a dipole moment is induced in buried conductive objects, and secondary fields are produced (blue), which are sensed by the receiver coil.

Time-Domain Electromagnetic. The basic operating principle of time-domain EMI involves the use of a wire loop transmitter carrying a pulsed current (in time) that produces a transient magnetic field that propagates into the earth. The magnitude and rate of decay of the fields depend on the electrical properties and geometry of the medium and any subsurface objects. The time-domain electromagnetic receiver measures the secondary magnetic fields created as a result of the incident magnetic field that produces eddy currents in the subsurface. The currents in the earth decay or dissipate first, followed by the induced currents in metallic objects (see Figure 3-15). Measurements are made in discrete "time gates," or time intervals, following the turn-off of current pulse generated by the transmitter. The early-time gates will detect small and large targets with short and long decay rates, respectively, but the late-time gates will detect only larger targets with relatively long response decay.

Frequency-Domain Electromagnetic. The basic operating principle of the frequency-domain EMI method involves a transmitter coil radiating an electromagnetic field at one or more selected frequencies to induce an electrical current (secondary EM field) in the earth and subsurface objects. The receiver coil detects and measures this secondary field. The instrument output is obtained by comparing the strength of the secondary field to the strength of the primary field.

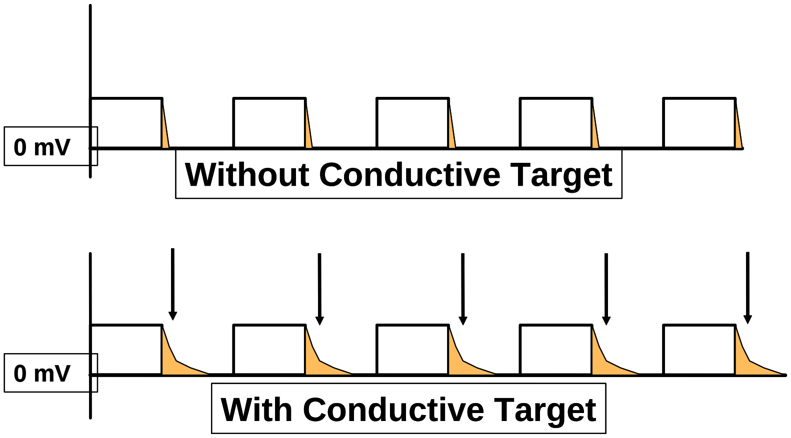


Figure 3-15. Operation of a time-domain EMI. Top series shows square-wave pulses of the transmit signal, which die away quickly when no conductive object is present. Bottom trace shows the extended decay observed from a conductive object. Arrows indicate a single time-gate measurement, but multiple measurements may be made throughout the decay period.

3.3.1.3 Dual-Sensor Systems

Dual-sensor systems incorporate magnetometer and electromagnetic sensors onto a single platform to perform simultaneous magnetometer and EMI surveys. Simultaneously measuring co-registered magnetic and electromagnetic data is challenging because the field transmitted by the electromagnetic system is seen as overwhelming noise in the magnetometer. A system in which the magnetic field is measured after the electromagnetic field has completely decayed has recently been developed. Figure 3-16 shows the interleaving of the signal measurements that makes this operation possible, and Figure 3-17 shows an example of the dual-sensor system (GEO-CENTERS 2004).

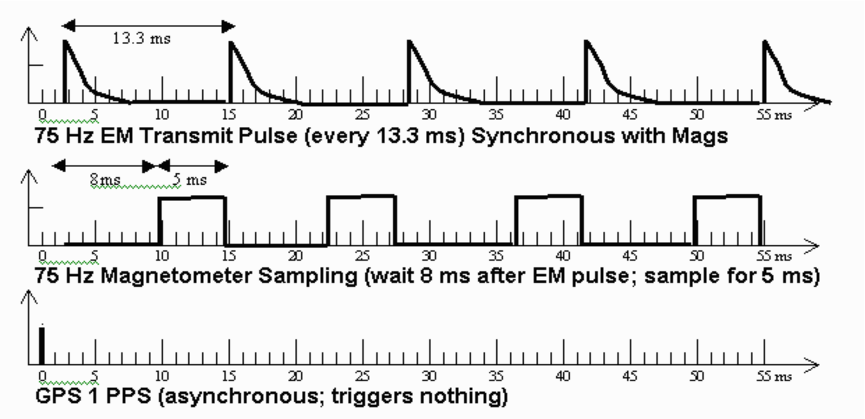


Figure 3-16. Interleaving of magnetometer and EMI measurements in dual-mode time-domain system. The top trace shows EMI pulse, center trace shows magnetometer detection window, bottom trace shows operations clock that governs overall system timing.

Figure 3-17. Dual-mode Man-Portable Simultaneous EMI and Magnetometer System (MSEMS) currently under development. Magnetometer is located in the center of the coil of the EM61 (SAIC 2006).

3.3.2 Survey Platforms

Survey platforms are used to deploy the geophysical sensors. There are six basic classes or types of survey platforms:

- Hand-held.
- Man portable.
- Cart mounted.
- Towed array.
- Airborne.
- Underwater.

Hand-held and man-portable survey platforms are also referred to as hand-carried systems. Underwater mapping platforms are currently under development, but none are currently commercially available.

The choice of survey platform is dictated by the type of munitions detection operation, the type of sensor deployed, and the site to be surveyed. Site features such as terrain, vegetation, and accessibility, and the overall size of the survey area will influence survey platform design and are often the deciding factor in selecting equipment. Table 3-11 summarizes the general strengths and limitations of each type of survey platform.

Table 3-11. Munitions survey platforms—applications, strengths and limitations.

Platform Type	Application	Typical Production Rates	Strengths	Limitations
Hand-held	Munitions-sweep operations. - Surface sweeps. - Mag-and-flag clearances. - Anomaly avoidance. Munitions-mapping operations. Munitions-reacquisition operations.	Less than 1 acre per day.	Lightweight, portable, and deployable under most site conditions. Particularly useful in areas of dense vegetation or challenging terrain where lightweight and compact devices are required. In heavily wooded areas or areas with steep or uneven terrain, hand-held sensors may be the only suitable sensor deployment method.	Hand-held systems have low area coverage and production rates compared with other platforms. Results are highly dependent on operator's skill and can be influenced by sensor height and uncertainty in coverage.
Man Portable	Munitions-mapping operation. Munitions-reacquisition operations.	1–5 acres per day.	Man-portable platforms are generally favored where vegetation and terrain limit other options, but they can be used in nearly any conditions.	Motion caused by operator carrying platform can cause ground strikes and fluctuating sensor height, which degrade the geophysical data collected during the survey. Can require significant operator stamina and physical strength to operate. Coverage rates for man-portable platforms are typically limited to a few acres per day.
Cart Mounted	Munitions-mapping operations. Munitions-reacquisition operations.	1–5 acres per day.	Greater stability, efficient coverage, and ability to carry more weight. Fixed sensor height minimizes ground strikes and variations in sensor height, which degrade the geophysical data collected during the survey. Accurate positioning, and the operator's influence on coverage can be mitigated.	Limited by topography and vegetation. Motion of a cart over rough terrain introduces additional noise sources, decreasing sensor performance. Limited access due to topography or vegetation.
Towed Array	Munitions-mapping operation.	5–20 acres per day.	Greater stability, efficient coverage, and ability to carry more weight. Fixed sensor height minimizes ground strikes and variations in sensor height, which degrade the geophysical data collected during the survey. Accurate positioning, and the operator's influence on coverage can be mitigated.	Limited access due to topography or vegetation.
Airborne	Munitions-mapping operation.	300–700 acres per day	Ability to collect data very rapidly over a large survey area.	Lower detection capability than ground-based systems (especially for smaller munitions). Limited to sites that are relatively flat and free of trees, shrubs, and other obstacles.

3.3.2.1 Hand-held Platform

A hand-held platform is simply an operator carrying a lightweight and compact sensor system. Hand-held systems are frequently used for munitions-sweep applications, including magnetometer assisted surface sweeps, mag-and-flag clearances, and anomaly avoidance sweeps. Hand-held systems are also used for reacquisition and are used exclusively in support of excavation operations. An example of a hand-held platform is shown in Figure 3-18.

Hand-held systems can be analog or digital. In analog mode, no data are recorded. Instead, the operator reacts in real time to an audio or visual signal. Magnetometers and appropriately sized EMI sensors (i.e., EM61–HH) can also be operated in digitally recording hand-held mode. In this case, the platform integrates a hand-held sensor unit, a geolocation unit, and a data-acquisition unit.

Figure 3-18. Hand-held analog electromagnetic systems.

Hand-held systems have the advantage of being lightweight, portable, and deployable under most site conditions. They are particularly useful in areas of dense vegetation or challenging terrain, where lightweight and compact devices are required. In heavily wooded areas or areas with steep or uneven terrain, hand-held sensors may be the only suitable sensor deployment method.

Hand-held sensor platforms have several limitations: low area coverage rates compared with other platforms and results that are highly dependent on the operator's skill and can be influenced by sensor height and uncertainty in coverage.

3.3.2.2 Man-Portable Platform

Man-portable systems are typically digital mapping systems that have been adapted to be carried by the operator or operators conducting munitions-mapping operations. Man-portable systems contain one or more sensors, as well as positioning, navigation, and data-acquisition systems. Man-portable platforms cover a broad range of deployment options, ranging from a single sensor at the end of a harness to an array of sensors mounted on a frame carried by the operator (see Figure 3-19).

Figure 3-19. Man-portable platform.

A typical man-portable system is deployed in two units—the sensor unit (sensor and GPS antenna) and a support unit (data acquisition, battery, electronics). These units can be combined and carried by a single operator or distributed between two operators and tied with an umbilical cord. Man-portable platforms are also being developed using wireless technology to reduce the amount of equipment carried by the operator.

Man-portable platforms are generally favored where vegetation and terrain limit other options, but they can be used in nearly any conditions. Depending on terrain and vegetation, coverage rates for man-portable platforms are typically a few acres of mapped area per day.

3.3.2.3 Cart-Mounted Platforms

The most commonly used geophysical survey instrument, the Geonics EM61, comes mounted on a wheeled cart in its standard configuration. Other magnetometer and EMI sensors have been similarly configured. The cart platform is typically integrated with a positioning system, such as RTK-GPS, for geolocation of sensor readings.

Advantages of cart-mounted platforms over hand-held and man-portable platforms include greater stability, more efficient area coverage, and ability to carry more weight. Fixed sensor height minimizes ground strikes and variations in sensor height, which degrade the geophysical data collected during the survey. Cart-mounted systems can be limited by topography and vegetation, however, and they may require significant operator stamina and physical strength to operate. Cart-mounted systems generally have lower survey rates than towed-array and airborne systems. Like man-portable systems, coverage rates are typically a few acres per day, depending on site conditions. Figure 3-20 shows examples of cart-mounted magnetometers and EM61 sensors.

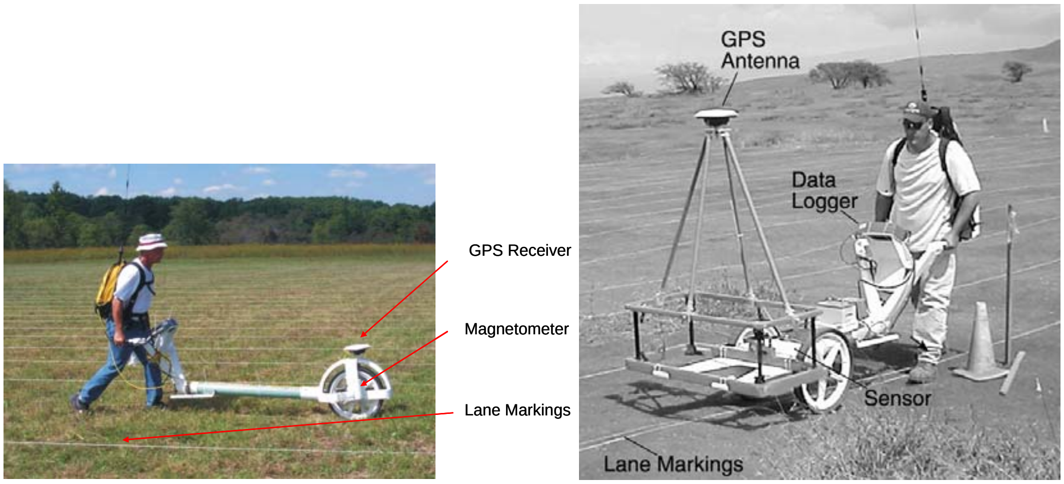


Figure 3-20. Examples of cart-mounted systems with cesium-vapor magnetometer sensors (left) and EM61 EMI sensors (right).

3.3.2.4 Towed Arrays

In recent years, commonly used geophysical survey equipment has been integrated into large arrays towed by motorized vehicles. These systems, in which multiple sensors cover a width of 2 or more meters with set line spacing, offer a number of advantages in sites where large areas of open terrain and sparse vegetation, suitable for driving, are to be mapped. Production rates are greatly increased to tens of acres per day and errors in data collection caused by insufficient coverage are minimized. These array systems also allow for very controlled data acquisition and greater system weight. The rigid spacing of sensors on the platform results in the collection of data that, within the array width, is very accurately positioned relative to adjacent sensors. An example towed array is the Multi-Sensor Towed Array Detection System (MTADS), shown in Figure 3-21. Limitations on towed array systems are generally the result of vegetation and terrain that affect site accessibility.

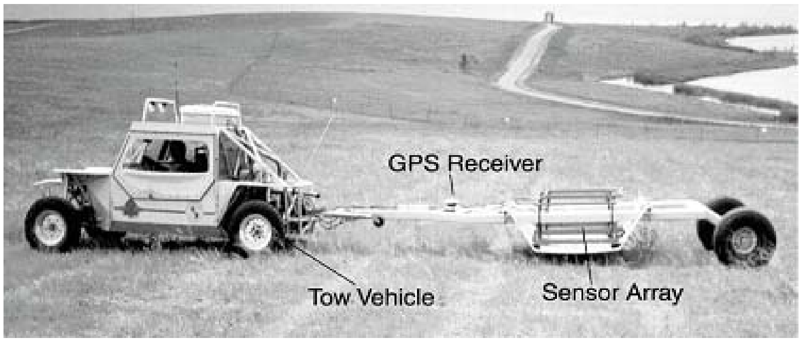


Figure 3-21. Towed sensor array platform.

3.3.2.5 Airborne

Airborne survey platforms have been deployed using helicopters or fixed-wing aircraft. Helicopter-based systems (Figure 3-22) have been configured to rapidly collect magnetic or electromagnetic data. These surveys require very low flying heights, typically 1–3 meters, to maximize detection capability. The main advantage of these systems is their ability to collect data very rapidly over a large survey area (300–700 acres per day). The main disadvantages are a lower detection capability than ground-based systems (especially for smaller munitions), platform noise, safety issues, and the requirement for the survey area to be relatively flat and free of trees, shrubs, and any other obstacles with heights above a meter or so.

Figure 3-22. Helicopter-based survey.

3.3.3 Positioning Equipment

A positioning technology is needed in digital geophysics to produce any type of representation or mapping of Earth’s surface or subsurface. Positioning technologies determine the sensor’s geographic location at each data point recorded. From this information, a map of the sensor response and a record of the travel pathways can be produced. Accuracy, effects of terrain, tree canopy, line of sight, ease of use, and costs are generally the most significant criteria for technology selection. Therefore, part of the purpose of a GPO is to test the capability of the positioning technology to be used at the site and evaluate the procedures used to merge the positional data and the geophysical data.

Locations can be determined by many different techniques of varying sophistication. Traditional surveying techniques may use tapes and trigonometry to determine relative positions from known ground points. Highly accurate, optical laser-based measuring equipment can provide centimeter accuracy in a continuous tracking mode in areas where line of sight is not obstructed by trees or other objects. Other techniques rely upon various applications of differential GPS (DGPS); ultrasonic, radio ranging; and inertial navigation systems (INS). In more advanced systems, positioning technologies are directly integrated with geophysical sensors to provide a digital output that can be directly merged with sensor readings to create a site map.

For digital geophysical mapping surveys, positioning systems locate the sensor position to enable data interpretation and geophysical anomaly selection for production of a dig list. The ability to correctly locate the position of an emplaced item from the geophysical data depends not only on the positioning technology selected, but also on the size of the sensor and the manner in which the geophysical data are processed. Various error sources can degrade anomaly location, including uncorrected motion of the platform in rough terrain, poor data analysis procedures, or timing discrepancies between sensor and positioning system readings.

The positioning system used in the survey or a separate system may then be used for the reacquisition of anomalies. It is common practice to employ a second sensor to pinpoint anomalies based on locations identified from the initial mapping and the data analysis. This practice may in fact introduce additional positioning errors, depending on the characteristics of the reacquisition sensor and positioning system. Overall system positioning accuracy can be measured by either the location picked during data processing or during reacquisition. Which is the appropriate measure of overall system location accuracy depends on how the contractor proposes to pick and reacquire targets and should be documented in the work plan.

Acceptable positioning accuracy results are based on site conditions, project objectives, and costs. The most desirable positioning systems are directly integrated with geophysical sensors, record data digitally, and map data to provide anomaly locations in all terrain and tree canopies.

3.3.3.1 Laser-Based Systems

Laser-based survey and tracking systems measure a position relative to a fixed base station location. In a common implementation, a base station is surveyed in at a known location. The base station tripod holds a transmit laser on a robotic mount. The roving sensor platform is outfitted with a prism that reflects the laser from the transmitter. The distance between the base station and the prism is measured by the time of flight of the laser pulse, and the azimuth and elevation angles are accurately tracked by the robotic mount. This information is processed by an on-board computer to calculate the position of the prism in three dimensions. The computer also contains software to lock onto and track the position of the prism in real time to allow on-the-fly data acquisition. Using laser systems, location accuracies of around 1 cm are possible (ESTCP 2004).

3.3.3.2 Differential GPS

GPS satellites orbit Earth, transmitting signals that can be detected by anyone with a GPS receiver. Differential GPS increases the accuracy of GPS readings by utilizing two receivers: a stationary receiver that acts as a base station and collects data at a known location and a second roving receiver that makes the position measurements. Base stations can be configured to either transmit the correction data to the rover system or to save the data to be used to correct positional data during post-processing. These corrections increase the accuracy of the GPS readings. Where a low-cost hand-held GPS has an accuracy of several meters, modern differential systems are capable of locating individual data points with an accuracy of 2 to 5 cm in the open.

Advantages of positioning using DGPS methods include the accuracy that can be achieved in open terrain, rapid update rate, unlimited range, and ease of operation. System weaknesses include intermittent loss of adequate satellite coverage, which will affect the accuracy of the results. In addition, tree canopy, deep ravines, or other topographical features can degrade the system's accuracy and ultimately make the system inoperable because they interfere with the GPS receiver's ability to detect satellite signals.

3.3.3.3 Fiducial Positioning

Fiducial positioning is a method of manually placing electronic markers that indicate locations within a set of recorded geophysical data. To perform the geophysical survey using fiducial positioning, the surveyor depresses the electronic switch to insert a fiducial marker at the beginning of a data set and simultaneously starts walking a straight line at a constant pace. The surveyor continues walking, depressing the electronic switch to place fiducial markers as he crosses the marker ropes. Fiducial markers are typically placed at 25-foot, 50-foot, or 100-foot intervals, depending on site-specific needs. It is generally accepted that a well-trained operator can maintain a constant pace and a straight-line dead reckoning (to within ±1 foot) between distances of up to 100 feet under good conditions (only minor obstructions to line of sight and relatively even ground). Greater distances can be achieved if range markers are used.

The purpose of placing fiducial markers in the geophysical data is to compensate for variations in the speed at which the surveyor walks or drives the geophysical sensor while acquiring data. Fiducial positioning can also be used in the event that the surveyor has to stop due to an obstruction in his path. The process for dealing with obstructions should be defined ahead of time in the work plan, demonstrated during the GPO, and documented in a field logbook during the geophysical survey.

Key factors governing the success of line and fiducial positioning are the assumptions that a straight line was maintained between fiducial marker points and that a constant pace was maintained during each segment. If either of these assumptions is incorrect, the accuracy of line and fiducial positioned data will degrade. Note that it is difficult to quantify the accuracy of line and fiducial positioning because, unlike DGPS or any other electronic positioning method, there is no physical or digital record of where the operator actually traveled while collecting the data.

3.3.3.4 Ropes Positioning

Rope can also be used as a local positioning method. Most commonly associated with mag-and-flag surveys, this method has the advantage of working when more sophisticated positioning methods break down.

The concept of ropes positioning is to use ropes on the ground to guide the surveyors (Figure 3-23). Two baselines are established across the opposite ends of the survey area (usually a grid, which is often a 100 × 100 feet or 200 × 200 feet). Grid lines can then be tied to the baseline knotted rope or stakes. The lines mark the boundaries of each lane (a lane is usually 3 to 5 feet wide) and are used as guides by the magnetometer operators to help ensure complete coverage of the grid. The grid lines are then swept. The sweep results are recorded with the relative position of anomalies or other features displayed on a grid map. While not suitable for accurate mapping, this method can locate anomalies within 1 foot if care is taken when recording data on the grid maps and field notes.

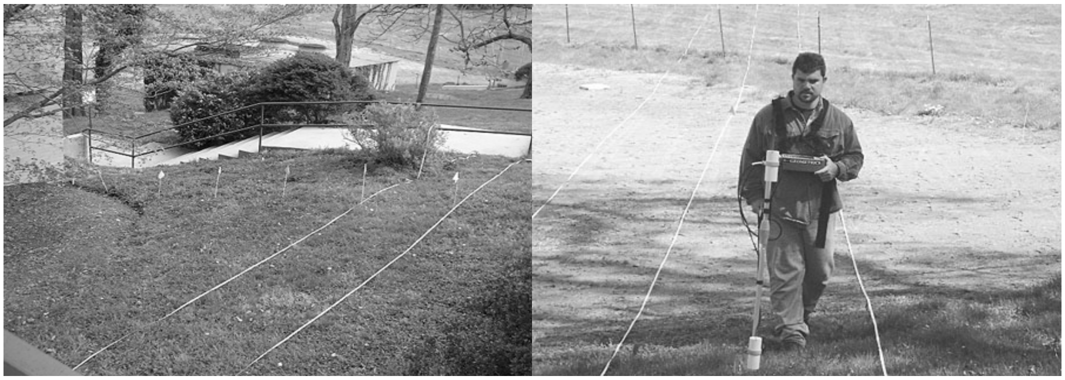


Figure 3-23. Ropes navigation in a geophysical survey area.

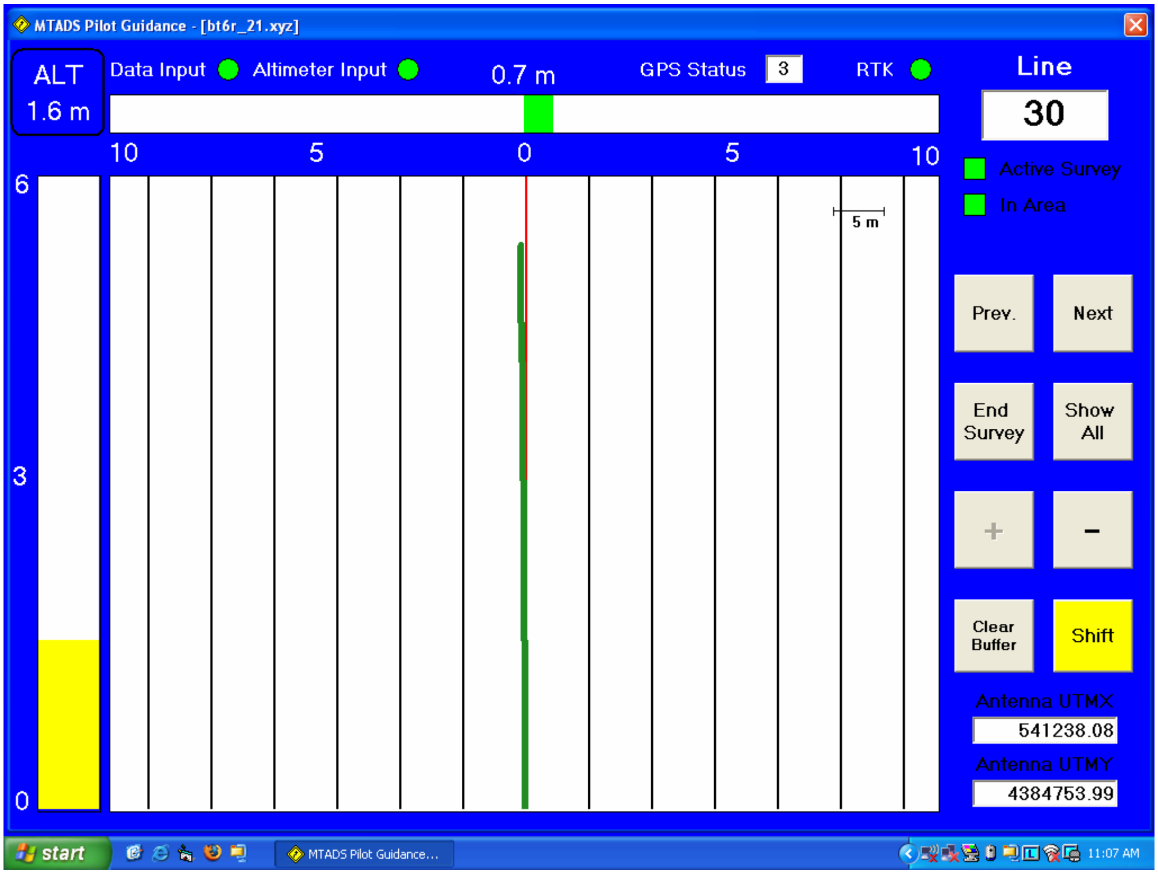
3.3.4 Navigation System

The navigation system guides the system operator over the area of interest to be mapped. Traditionally, the operator has navigated using visual aids, such as lines or cones set out in regular patterns. With the advent of towed-array and airborne mapping systems, advanced navigation systems based on geolocation technologies, such as DGPS, have been developed. These systems provided real-time guidance and feedback that indicates whether a preplanned course is being correctly followed. Navigation systems can also provide real-time feedback on data quality and coverage, allowing coverage errors and data gaps to be corrected in the field.

The major components of a navigation system are the geolocation receiver (i.e., DGPS), navigation computer, and navigation aids. Towed-array navigation system guidance errors of less than half the survey line spacing are needed for efficient field mapping of most full-coverage surveys. However, greater accuracy may be needed at sites with tighter data-quality objectives.

Navigation aids range from simple directional arrow indicators to complex route or lane tracking displays. Figures 3-24 and 3-25 show examples of navigation systems.

Figure 3-24. A local radio frequency navigation system integrated with an EM61.



MTADS Pilot Guidance - [bt6r_21.xyz]

ALT 1.6 m

0.7 m

GPS Status 3

Line 30

Antenna UTMX 541238.08

Antenna UTMY 4384753.99

Figure 3-25. Screen shot of a towed-array navigation system based on DGPS.

The MTADS pilot-guidance application runs on a sunlight-readable computer mounted in the front seat of the aircraft or in a position visible to the vehicle operator. Inputs are the GPS output signal and, in the case of the helicopter, the laser altimeter output string. Track files are developed in a stand-alone application. The track files are stored so they can be displayed easily in the system's data-analysis program and integrated with GPS data.

The operator loads the appropriate track file at the beginning of each mission. The tracks to be followed are displayed with the current selected lane. The operator sees the course-over-ground of the system plotted on the track lines, as well as a left/right bar and numeric representation of how the course is being followed. Note that pilots are trained to "turn into the color," so that is how the left/right bar is arranged. If there is altimeter input, there is a bar and digital representation of that stream displayed as well. Notification warning lights are used to monitor critical survey elements such as sensor data streams, GPS fix quality, and a number of survey-related flags.

3.3.4 Digital Data Processing

For digital geophysical mapping surveys, digital sensor data are recorded in the field by a data-acquisition system (i.e., a data logger or computer) and are typically processed and analyzed after the survey is completed. Qualified personnel and processing procedures are critical to producing accurate data.

The main stages of geophysical data processing and analysis for buried munitions are field editing, preprocessing, processing, target selection, advanced processing (if needed), quality control, and preparation of deliverables. Proper documentation should be maintained, including digital logs of the sequence of processing such as Oasis Montaj log files, spreadsheets, output from processing software, etc.

Data processing encompasses the steps necessary to convert raw survey data into meaningful position-correlated data. Data-processing steps include the following:

- Initial field check for data integrity/quality/coverage.
- Standard data analysis.
    - Leveling/drift correction.
    - Latency correction.
    - Base station magnetometer correction.
    - Heading correction.
    - Offset correction.
    - Coordinate conversion.
    - Gridding of data.
    - Selection of initial targets.
    - Preparation of geophysical maps.
- Standard quality-control procedures for data integrity.
    - Repeatability.
    - Along-line and across-line data coverage.
    - Background noise.

Advanced processing, which can sometimes be beneficial to improve project results, involves further steps beyond target selection to rank and discriminate selected targets. Considerable research in the buried munitions discrimination field is being conducted, and some new methods are producing positive results. The following items should be regarded as a brief list of the more established advanced processing topics currently being used and developed.

- Mass and depth estimates.
- Analysis of spatial anomaly shape, the response tensor, or aspect ratio.
- Model matching.
- Multichannel analysis (e.g., time-decay curve or amplitude and phase response).
- Merging of multisensor data.

Outputs from data analysis and interpretations will usually include maps of the interpreted data and databases of anomaly selections, which include coordinate information and anomaly characteristics. Targets are typically selected by setting a threshold that is dictated by the expected response of the targets of interest and the apparent noise level of the data set.

Analytical Tools

Geosoft Oasis Montaj Utilities. Oasis Montaj, provided and supported by Geosoft, Inc., is widely accepted and used by the UXO community to manage data. It is a platform for importing, viewing, processing, and sharing data images and geophysical data. The Oasis Montaj basic processing engine contains various tools for profile viewing, data manipulation, and mapping as described in the processing steps listed above. The UX-Detect module provides automated target selection.

Geosoft UX-Process Module. UX-Process is a tool set that has been developed through a partnership between Geosoft, the U.S. Army Corps of Engineers, and ESTCP. It contains tools for planning surveys, correcting common errors in data sets, and testing data quality and completeness. UX-Process runs from a menu in the Oasis Montaj platform.

Other Commercial Tools. Golden Software produces a software package called Surfer, which is widely used for geophysical processing and analysis. In addition, equipment manufacturers have their own proprietary instrument-specific software used to download data (e.g., Geonics dat61MK2, Geometrics MagMap2000). Many of these software systems can also be used to perform some basic processing steps. Output from these packages is ready for importing into advanced processing software. Specialized data-reduction and analysis tools have been developed throughout the R&D and contractor communities.

4.0 SOURCE DATA AND METHODS FOR ANALYSIS OF DETECTION TECHNOLOGIES

The geophysical technologies used to detect munitions are important to successful MR projects. The detection capabilities of geophysical technologies will determine how effective a response action is in removing all the hazardous munitions at a site, and the associated productivity and false-alarm rate will be dominant factors in the cost of a response action. Substantial effort has gone into characterizing these technologies. Their performance depends on the capabilities of the detection system and characteristics of the MR site. Site-specific conditions affecting performance can include the types and depths of munitions of interest; the density of munitions and other metal objects; and the local site geology, terrain, and vegetation. System characteristics that influence performance can include the sensitivity of the sensor element, as well as the operator, field procedures, positional accuracy platform effects, data processing, and target-selection methodology.

This chapter describes the two primary sources of data used in the analysis of detection systems, the Standardized UXO Test Sites and a survey of geophysical prove-outs (GPOs). The test sites, located at Aberdeen Proving Ground (APG), Md., and Yuma Proving Ground (YPG), Ariz., are used to extract primary performance parameters measuring the ability of technologies to detect munitions and screen out responses to nonmunition items under controlled but realistic conditions. The test sites are between 10 and 20 acres in size and contain a variety of munitions types. GPOs are constructed at most munitions response projects to test and select equipment and to validate system performance throughout the project (ITRC 2004). However, GPOs are typically much smaller than the test sites—usually less than an acre—and contain only the munitions of interest to the specific project. Recent GPOs were studied to obtain performance across a wider variety of conditions in a production environment.

4.1 Standardized Test Sites

4.1.1 Description of the Standardized Test Sites

The Standardized UXO Technology Demonstration Site Program is a joint effort of the U.S. Army and SERDP/ESTCP to provide a controlled but realistic environment in which to test munitions detection and discrimination technologies. The objective of the test sites is to remove site-specific variables, so that systems may be compared side by side. The goal of the program is to allow users and developers to demonstrate the range of applicability of specific MR technologies, gather data on sensor and system performance, compare results, and document relative cost and performance information. Two sites have been established, one at APG and the other at YPG. The two sites provide different soil types, vegetation cover, geologic background, and climate challenges to the demonstrators. Detailed information on the test sites is available at http://www.uxotestsites.org.

The UXO Standardized Sites were designed to imitate conditions commonly found at munitions response sites. While different in the challenges they present, the gross structure of the two sites is similar. The same types of inert munitions are emplaced at both sites (YPG contains the M754, a submunition not found at APG). To satisfy the research and development community and the technology demonstration community, the standardized sites are made up of four areas:

- The *Calibration Grid* allows demonstrators to test their equipment against known targets at known depths, build a signature library, and account for site-specific variables.
- The *Blind Test Grid* allows the demonstrator to blind test the detection capabilities of a sensor system while minimizing the effects of platform access, navigation concerns, and geolocation accuracy. Demonstrators are directed to grid square locations, which may contain munitions, clutter, or neither. The Blind Grid contains 400 grid cells (or opportunities) that are 1 m^2.
- The *Open Field* documents the performance of detection and discrimination systems in realistic conditions, where targets in unknown locations must be detected, located, and characterized. The APG open field is about 13.5 acres, and the YPG open field is about 14.5 acres. Many more munitions and clutter are in the open field scenarios than in the Blind Grid.
- The *Challenge Areas* (Mogul Area, Wet Area, and Wooded Area at APG and Mogul Area and Desert Brush Area at YPG) test systems in places where topography or overhead canopy make survey and navigation difficult. Analysis of the challenge areas is not pursued in this document.

Figure 4-1 provides an aerial view of the APG Standardized Site. The total site area is 18 acres, with the open field accounting for the largest portion.

4.1.2 Target Emplacement at UXO Standardized Sites

As part of the site preparation, the two sites were cleared of munitions and metallic clutter. Standard inert targets from a repository established by the U.S. Army Environmental Center; inert items recovered from actual munitions recovery efforts; and realistic clutter items, including munitions scrap and other common metallic field debris, were buried at precisely surveyed locations and orientations. Table 4-1 lists the inert munitions items buried at the two sites. All standard targets were checked for remnant magnetism prior to use and were degaussed if necessary.

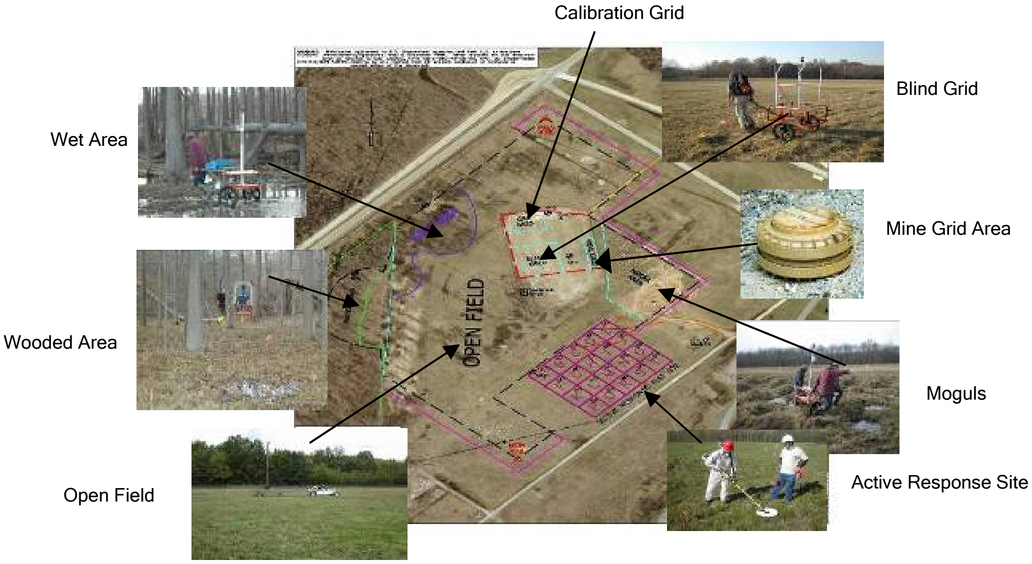


Figure 4-1. Aerial photograph of the APG Standardized Site. Total size is about 18 acres.

Table 4-1. Standard targets used in the test sites.

Type	Nomenclature	Length (mm)	Width (diameter, mm)	Weight (lbs)
20 mm	20 mm M55	75	20	0.25
37 mm	37mm M74	120	37	1.9
40 mm	40 mm MK II	179	40	1.55
40 mm	40 mm M385	80	40	0.55
M42	Submunition	62	40	0.35
BDU-26	Submunition	66	66	0.95
BDU-28	Submunition	97	67	1.7
57 MM	57 MM M86	170	57	6.0
MK118	MK118 ROCKEYE	344	50	1.35
60 mm	60 mm M49A3	243	60	2.9
81 mm	81 mm M374	480	81	8.75
M230	2.75" ROCKET	328	70	9.41
105 mm	M456 HEAT ROUND	640	105	19.65
105 mm	105 mm M60	426	105	28.35
155 mm	155 mm M483A1	803	155	56.45

4.1.3 Scoring Metrics at the Standardized Sites

The scoring of demonstrator performance at the test sites is conducted in two stages, the Response Stage and the Discrimination Stage. Response Stage scoring evaluates the ability of the system to detect emplaced targets without regard to ability to discriminate munitions from other objects that give rise to geophysical anomalies. The Discrimination Stage evaluates the demonstrator’s ability to correctly identify munitions as such and to reject clutter. Only the Response Stage is considered in any detail in this document. Several ongoing studies are addressing discrimination performance, but it is beyond the scope of this effort.

The primary scoring metrics from the standardized scoring considered in this analysis are probability of detection (Pd) and background alarm rate (BAR) or probability of background alarm (Pba). A munition is considered detected if the demonstrator indicates a geophysical anomaly within 0.5 m of the known true location. For ground-based systems, this accuracy should be well within the capability of modern positioning equipment. A small radius helps to ensure that correct one-to-one matches are made between the demonstrator anomalies and the emplaced targets, especially in areas where the density of either is high. It is not intended as guidance for reacquisition, which should be determined based on demonstrated performance of the system used.

Probability of detection is approximated by the percentage of emplaced munitions detected. That is, Pd equals the number of munitions detected divided by the number of munitions emplaced.

A background alarm is a location where a demonstrator indicates a geophysical anomaly, but no object is emplaced.[1] Two metrics are used for background alarms. In the Blind Grid, where the number of opportunities for a background alarms is known (i.e., the number of blank spaces is known), the metric is a probability of background alarm (Pba). For the open field, where defining the number of opportunities is problematic, a rate per unit area is used. That is, Pba equals the number of background alarms divided by the number of blank spaces in the Blind Grid. BAR equals the number of background alarms divided by the area of the open field.

To protect the number of items buried in the open field, the background alarm rate is calculated using unspecified units for the area of the open field and is normalized to the BAR of the demonstrator with the lowest number of background alarms. That is, this demonstrator is assigned a relative background alarm rate (rBAR) of 1; all other demonstrators will have rBAR greater than 1.

Pd and Pba are commonly plotted in receiver-operating characteristics (ROC) curves. The ROC curve in Figure 4-2 shows how detections and background alarms increase as the threshold is lowered (and more objects with lower signals are added to the declared

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[1] In other studies, background alarms may be referred to as false alarms. Because the sources of such alarms are unknown, and they may in fact correspond to metallic objects of interest, the test sites use the term “background alarm” instead of “false alarm,” and we have maintained this convention.

target list). In theory, the threshold can be lowered until the Pd and Pba both equal 1, in which case all measurements are declared to be targets. The symbol shows the point at which the demonstrator declared that weaker signals were all indistinguishable from noise and no further objects of interest could be detected. The vertical distance from this point to the top axis, where Pd equals 1, represents the missed targets. The key to understanding the performance drivers is to identify the types of targets in this band and the reasons that they were missed. The types of munitions on a site and the response action objectives and risk tolerance will determine whether missing these targets is acceptable. Although no Pba is measured for the open field, comparable plots of Pd versus BAR are used for that area.

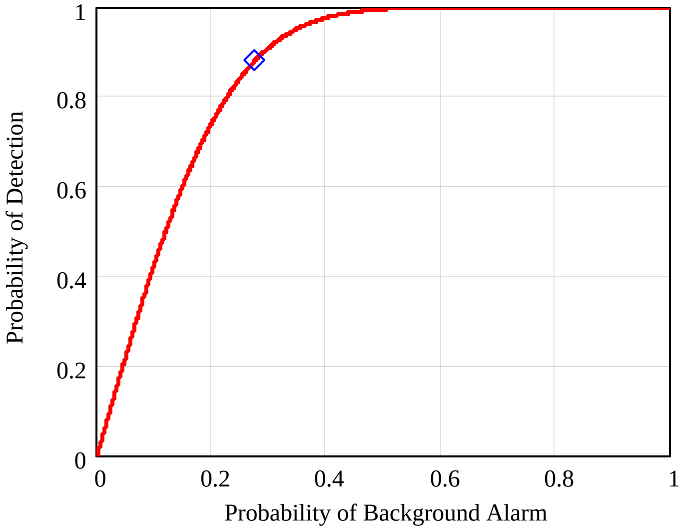

Figure 4-2. Example of a ROC curve. The red line represents the probability of detection versus probability of background alarm attained as the threshold for detecting a target is varied. At high thresholds, few targets are detected and few background alarms are registered. As the threshold is lowered, the number of detected targets and background alarms increase. Good sensors have a high probability of detection and a low false-alarm rate. The blue diamond indicates the threshold chosen by the operator as an appropriate threshold for detecting targets.

4.1.4 Additional Analysis of the Standardized Test Sites Data

The Institute for Defense Analyses (IDA) conducted an independent analysis of the data generated by the demonstrators at the UXO test sites. At the end of testing, demonstrators are required to submit a data set, including raw sensor data, processed geo-referenced geophysical data, and a target “dig” list. The dig list contains the location of each detection, magnitude of response (response stage reading), and a confidence level that the detected item is either a munition or clutter. Based on the final dig list, the AEC reviews the performance of the demonstrator and provides a standardized scoring report. The standardized scoring includes all the targets at each site for all the demonstrators.

Results are sorted by munition size (small, medium, or large) and depth bands. The IDA analysis extends the standardized scoring reports in three important ways: it provides scoring metrics that allow for more straightforward comparison to typical GPO results, it excludes more difficult or ambiguous targets, and it does a failure analysis on processed demonstrator data. Summary results of this work are presented in Chapter 5. A comprehensive companion report is in preparation by IDA.

A project manager or regulator may need information like Pd (and associated uncertainty) for each type of munition as a function of sensor type, depth, orientation, track spacing, and other factors that will affect performance. In this document, the test site data are parsed to examine these parameters. Our analysis scores the demonstrator dig lists with the same matching rules as used for the standardized scoring, but with a computer code independent of the one used by the AEC. All results presented here have been checked against, and match, the identical calculations for the standardized scoring, but additional analyses are presented here as well.

Several considerations influence this analysis of data from all the test sites and its application to specific MR sites:

- Although the number of munitions buried at the test sites is large compared with any other demonstration, the number of each individual item required to do meaningful statistical comparisons as a function of type and depth exceeded the resources available. Instead, realizations of particular munitions are grouped into “bins” of depth ranges where statistical measures are needed. Other analyses focus on individual item detections.
- The number and variety of targets at the standardized sites are not intended to represent a specific munitions response site, but instead to facilitate the analysis of a broad range of potential targets that maybe found at MR sites throughout the Unites States. Target-selection strategies will differ depending on the munitions of interest, and the requirement to detect such a wide variety of targets may have resulted in demonstrators choosing a methodology that is less than optimal for certain subsets of the targets.
- Because of the research, development, test, and evaluation focus, the process used during demonstrations at the standardized sites does not by its nature duplicate the process used at actual MR sites. Two effects seem most likely: (1) demonstrators in a research environment, not driven by cost and schedule constraints, can afford to be more careful on the test sites, and (2) the diversity of ordnance, which is generally greater than on any given cleanup, may drive demonstrators to field procedures and target picking methodologies that are more universal, but not necessarily optimal for any given subset of munitions.

4.1.4.1 Depth Considerations

Munition depth influences test designs and apparent results. In general, the larger the target item, the deeper it can be detected. The magnetic field falls off as a function of distance between the object and the sensor cubed. For electromagnetic devices, active systems with losses in both the transmit and receive directions, the falloff is even more severe. Other factors that can have a strong influence on the detectabilty of an item include the shape and orientation of the item relative to the geophysical instrument. For elongated items, such as most munitions, the difference in signal strength between horizontal and vertical orientations can be a factor of several times at common depths.

Until recently, detectability was often discussed in terms of “magnetic mass.” However, modeling of magnetic signatures has shown that for the same size and shape munition, mass has a negligible effect on the magnetic signature. That is, a solid or hollow shell of the same dimensions will have identical signatures. Similarly, items having the same mass but different shapes will have different signatures.

Based on work at Jefferson Proving Ground and other sites, the U.S. Army Corps of Engineers developed two empirical formulas that reflect how deeply a munitions item can be expected to be detected with existing magnetic and EMI technology (USACE 2003). More recently, the industry has adopted a single, simpler formula that correlates expected maximum detection depth with munitions diameter: depth = 11 × diameter, where depth is the distance to the top of the buried munition, and diameter equals the diameter of the munition’s minor axis. This relationship reflects a correlation observed across several sites and is not based on any underlying physical model. Because this formula has guided design of numerous GPOs and response action requirements, it will be used throughout this report as a benchmark for defining common target sets to allow for closer comparison among various tests. This relationship is used as a guideline, but is not an offical government or industry standard.

For buried munitions, which generally have an elongated shape, the defintion of depth can be important. Figure 4-3 shows identical munitions in three orientations. The difference in reported depth can be substantial, depending on whether the definition specifies the top, middle, or bottom of the object. The depth to the top of the item is typically used by the production community, whose primary interest is the depth at which an excavator can be expected to first encounter an item. On the other hand, the research community typically reports depth as the center of volume of the item. Regardless of orientation, the depth to center corresponds to the depth estimated from interpretating the geophysical measurements. The 11× equation above was developed using the depth to the top of the item. Most GPOs also specify depth to the top of the item. The standardized test site definitions are to the center of the item.

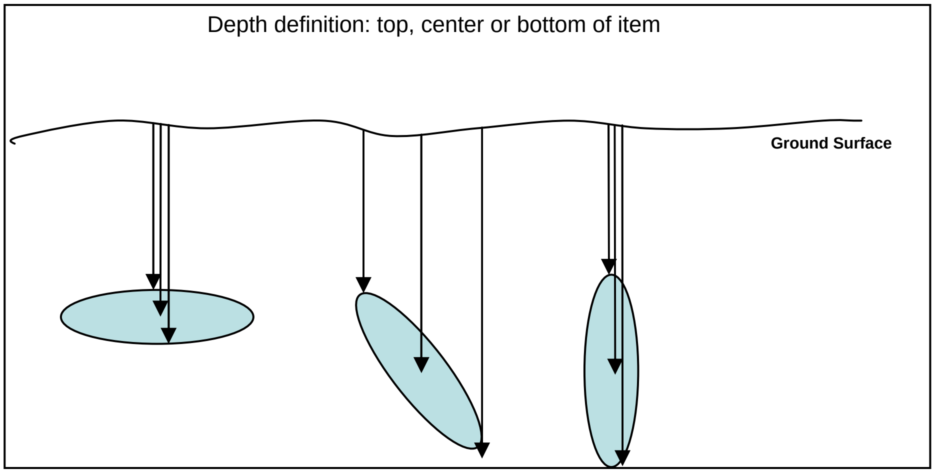

Figure 4-3. Depth definitions for munitions.

Figure 4-4 provides the depths of burial for the APG Blind Grid, with the COE 11× diameter rule-of-thumb guidance depth shown as a line. Note that while a significant number of targets are shallower than the 11× guidance, many are also deeper. (Compare this to the depth distributions of field GPOs in section 4.2.) Deeper targets were deemed necessary at the test sites to explore improvements gained in the development of new detection sensors. As a result of the depth distribution, however, overall probabilities of detection will be lower at the standardized sites than typical GPOs, where few if any targets are buried deeper than 11×. The exact depth distribution for the open field is restricted from public release, but it is qualitatively similar.

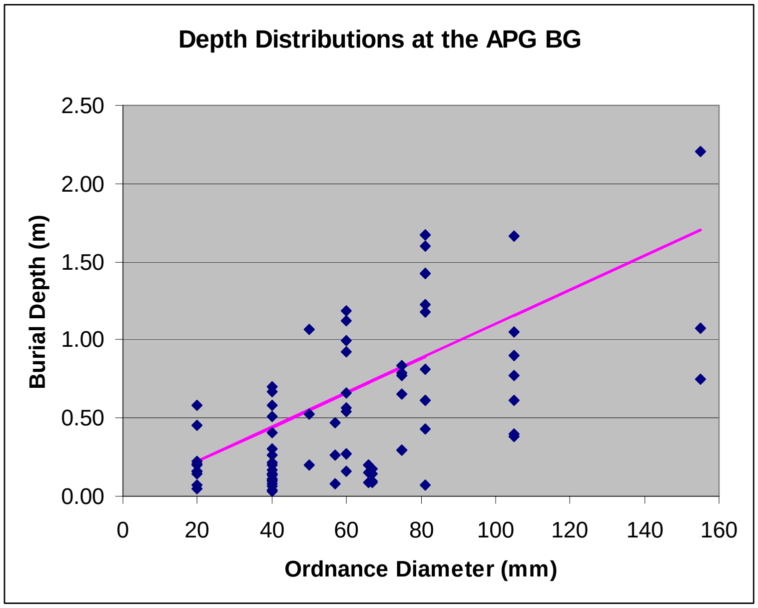

Figure 4-4. Depth distributions in the APG Blind Grid. The solid line shows depth = 11× diameter. Note the large number of targets of all types buried at greater depths.

4.1.4.2 Ambiguities

During this analysis we discovered that the standardized scoring process results in ambiguities for certain targets, particularly those that have been emplaced in clusters. Figure 4-5 shows two examples of target clusters. In the case on the left, many munitions and clutter items are emplaced within about a 5 m^2 area. The demonstrator declares a number of anomalies to be of interest, shown by the circles, but few of them correspond directly to the locations of emplaced munitions. With the scoring algorithm, this demonstrator gets credit for detecting only one of the seven munitions in the cluster. Although the entire cluster would undoubtedly be flagged in a real MR action, it is impossible to determine how many items were actually detected, due to the overlapping nature of the geophysical data.

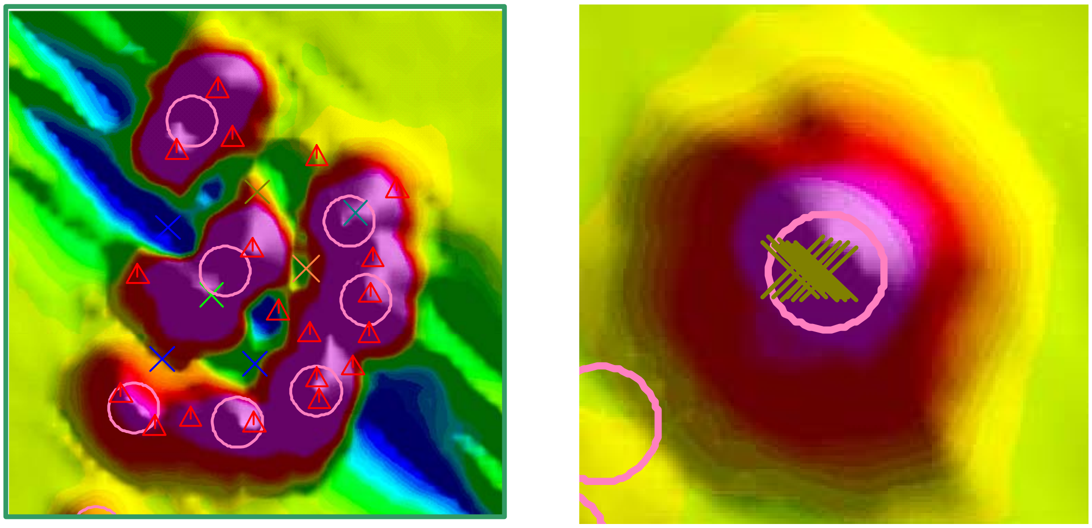

Figure 4-5. Image on the left shows a cluster of targets at APG. The X's represent emplaced munitions, the triangles represent emplaced clutter, and the O's represent demonstrator target declarations. The difficulty of doing one-to-one associations is evident. The image on the right shows a simulated burial pit with 10 items, all at virtually the same *x, y* location. For scale, the diameter of the circles is 1 m.

In the case shown on the right, 10 mortars were buried together to simulate a burial pit. The scoring software allows each anomaly to be associated with only one emplaced munition, so this demonstrator gets credit for detecting only 1 of the 10 mortars.

Other ambiguities arose for items emplaced in smaller groups. For example, a shallow buried 105 mm projectile was overlapping a large clutter item. Most demonstrators indicated a single target declaration that was nearer to the clutter item. The result was that few demonstrators were credited with detecting the projectile, although all were given credit for finding the clutter. Including the 105 mm projectile in the analysis resulted in the incorrect conclusion that this item was commonly missed at a depth where it is in fact easily detected. All the overlapping munitions and clutter have been identified and removed from the overall analysis presented in this report. They will be considered as special cases in the failure analysis.

4.1.4.3 Inaccessible Targets

At some times of the year, parts of the APG site were flooded and inaccessible to demonstrators. Targets from these areas, which were never surveyed, were removed from scoring for demonstrators who were affected. In addition, obstacles designed to present special challenges, such as a fence at APG, prevented access to some parts of the site by some systems, particularly the vehicle-towed arrays. For these systems, these inaccessible targets were similarly removed from the scoring.

4.1.4.4 Presentation of Results

Figure 4-6 plots top-level results from the test sites. For the open field, three points are plotted for each demonstrator. The bottom point is identical to the standardized scoring employed by the AEC/ATC. The middle Pd point represents the Pd with ambiguities and inaccessible targets removed. It is our best estimate of Pd against the ensemble of individual isolated targets for each system. The top point also removes those targets buried at depths that exceed 11× their diameter. This will allow for closer comparison to both typical GPO setups and to currently expected performance.

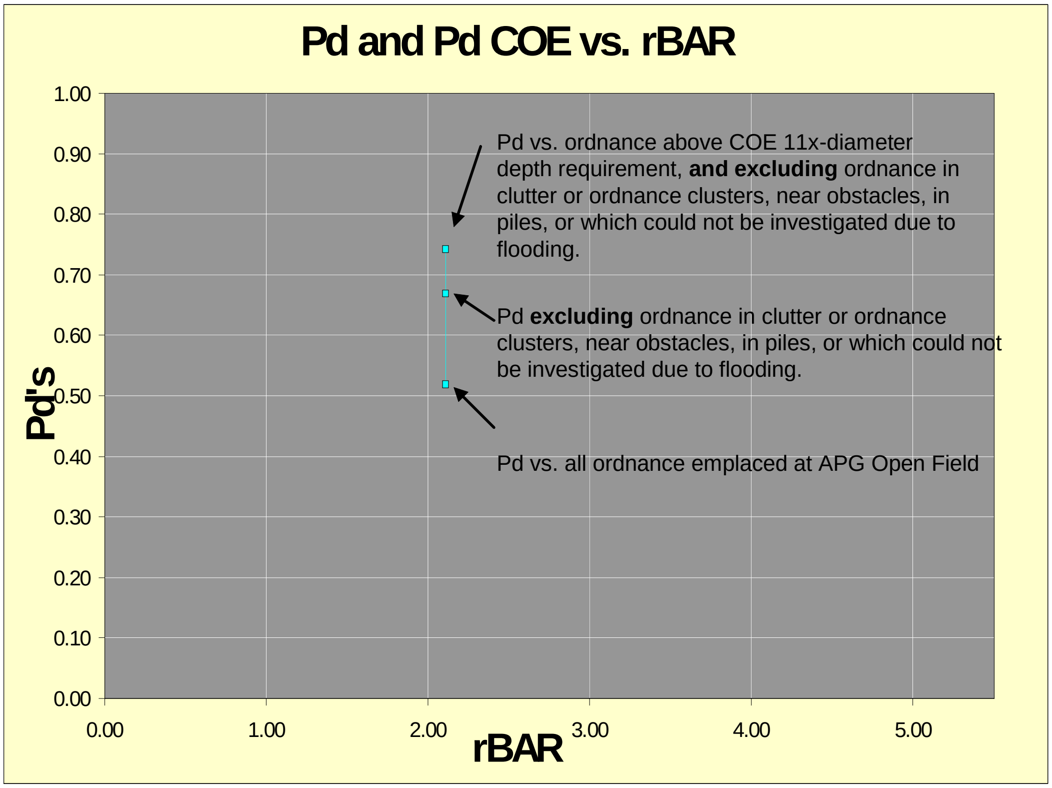

Figure 4-6. Example of standardized test site performance presentation. Pd is plotted against BAR. Good performers have high Pd and low BAR.

4.1.4.5 Failure Analysis

A group of demonstrators was identified as consistently better performing. Their overall detection rates were high, and their false-alarm rates were lower than some of the poorer performers. A failure analysis was performed on their processed sensor data from the APG open field to determine reasons for failures on munitions larger than 20 mm. Two types of failures were examined:

- Targets that were commonly missed by many of the better demonstrators.
- Targets that were commonly found, but were missed by one or more of the better demonstrators.

In each case, the target and the sensor data were examined. Targets were examined for nearby munitions or clutter objects that could shadow their signatures, depth and orientation effects, accessibility, and so forth. Sensor data were analyzed to look first for the presence of a signal that may have been mislocated, then for appropriate lane spacing, coverage gaps, locally high noise, appropriate thresholding, and typical data problems such as time lags and dropouts.

In a number of cases, performance among demonstrators using the same equipment varied greatly. Analysis of the poorly performing demonstrators was limited to examining their data for gross problems that would indicate instrument malfunction or inappropriate field techniques. Results of the failure analysis are discussed in Section 5.3.5.

4.1.5 Additional Metrics

Additional analysis looked in detail at the detectability of the various munitions types found at the test sites—in particular, how detectability is influenced by burial depth. Two metrics, which are applied to a subset of the targets from the standardized test sites that were commonly found in GPOs, were used for this analysis:

- **100% Detection Depth (DD_{100}) (meters)**—Deepest depth to which *all* instances of a particular munitions type were detected.
- **Maximum Detection Depth (DD_{max}) (meters)**—Deepest depth to which *any* instance of a particular munitions type was detected.

4.1.6 Signal-to-Noise Ratio

The test site data may also be used to determine the operating envelope of a system. In this case, the appropriate metrics relate to signal strength and the noise environment in which signals must be detected. Signal strength is often divided by system noise to produce a signal-to-noise ratio (SNR).

The signal is reported in the operating units of the instrument (i.e., nanoteslas for a magnetometer or millivolts for an EM-61). The appropriate number may be the maximum amplitude of a target signal or the signal integrated over its spatial extent, depending on how the targets will be selected. In either case, the signal strength for a selected target at a specified distance and orientation may be measured and compared to the associated noise measurements to establish the operating envelope of the system. The repeatability of this value may be used to determine whether the equipment is functioning correctly and being used properly.

Noise is commonly divided into sensor noise and environmental noise. Sensor noise, the fluctuation in sensor output in the absence of an external signal, is generally dominated by noise in the sensor electronics. Like signal, it is measured in the output units of the sensor. Depending on the application, the sensor noise may be reported as a peak-to-peak fluctuation, as a root mean square measurement, or using some other statistical measure. Because the sensor noise characteristics should remain stable with time, this quantity is relevant to determining whether a sensor is operating properly.

Environmental noise captures other external sources that also compete with the signal of interest. These sources can include electromagnetic interference, geological noise, or other types of clutter. This quantity is relevant to determining the signal that will be required to reliably detect the items of interest in the real-world environment of the site; that is, their signals must exceed the sum of the sensor noise and the environmental noise. In the case of munitions detection, the latter is generally the dominant contribution.

Signal and noise are often combined and reported as an SNR, a dimensionless quantity. The SNR will determine the level at which a threshold must be set to detect a target of interest and will thus govern the false-alarm rate. In general, SNRs of a minimum of 2 to 3 are required for reliable detection. Higher values will be required if any analysis is to be attempted.

4.2 Geophysical Prove Outs: State of the Practice

To determine usage and, to the extent possible, performance of geophysical equipment in field conditions, GPOs for 22 separate munitions response actions on 18 sites since the year 1998 were examined. The GPOs were conducted to support various actions such as engineering evaluation/cost analysis, and remedial investigation/feasibility study, and removal and remedial action activities. The sites, shown in Figure 4-7, span a variety of physiographic provinces. Site conditions range from flat and open to mountainous and wooded. Soil and geologic conditions vary from sandy with low iron content to rocky with high iron content. (Table C-1 in Appendix C shows the various actions considered at each site.)

Typically, as technologies are selected and evaluated for use on a munitions cleanup project, their performance is measured on a GPO, which provides a snapshot of capabilities against a target set of interest under local site conditions. Determining acceptable performance is done by measuring the ability to detect a set percentage of emplaced targets. While this can be useful for project-specific decisions, detection rates are strongly influenced by the distribution of types, depths, and orientations of munitions in the GPO test plot, and detection rates among GPOs are not easily compared. Where the data exist to do so, we have reanalyzed results from a number of recent GPOs in an attempt to understand these influences and present capabilities that are more directly comparable from one GPO to another, as well as to standardized test site data. The case studies discussed below were selected as representative examples of performance in the field at recently conducted (1998–2004) GPOs and removal actions.

Figure 4-.7 Installation locations examined in this study.

4.2.1 Performance in the Field—GPO Evaluations

To gain a deeper understanding of how various instruments performed, a more detailed analysis of a selected number of GPOs was conducted. The approach was to look at the GPO results in terms of "hits" and "misses" of seeded target items, compile various metrics based on these results, and evaluate (to the extent possible) what factors influenced the outcomes and ultimately the recommendations made. Twenty two GPOs were studied, comprising 27 test areas, 20 different instrument types, and involving 113 separate trials.

4.2.2 Characteristics of GPO Design

GPOs are used to test and verify the performance of geophysical systems used on munitions sites. Their two main purposes are selection of equipment and verification that the equipment configuration as used on the site is capable of meeting project objectives. Test sites are often selected to represent the range of soil, terrain, and vegetation conditions likely to be encountered on the overall site. The typical prove-out consists of a sampling of munitions items of interest buried at representative depths to which detection is required. The contractor is scored on the percentage of items detected. The scoring criteria for GPOs usually require the contractor to identify the target within a 1-meter radius. (Note that the standardized test site scoring criteria use a 0.5-meter radius.)

The distribution of munitions types, depths, and orientations have a great influence on any overall metric involving detection of the ensemble of items. Most GPOs are limited in area and number of items, typically on the order of an acre or less, with a few tens of emplaced items. (Table C-3 in Appendix C gives design characteristics of the various GPOs.) Figure 4-8 presents the types and distribution of munitions types seeded across all the test sites studied.

Figure 4-9 shows an example of munition distributions by size and depth at a representative GPO. Overlaid on the plot is a line showing the 11× depth typically required by the USACE. Note that most items are emplaced shallower than the USACE line. This plot is fairly typical. The notable exceptions were the Badlands Bombing Range and the Camp Beale GPOs. Figure 4-10 shows the Camp Beale seed chart for three test areas. For each munition type represented, except 57 mm hand grenades, at least one item was buried deeper than this depth line. The other GPOs often had one or two (occasionally more) munition types seeded below the 11× depth, but this was not consistent across the range of munitions diameters.

These depth considerations are important when comparing results from one site to another. Of the 27 GPO test areas that were considered here, 8 had no items deeper than the 11× line. For all the GPOs, of a total of 1,190 items across all munitions types, 90% are shallower the USACE line. In some cases, particularly for larger items, all samples are significantly shallower than 11×. These depth profiles are selected to support the requirements of the project and, as such, are often no deeper than the contractual requirement. However, the depth profiles are in great contrast to the depths often used in demonstrations, such as at the Standardized UXO Test Sites, where the depth profiles are designed to test the detection limits of the systems. For this reason, we have taken great care to define metrics and methods of comparison that allow for the most meaningful comparisons of systems, beyond simple percentage detected on an ensemble that differs from site to site.

4.2.3 GPO Metrics and Analysis

Data from several GPOs were compiled into a database from which the results could be reanalyzed in a uniform format, consistent with the analysis of the standardized test sites. All GPO analyses were based on the “hit and miss” results for the seeded munitions items of each GPO, as scored in the original project reports. The hit-and-miss results reflect the halos used in the initial scoring, which were usually 1 m. No attempt was made to rescore any results or reinterpret sensor data. The data required for such an exercise are generally not available. Metrics from the analysis of test sites were applied to the extent possible to the GPO data to allow comparison of controlled and real-world examples.

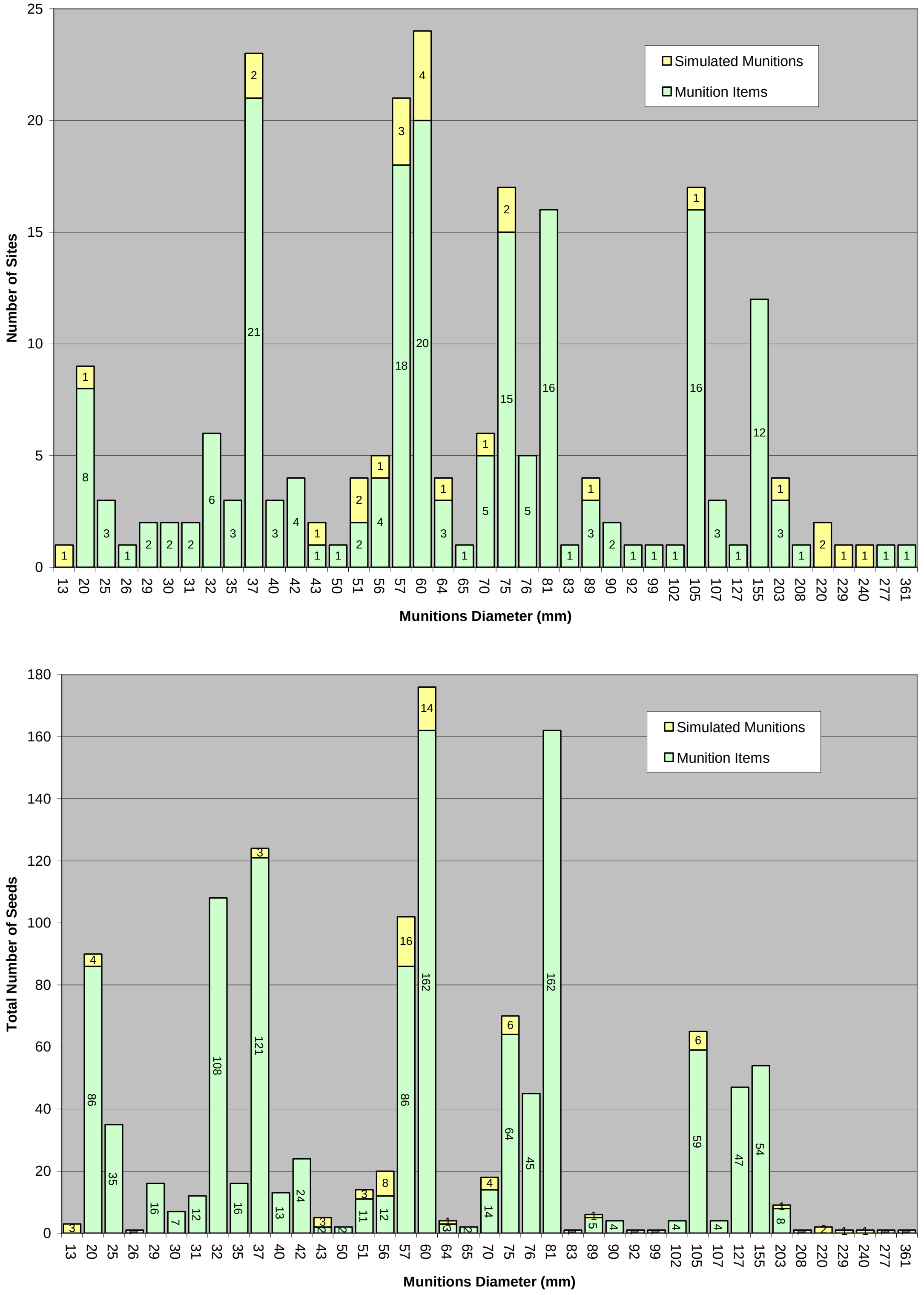

Figure 4-8. Muntion types seeded at GPO sites by number of sites (top) and by number of items (bottom)

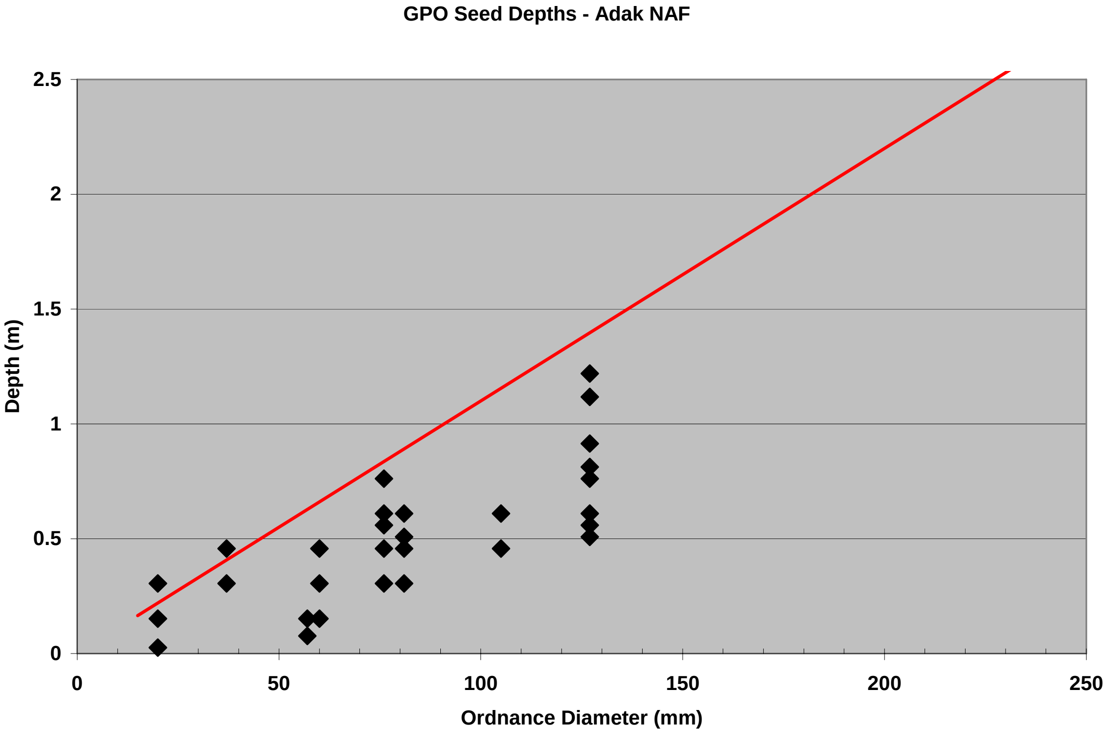

Figure 4-9. ADAK GPO seed items depth versus munitions size. (Depth distributions that include few or no items below the 11× line are typical.)

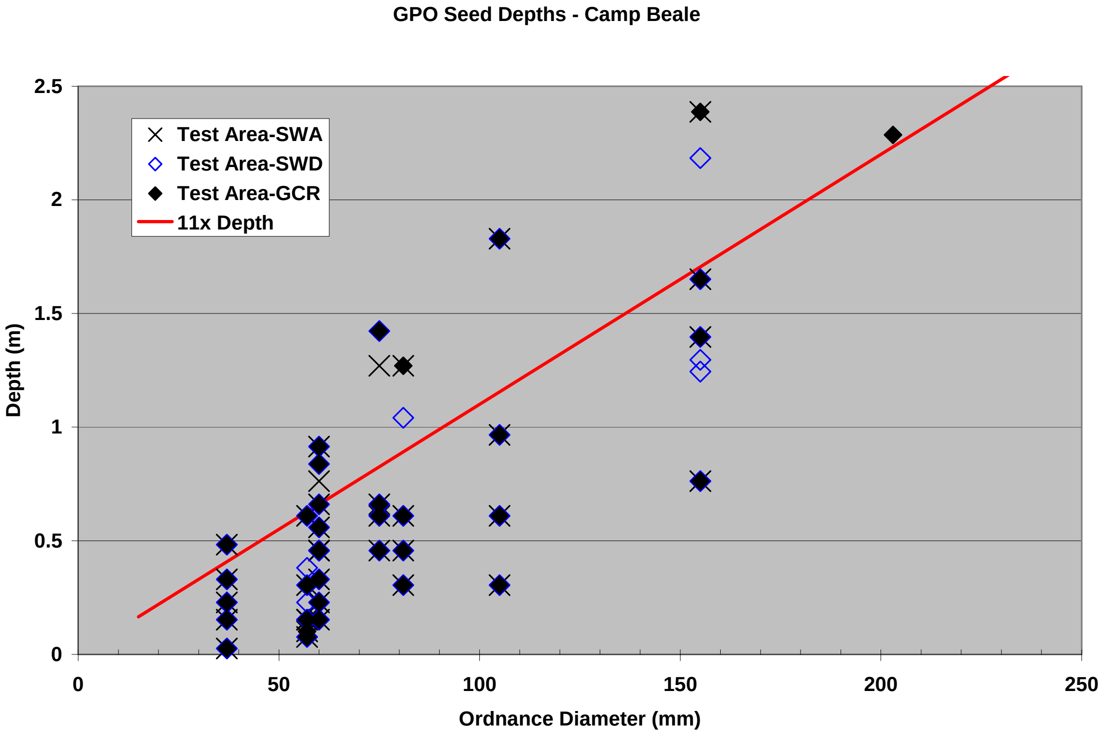

Figure 4-10. Camp Beale GPO seed depths versus munitions size.

5.0 DETECTION TECHNOLOGIES

5.1 Goal, Scope, Limits of this Analysis

This chapter documents the performance of UXO geophysical detection technologies as they have been demonstrated on test sites and geophysical prove-outs (GPOs). Data from the Standardized UXO Test Sites at Aberdeen Proving Ground and Yuma Proving Ground were analyzed to extract performance parameters as described in Chapter 4. These parameters are used to compare test site performance with that demonstrated at GPOs, which provide a broader spectrum of real-world technology evaluations. This chapter documents what can be expected in detection system performance under near-ideal conditions and how that performance translates and degrades as real-world challenges are encountered.

The two primary instruments in use are magnetometers and electromagnetic induction (EMI) devices. The most common EMI devices are the time-domain EM61 and its variants; the most common digital magnetometer is the cesium-vapor G-858. Detailed analysis is limited to these two instruments, plus the frequency-domain GEM-3 EMI, which records data and affords the opportunity of retrospective analysis. Since no data are recorded for post-test analysis, mag (magnetometer) and flag detection systems (i.e., the Schonstedt) are considered only at the level of reported detections and false alarms.

5.2 Theoretical Performance of Commonly Used Sensors

Whether a target can be detected is a function of the strength of its signal and the noise environment in which that signal must be detected, as measured by the signal-to-noise ratio (SNR). Signal strengths for munitions are readily estimated from physics models for magnetic and electromagnetic sensors. Noise, which has contributors from many sources, can be more complicated. For most geophysical surveys, the main contributors to noise will be local geologic background and metallic clutter. However, if sufficient care is not taken, this can be overtaken by platform and motion noise or geolocation and timing errors, which essentially function as noise sources. In either case, the intrinsic sensor noise is generally not the limiting factor for UXO geophysics.

Theoretical signal levels for a number of targets of interest are calculated for magnetometer and EMI sensors. Comparing these signal levels to the appropriate noise values for a particular site or system will give the theoretically achievable performance. Many implementation factors will result in observed performance that does not match these predictions—examination of the plots shows that theoretical detection limits are far deeper than the commonly observed 11× diameter rule. Nevertheless, the theoretical values are useful as a benchmark for comparison of observed performance and as a basis for checking extraordinary performance claims. In other words, an object cannot be detected if its signal is lower than the noise it competes with. At that point, target selection essentially transitions to random guessing.

5.2.1 Magnetometry

Theoretically achievable magnetometer performance can be predicted from a model of the physical response of the object of interest, shown in Figure 5-1. The curves represent the falloff in magnetic field as the distance between the sensor and the target increases. This signal will be invariant with regard to local site conditions. What will change is the local noise background, indicated by the horizontal lines. As the noise floor increases, the distance at which an object can be detected will decrease. The sensor electronic noise is indicated by the horizontal lines at 0.1 nT for a cesium vapor magnetometer and 1 nT for a flux gate (Barrow and Nelson 1998, DiMarco and Barrow 1996). These noise figures are meant to be rough order-of-magnitude estimates for sensor classes as used in the field, rather than factory specifications for any particular sensor brand. The sensor noise is almost never the limiting factor in detection for munitions applications using magnetometry.

For a quiet site, with noise in the 1 nT range, the 105 mm is theoretically detectable to a distance of 4 m.[1] Of course, this is the best case. It represents a single measurement that just exceeds the noise. Most detection schemes rely on more than one sensor reading significantly above background, with SNR of 2 or more. At most sites, the noise floor is higher (5–10 nT). At 10 nT, even the theoretical detectable range of the 105 mm is reduced to about 2 m; for the 20 mm, it is only a few tens of centimeters. In addition, field conditions degrade the quality of the sensor data with motion noise, location uncertainties, data-collection gaps, and the like. All these factors will cause performance to degrade.

5.2.2 Electromagnetic Induction

Figure 5-2 shows an analysis performed for an EM61 Mk2. This analysis is somewhat more complex due to the characteristics of the transmitted field and the effects of an active sensor on conductive properties in the ground. But for a quiet site, detectability of several example munitions types is shown for SNR of 3. In essence, the plot shows the peripheral vision of the EM61. Each munitions type is considered at the surface and increasing depths. The distance from the centerline of the EMI sensor coil to the point at which the SNR falls below 3 is calculated. At a depth of 0.25 m, all the items are detectable, and the larger ones may be detected at a considerable distance outside the 1 m coil width of the instrument. When the depth is increased to 1 m, only the largest three

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[1] Nanoteslas (nT) are the units used to measure magnetic fields. Earth's magnetic field is approximately 50,000 nT, and the perturbations caused by magnetic objects are typically measured relative to Earth's field. Geophysical measurements commonly show perturbations of a few nanoteslas for small objects to a few thousand nanoteslas for large bombs.

items, the 60 mm and 81 mm mortars and the 105 mm projectile, are detectable at all, and the 60 mm mortar is only seen within the coil width.

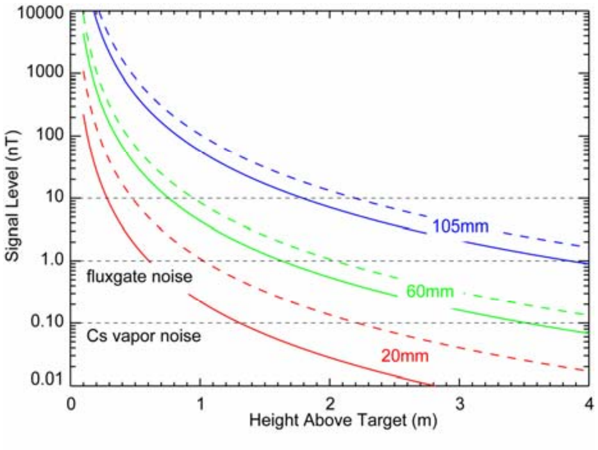


Figure 5-1. Theoretical performance for magnetometer system. The solid curve represents the target at its least favorable orientation (long axis horizontal) and the dashed curve at its most favorable orientation (long axis vertical). The theoretical detection threshold is where the signal curve crosses the noise line. Sensor is assumed to be directly over the target and the height above target is the sum of the target depth and the sensor height above ground. (Figure courtesy of AETC, Inc.)

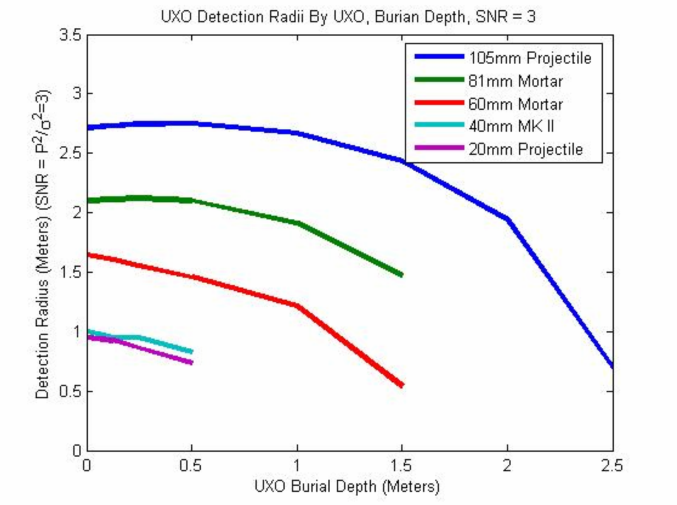


Figure 5-2. Theoretical performance of an EM61 Mk2 system for a required SNR = 3. The detection radius is measured from the center of the coil. (Figure courtesy of Duke University.)

This analysis does not reflect noise introduced by surveying under field conditions or clutter and geology. It speaks only to the detectability of the objects. Although this analysis does not allow for a rigid determination of the detection envelope for any specific system or implementation, it does provide a useful point of departure for analyzing field data and understanding the impact of real-world effects compared to the ideal. It also provides a bar against which extraordinary performance claims may be measured, as well as a performance delta that is potentially exploitable by future research and development.

5.3 Performance at Standard Test Sites

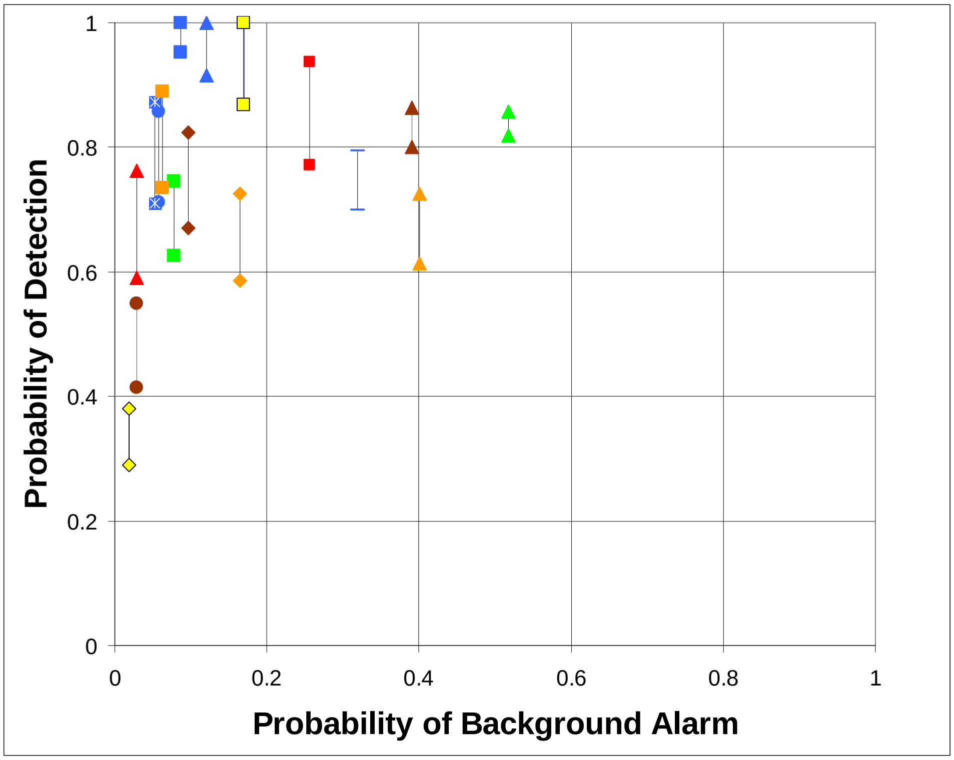
5.3.1 Blind Grid—Standard Test Sites

Figures 5-3a and 5-3b present results from the Blind Grids (described in detail in Chapter 4), which capture detection capability of the sensors without contributions related to site coverage and geolocation capability. Top-level results from the Blind Grid are shown as single points along the receiver operating characteristic (ROC) curve. Each line represents a different demonstrator. Each demonstrator made an individual determination of a targe-selection philosophy, which will determine where the observed probability of detection/probability of background alarm (Pd/Pba) will fall on the overall ROC curve that defines the Pd/Pba trade-off for each system. The probability of detection on the vertical axis is the percentage of the ensemble of targets that were detected at the threshold specified by each demonstrator for differentiating target signals from noise or background. Two probabilities of detection are displayed for each demonstrator. The lower symbol indicates the percentage of all targets that were detected; the upper symbol indicates the percentage of targets detected whose depth does not exceed 11 times their diameter. The probability of background alarm on the horizontal axis represents the relative number of background alarms, points at which no target is present, but the demonstrator declared a detection.

Under the highly controlled conditions of a gridded test, where the locations of the potential targets were known, both EM61-based systems (blue symbols in Figures 5-3a and 5-3b) and GEM3-based systems (yellow symbols in Figures 5-3a and 5-3b) were capable of detecting all targets seeded in the standardized sites to a depth of 11 times their diameter. Several systems detected more than 90% of *all* targets, regardless of depth.

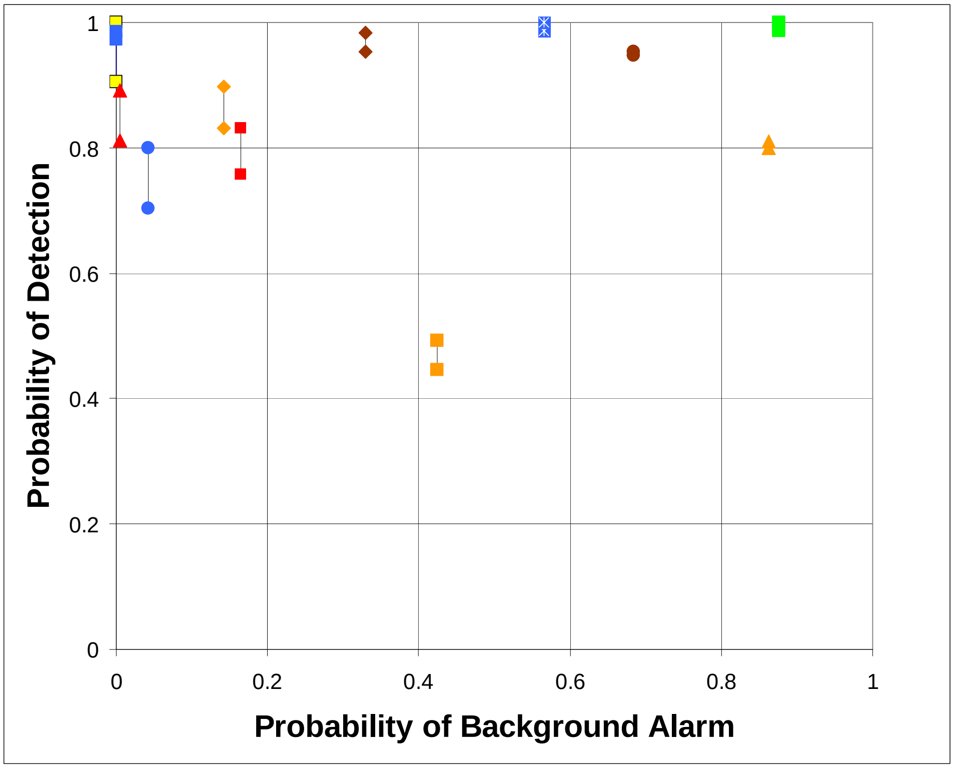
Few magnetometers were demonstrated on the Blind Grids at APG and YPG. Mag-and-flag (and the one EM-and-flag by Parsons) systems are plotted in orange. DGM systems are in dark brown. At APG, mag and flag found no more than 70% of the targets even when the 11 times diameter rule-of-thumb depth was considered. The Gtek TM4 DGM system was able to find more than 80% of the munitions down to 11 times their diameter with a lower FAR than either of the mag-and-flag systems.

At YPG, the HFA mag-and-flag system approached 90% Pd, and had half the background alarm rate (BAR) of the Gtek TM4 DGM type system. In the open field portion of the YPG, HFA would again have roughly half of the BAR of the Gtek system, but at a lower Pd. Neither HFA nor Gtek falls within the low BAR section of the YPG results. Another DGM system demonstrated in the open field, the NRL MTADS, would surpass the HFA system by about 20% yet have the same BAR. (Note that the Parsons mag-and-flag system had a higher BAR than the HFA system on the Blind Grids at YPG and APG.)



GEM3 Type	☐	NRL	3x GEM3	Towed Array
	◇	GeoPhex	GEM3E	Towed Array and Push Cart
EM61 Type	■	TTFW	EM61MKII	Push Cart
	◆	NRL	3x EM61 Variant	Towed Array
	▲	NAEVA	EM61MKII	Towed Array
	●	Shaw	EM61MKII	Push Cart
	☒	GeoCenters	EM61MKII	Towed Array
	—	Black Hawk	EM61MKII	Pull Cart
Other EMI	■	Gtek	TM5 EMU	Sling
	▲	Zonge	nanoTEM3D	Push Cart
Fused EMI and Mag.	■	GeoCenters, 2002	STOLS, Fused EM & Mag	Towed Array
	▲	Black Hawk	Fused EM and Mag	Pull Cart
Magnetometer Type	—■—	NRL (low threshold)	8x G822 Variant	Towed Array
	---■---	NRL (high threshold)	8x G822 Variant	Towed Array
	◆	Gtek	TM4 (G822A)	Sling Array
	▲	Black Hawk	4x G822	Pull Cart
	●	GeoCenters	5x G822A	Towed Array
Mag/EM and Flag	■	Parsons	EM61MKII	Analog Push Cart (EM and Flag)
	◆	HFA	Schonstedt	Analog Hand Held (Mag and Flag)
	▲	Parsons	Schonstedt	Analog Hand Held (Mag and Flag)

Figure 5-3a. Blind Grid Results from the APG standard test site. The lower marker is the probability of detection against all targets. The higher marker is the probability of detection against only those targets shallower than 11 times their diameter.



GEM3 Type	☐	NRL	3x GEM3	Towed Array
	◇	ERDC	GEM3	Push Cart
EM61 Type	■	TTFW	EM61MKII	Push Cart
	◆	NRL	3x EM61 Variant	Towed Array
	●	Shaw	EM61MKII	Push Cart
	⊠	GeoCenters	EM61MKII	Towed Array
	▬	Black Hawk	EM61MKII	Pull Cart
Other EMI	■	Gtek	TM5 EMU	Sling
	▲	ERDC	EM63	Push Cart
Fused EMI and Mag.	■	GeoCenters	STOLS, Fused EM and Mag	Towed Array
	▲	Black Hawk	Fused EM and Mag	Pull Cart
Magnetometer Type	■	NRL	8x G822 Variant	Towed Array
	◆	Gtek	TM4 (G822A)	Sling Array
	▲	Black Hawk	4x G822	Pull Cart
	●	GeoCenters	5x G822A	Towed Array
	▬	ERDC	TM4	Sling
Mag/EM and Flag	■	Parsons	EM61MKII	Analog Push Cart (EM and Flag)
	◆	HFA	Schonstedt	Analog Hand Held (Mag and Flag)
	▲	Parsons	Schonstedt	Analog Hand Held (Mag and Flag)

Figure 5-3b. Blind Grid Results from the YPG standard test site. The lower marker is the probability of detection against all targets. The higher marker is the probability of detection against only those targets shallower than 11 times their diameter.

High probability of detection and low background alarm rate were consistently achieved by the same demonstrators. Many demonstrators performed far worse, even those using systems based on the same sensor technologies. These results suggest that most targets exhibit sufficient signal strength to be detectable to depths of interest by currently available technology. Failures of similar systems to achieve equivalent performance suggest that poor field technique or improper target selection can negate a sensor’s inherent capabilities. Specific data problems are considered in more detail below.

5.3.2 Open Field—Standard Test Sites

The Pd in the open field ROC, shown in Figure 5-4, is scored in three ways. For each demonstrator, the lowest probability of detection shown is that calculated on all ordnance buried at each site. In the course of this analysis, it was discovered that the standard scoring results in ambiguities for certain targets, particularly those that have been emplaced in clusters (see Chapter 4 and Appendix A). In addition, at some times of the year, parts of the APG site were flooded and inaccessible to demonstrators. The middle probability of detection point in Figure 5-4 represents the probability of detection with ambiguities and inaccessible targets removed. It is our best estimate of probability of detection against the ensemble of individual isolated targets for each system. The upper symbol for each demonstrator additionally removes those targets buried deeper than 11 times their diameter and is comparable to the upper symbol in the Blind Grid results. In the cases where only two marks are shown, the probability of detection against all targets and the probability of detection with clusters and unsurveyed targets removed rounded to the same point. The relative background alarm rate (rBAR) does not vary (it is only calculated in the first step where the entire truth is considered for matching).

We would expect the open field results to exhibit a wider variation in performance among similar systems and a degradation in overall performance because gaps in site coverage and geolocation problems present additional potential error mechanisms. Indeed, the probabilities of detection for the top demonstrators do decrease from the Blind Grid to the open field, with probability of detection for the better demonstrators falling by about 10%. Note, however, that the relative positions of most demonstrators in the Pd versus BAR plots remains the same going from the Blind Grid to the open field. Consistency of performance is also evident from APG to YPG (Figure 5-5).

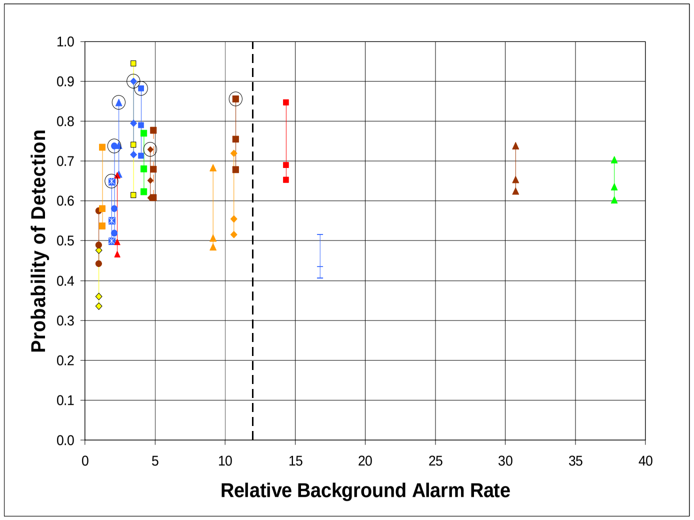


Figure 5-4a. ROCs for the APG open field standard test site. The area to the left of the dotted line is blown up in Figure 5-4b. The black circles indicate the demonstrators whose results were used to plot the detectability by depth graphs that follow.

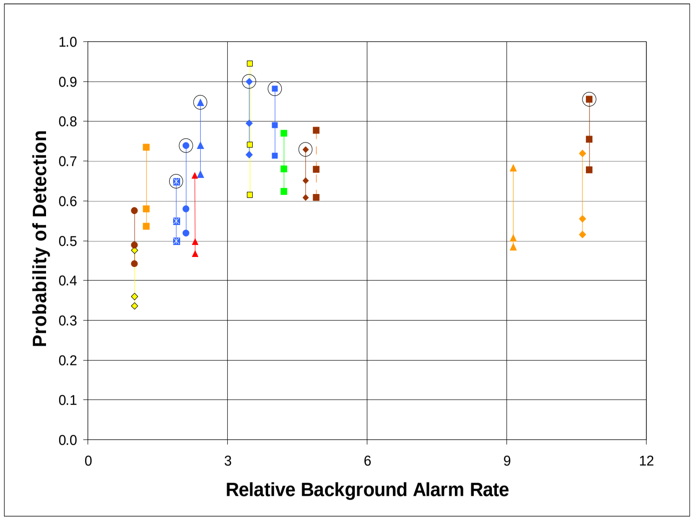
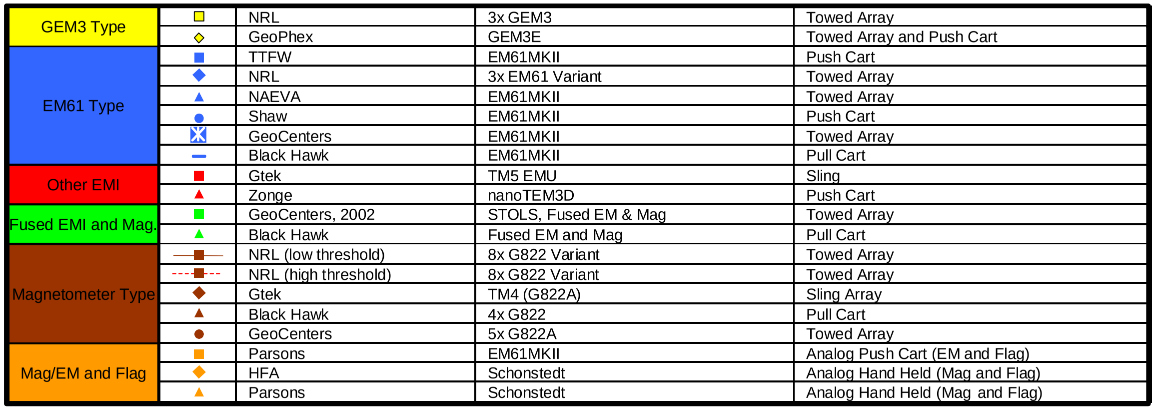


Figure 5-4b. ROCs for the APG open field standard test site zoomed to expand the low rBAR region. The lowest probability of detection is scored against all targets, the middle point is scored removing the ambiguities and inaccessible areas and the highest probability of detection also removes the items deeper the 11× diameter.



GEM3 Type	□	NRL	3x GEM3	Towed Array
	◇	GeoPhex	GEM3E	Towed Array and Push Cart
EM61 Type	■	TTFW	EM61MKII	Push Cart
	◆	NRL	3x EM61 Variant	Towed Array
	▲	NAEVA	EM61MKII	Towed Array
	●	Shaw	EM61MKII	Push Cart
	⊠	GeoCenters	EM61MKII	Towed Array
	—	Black Hawk	EM61MKII	Pull Cart
Other EMI	■	Gtek	TM5 EMU	Sling
	▲	Zonge	nanoTEM3D	Push Cart
Fused EMI and Mag.	■	GeoCenters, 2002	STOLS, Fused EM & Mag	Towed Array
	▲	Black Hawk	Fused EM and Mag	Pull Cart
Magnetometer Type	—■—	NRL (low threshold)	8x G822 Variant	Towed Array
	--■--	NRL (high threshold)	8x G822 Variant	Towed Array
	◆	Gtek	TM4 (G822A)	Sling Array
	▲	Black Hawk	4x G822	Pull Cart
	●	GeoCenters	5x G822A	Towed Array
Mag/EM and Flag	■	Parsons	EM61MKII	Analog Push Cart (EM and Flag)
	◆	HFA	Schonstedt	Analog Hand Held (Mag and Flag)
	▲	Parsons	Schonstedt	Analog Hand Held (Mag and Flag)

Figure 5-4c. Key to Figures 5-4a and 5-4b

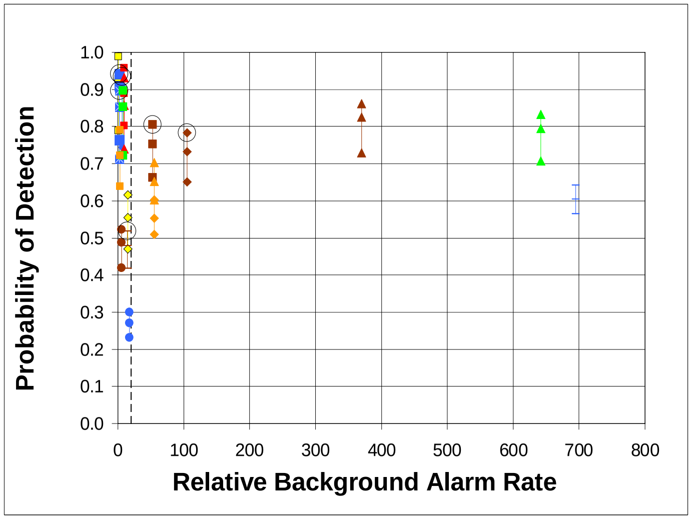


Figure 5-5a. ROCs for the YPG open field standard test site. The area to the left of the dotted line is blown up in Figure 5-5b. The black circles indicate the demonstrators whose results were used to plot the detectability by depth graphs that follow.

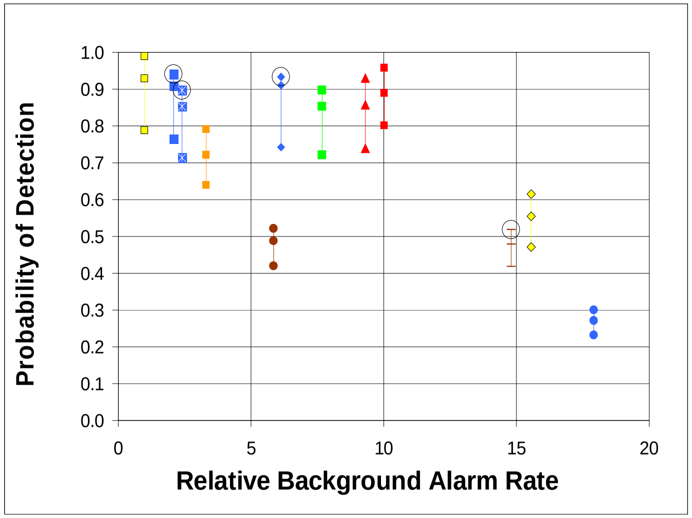


Figure 5-5b. ROCs for the YPG open field standard test site zoomed to expand the low rBAR region

GEM3 Type	□	NRL	3x GEM3	Towed Array
	◇	ERDC	GEM3	Push Cart
EM61 Type	■	TTFW	EM61MKII	Push Cart
	◆	NRL	3x EM61 Variant	Towed Array
	●	Shaw	EM61MKII	Push Cart
	☒	GeoCenters	EM61MKII	Towed Array
	–	Black Hawk	EM61MKII	Pull Cart
Other EMI	■	Gtek	TM5 EMU	Sling
	▲	ERDC	EM63	Push Cart
Fused EMI and Mag.	■	GeoCenters	STOLS, Fused EM and Mag	Towed Array
	▲	Black Hawk	Fused EM and Mag	Pull Cart
Magnetometer Type	■	NRL	8x G822 Variant	Towed Array
	◆	Gtek	TM4 (G822A)	Sling Array
	▲	Black Hawk	4x G822	Pull Cart
	●	GeoCenters	5x G822A	Towed Array
	–	ERDC	TM4	Sling
Mag/EM and Flag	■	Parsons	EM61MKII	Analog Push Cart (EM and Flag)
	◆	HFA	Schonstedt	Analog Hand Held (Mag and Flag)
	▲	Parsons	Schonstedt	Analog Hand Held (Mag and Flag)

Figure 5-5c. Key to Figures 5-5a and 5-5b

5.3.3 Detection by Ordnance Types at the Standard Test Sites

Figure 5-6 shows the depths of 100% detection (solid bar) and the depth of the deepest target detected (whisker) in the open field at APG for three different ordnance types. For reference, each plot indicates the 11× depth. The 20 mm, 60 mm, and 155 mm were selected as examples of small, medium, and large ordnance. Similar plots for other ordnance types found at the standard sites are provided in Appendix A. Similarities and inconsistencies between similar items are summarized.

The 100% detection depth is nearly always shallower than the 11× line. However, the depth of deepest detection exceeds the 11× depth in most cases for all ordnance types. Since the analysis is by necessity based on one pass over a modest number of each ordnance type, the 100% detection depths are particularly susceptible to statistical effects. One “unlucky” miss of an ordnance item at shallow depth can significantly alter the 100% detection depth. Nevertheless, we highlight some trends from these plots.

5.3.3.1 Small ordnance—20 mm

The 20 mm plot illustrates difficulties encountered by all demonstrators in detecting this item. In general, better overall demonstrators did not fare significantly better in detecting 20 mm projectiles. The 100% detection depth (i.e., shallowest miss distance) is very shallow and even at the surface for some demonstrators. All demonstrators experienced a high variability between the 100% detection depth and the deepest 20 mm detected, indicating that these items can be detected, but not reliably. To a large extent, this likely depends on whether the sensor passed over or very near these small items with small signatures. If this is the case, higher data densities may improve detection of these small items.

The other small item analyzed (and shown in Appendix A) is the 40 mm projectile. The trends are similar to what is observed for the 20 mm, but less pronounced. Again, there is a large difference between the depths of 100% detection and the deepest item detected. However, for the 40 mm projectile, the 100% detection depth for a few of the best demonstrators approached the 11× line, which is not the case for the 20 mm.

5.3.3.2 Medium ordnance—60 mm

The 100% detection depth for the 60 mm approaches, but does not reach, the 11× line for the best demonstrators. Two EMI systems detected some of the deeper items, and the DGM magnetometer and magnetometer-EMI fused systems all had at least one detection well deeper than the 11× line. In addition, this plot shows that the deepest 60 mm detected by the mag-and-flag systems is systematically shallower than those detected by the other magnetometer-containing systems.

The other medium ordnance analyzed was the 81 mm mortar. It is shown in Appendix A. With the exception of one towed-array magnetometer system, which detected 100% of the 81 mm mortars to a depth of about 1.1 m, the results are similar to the 60 mm. A few demonstrators exhibited 100% detection depths that approach the 11× line, and most detected at least one item at depths well in excess of 11×.

5.3.3.3 Large ordnance—155 mm

Across the board, the 100% detection depths for EMI and magnetometer systems are comparable for the 155 mm. However, the deepest 100% detection depth is attributed to a magnetometer. Within the EM61s, there is a tremendous difference in 100% detection depths (from 0.25 m to 1.5 m), but relative consistency among the deepest item detected (all 1.7 m or greater). The 100% detection depths and deepest item detected for mag-and-flag operators are well below those seen for the better DGM magnetometer-containing systems.

The other large ordnance analyzed was the 105 mm. It is shown in Appendix A. Three better demonstrators achieved 100% detection depths in excess of 11×, but in general the depths to which 100% of 105 mm munitions were detected were proportionally shallower than for the 155s.

5.3.4 Detectability Plots for the Standardized Test Sites

Figures 5-7 through 5-12 capture the detectability demonstrated at the standard sites for a variety of ordnance types as a function of depth. Analysis done for the EM61 and magnetometer systems reflects the detectability in the noise environment at each site. The hit-and-miss results of individual item detections for the better demonstrators were combined to produce overall detectability analyses for each instrument type. The source data were limited to better demonstrators in an attempt to define the operating envelope of properly deployed equipment (Table 5-1). Demonstrators who experienced systematic problems due to poor field technique, uncorrected noise, geolocation problems, improperly set thresholds, and the like were deliberately excluded.

Table 5-1. Technology and demonstrators.

Technology	APG	YPG
EMI (EM61MKII)	NRL MTADS GeoCenters Shaw NAEVA TTFW	NRL MTADS GeoCenters TTFW
Magnetometer	NRL MTADS Gtek	NRL MTADS Gtek ERDC

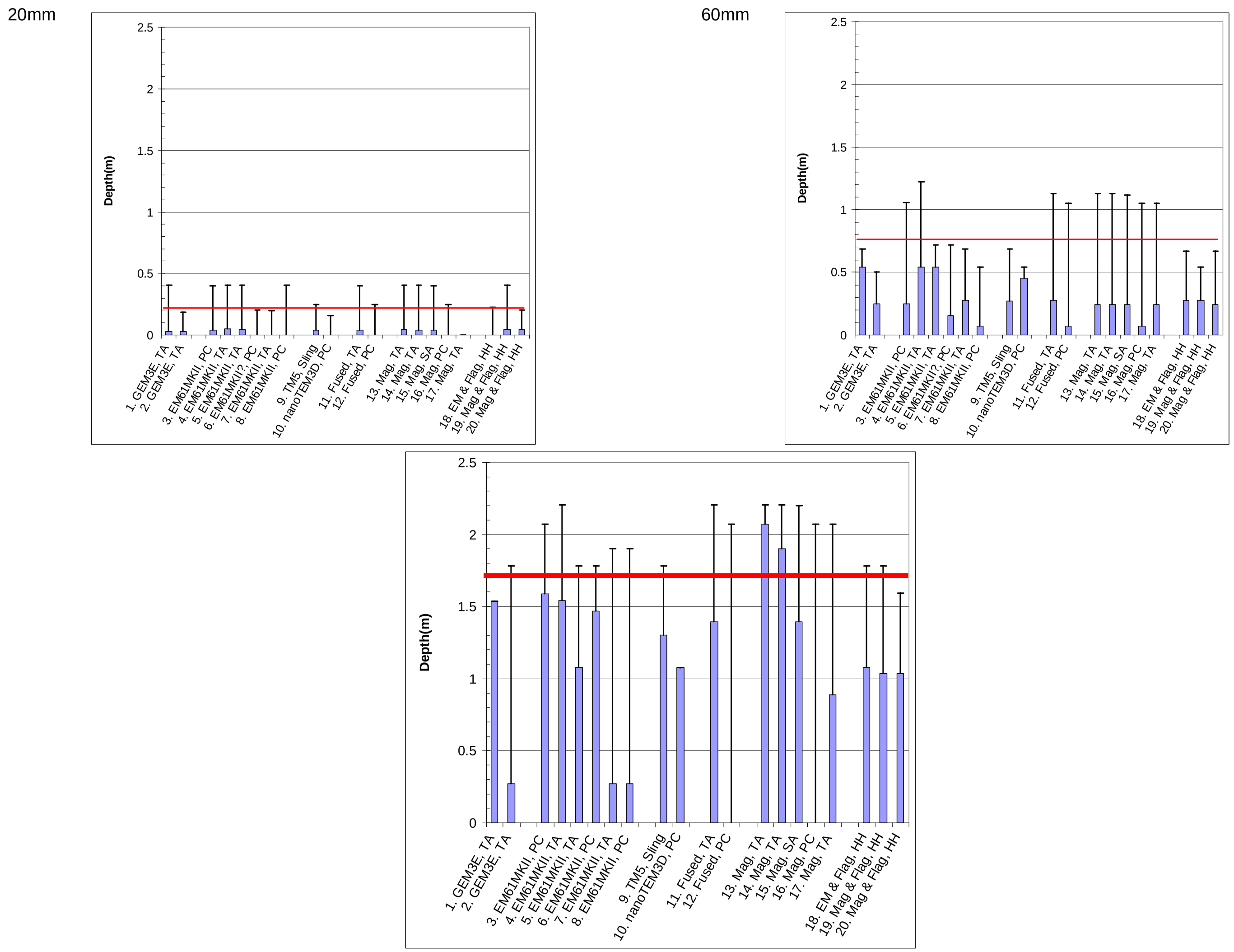


Figure 5-6. Performance at the APG standard test site detecting 20 mm projectiles, 60 mm mortars and 155 mm projectiles. The bars indicate the depth at which 100% of the each ordnance type were detected by each demonstrator. The black lines terminate at the deepest item detected. The red horizontal lines indicate the 11× depth.

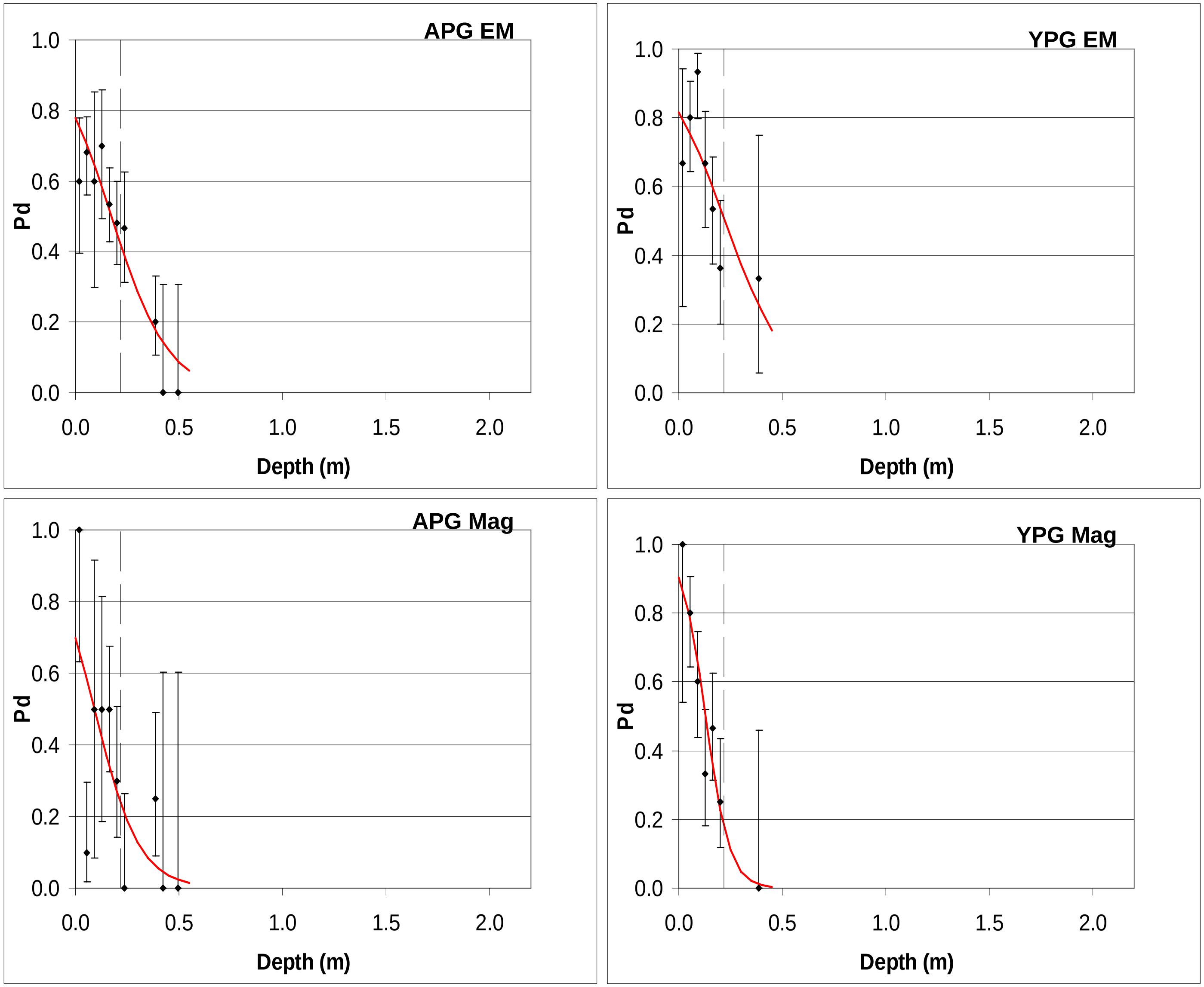


Figure 5-7. Detectability versus depth for 20 mm projectiles for better performing magnetometer and EM sensors at APG and YPG. Dashed vertical line indicates the 11× depth.

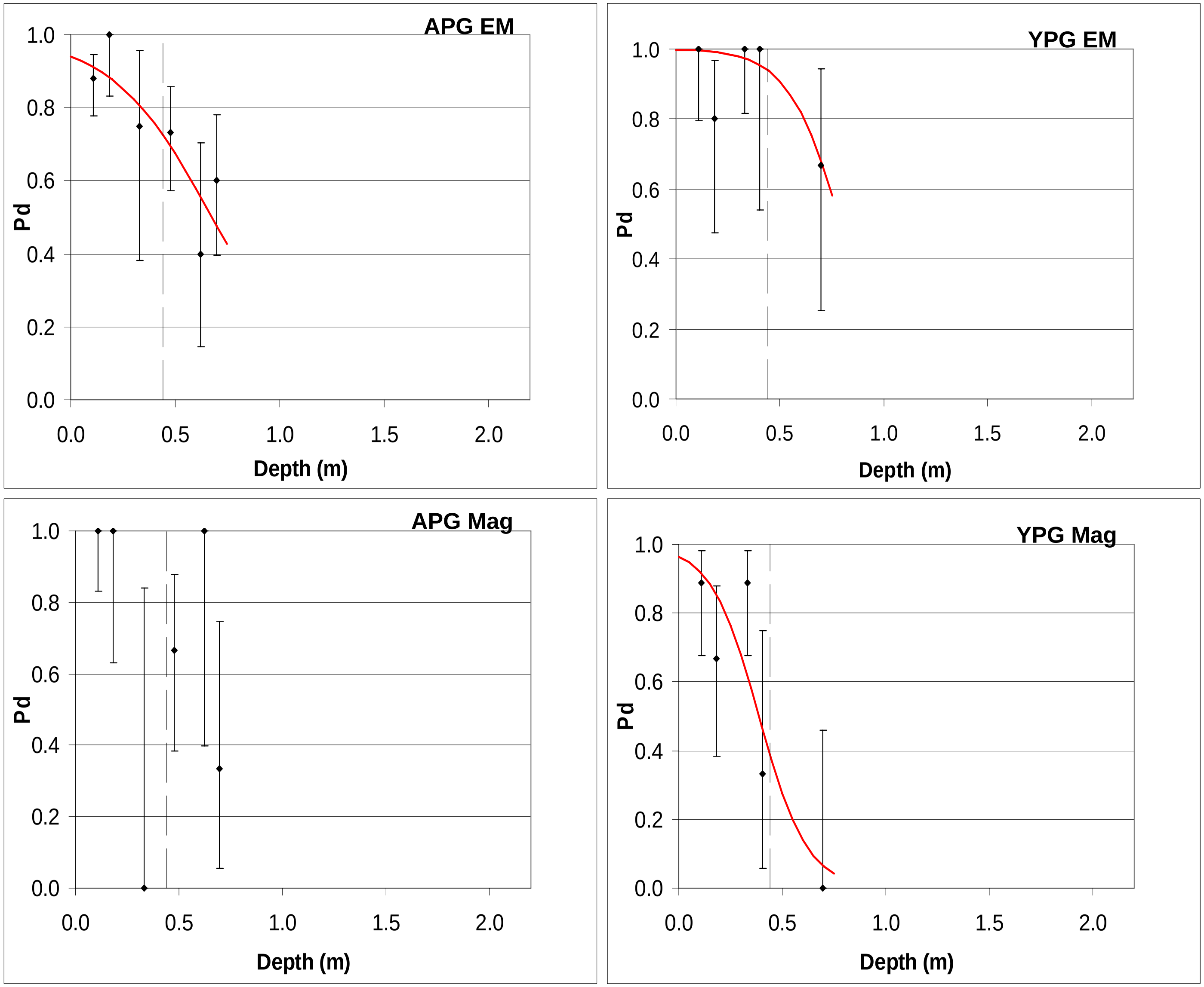


Figure 5-8. Detectability versus depth for 40 mm projectiles for better performing magnetometer and EM sensors at APG and YPG. Dashed vertical line indicates the 11× depth.

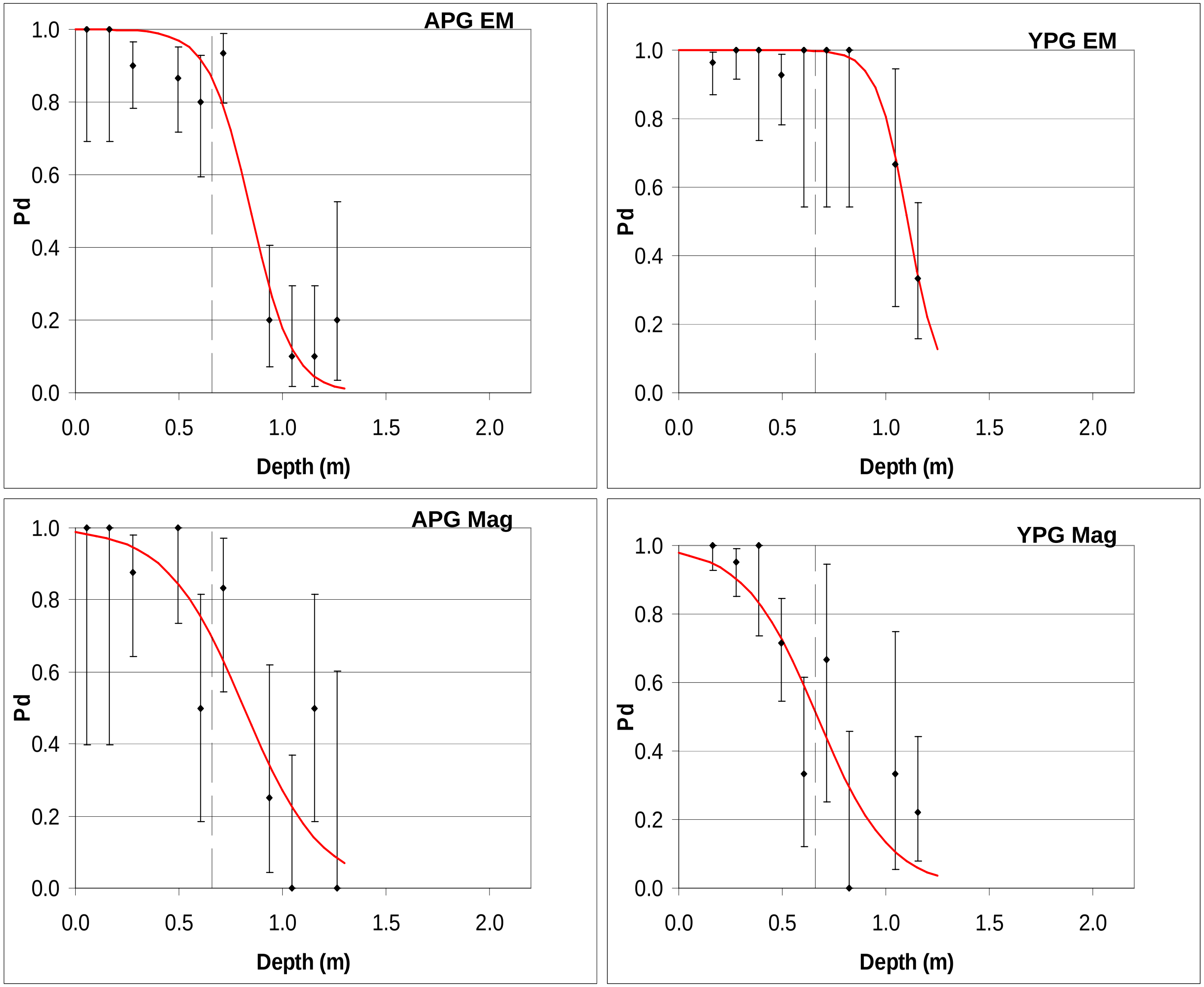


Figure 5-9. Detectability versus depth for 60 mm mortars for better performing magnetometer and EM sensors at APG and YPG. Dashed vertical line indicates the 11× depth.

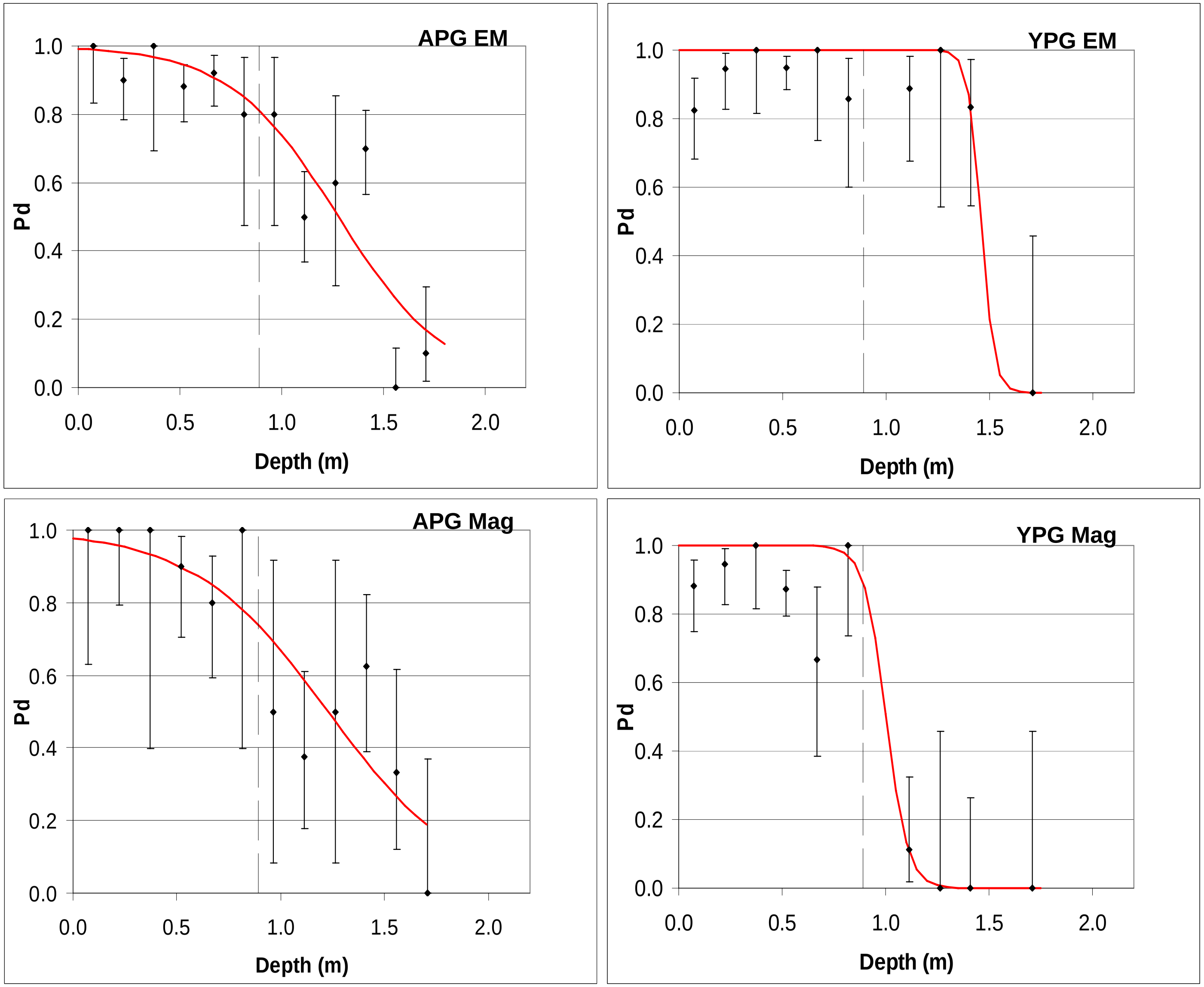


Figure 5-10. Detectability versus depth for 81 mm mortars for better performing magnetometer and EM sensors at APG and YPG. Dashed vertical line indicates the 11× depth.

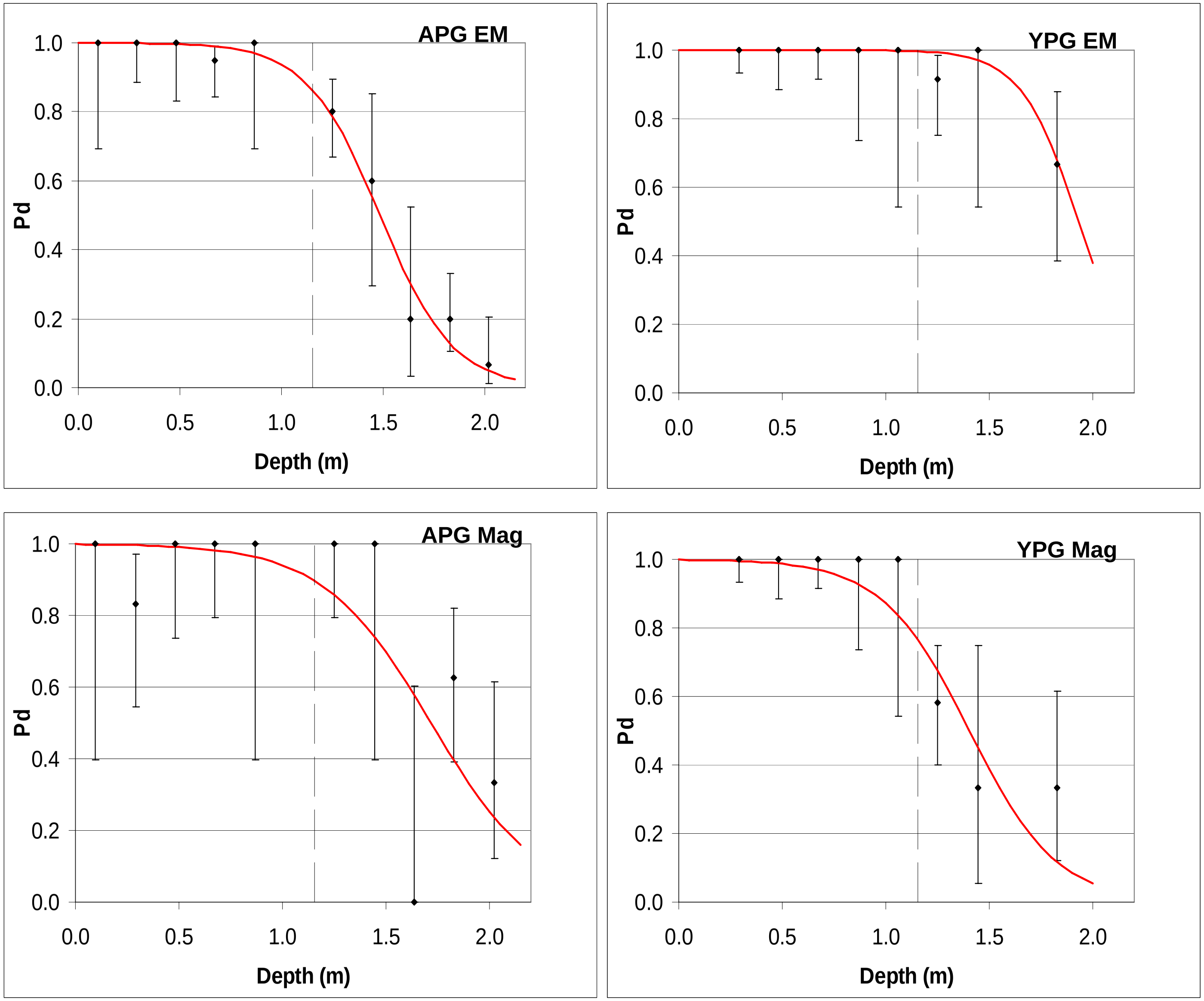


Figure 5-11. Detectability versus depth for 105 mm projectiles for better performing magnetometer and EM sensors at APG and YPG. Dashed vertical line indicates the 11× depth.

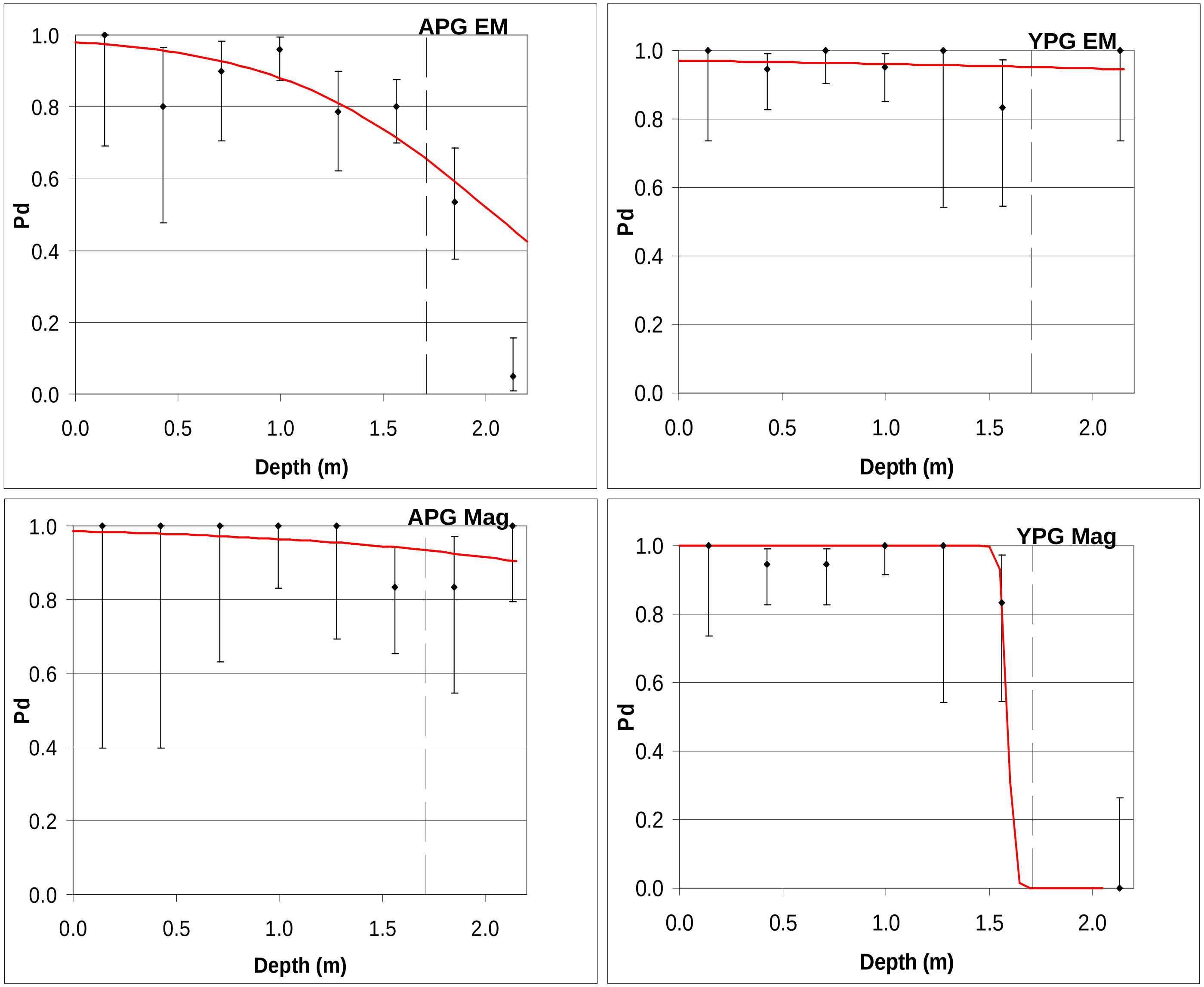


Figure 5-12. Detectability versus depth for 155 mm projectiles for better performing magnetometer and EM sensors at APG and YPG. Dashed vertical line indicates the 11× depth.

The points plotted in these figures represent probability of detection for a subset of the munitions that are buried at approximately the depth at which the point is plotted. Several closely spaced burial depths were grouped to calculate a probability of detection. The error bars on Pd represent one standard deviation statistical uncertainty for the population used in the calculation. Some bins had very small populations, resulting in huge statistical uncertainties. The curve used to fit the points is a tanh function that has a shape appropriate for the data points and the expected behavior, but should not be regarded as having parameters that are representative of any physical process. It is discussed in detail in Appendix B.

The *high detection probability region* of the curve (i.e., the initial flat part of the curve at shallow depth where Pd ~ 1) indicates the depth to which reliable detection may be expected. The *low detection probability region* of the curve (i.e., the terminal flat part of the curve at the deepest depths where Pd approaches zero) indicates the depth at which few, if any, of this munition type will be detected. These items likely have insufficient signal strength for detection under any circumstance using currently available sensors. The slope between these two regions represents a *transition region*, where the target's detectability is governed by statistical factors, such as where the target lies in relation to the travel path of the sensor and the relative orientation of the sensor and the target. These targets can be detected, and a certain fraction are, but they are not detected reliably.

Trends and General Observations on the Depth Plots

The behavior of the larger items (60 mm mortar, 81 mm mortar, and 105 mm projectile) shown in Figures 5-9, 5-10, and 5-11 is qualitatively different from the smaller items (20 mm projectile and 40 mm projectile) shown in Figures 5-7 and 5-8. All the larger items show 100% probability of detection at the shallowest depths, but neither the 20 mm nor the 40 mm do.

The results for the 20 mm projectiles and 40 mm projectiles are similar for magnetometers and EMI systems and are similar at APG and YPG. The results are qualitatively consistent with the theoretical detection limits discussed in section 5.3. For magnetometers, the theoretical detectable distance for these items is only a few tens of centimeters (comparable to typical track spacings) for sites with moderate noise. Some of these items will be missed simply because the horizontal distance from the sensor to the target is too great. Figure 5-2 for the EM similarly shows that the detectable swath for these two smaller items is much narrower than for larger items, even in ideal conditions.

For the larger items (60 mm mortar, 81 mm mortar, and 105 mm projectile):

- The curves are qualitatively similar for both sensors at both sites. For all, the probability of detection starts at or near 1 for the shallowest items. The 11× depth (dashed vertical line) falls on the steep part of the slope, but 11× does not represent 100% detection.

- The 11× line appears to be a good predictor for the depth at which detectability falls off sharply for the 105 mm projectile, the 81 mm mortar, and the 60 mm mortar under the conditions at the test sites. In each case, the probability of detection at this depth is in the 80–90% range, which suggests that this is a depth at which most, but not all, items can be expected to be detected.
- For all munitions types, there is remarkably little difference between magnetometers and EMI or from APG to YPG.

The results for the 155 mm projectile (Figure 5-12) are far more erratic. This is at least in part due to the finite burial depths at the standardized sites, which do not test the limits of the detectability of these larger items, and the somewhat smaller data set. There are not enough data to do a good fit to this function.

5.3.5 Individual Miss and Failure Analysis for the Standard Test Sites

This analysis focuses on understanding the reasons that specific targets were missed by the better demonstrators, who represent the best performance achieved with careful application of their sensors. For these systems, the probabilities of detection for all munitions except 20 mm projectiles are near 90%, after clusters, unsurveyed targets, and greater than 11× diameter deep targets are removed from scoring. The better performing demonstrators included NRL EM61 array, TTFW (EM61 type), NRL GMTADS (GEM3) array, NAEVA (EM61) array,[2] and NRL MATDS magnetometer array.

The detailed analysis of the test site data finds that the probability of detection of most targets above the 11× line is not limited by the signal-to-noise ratio (signal strength). This suggests that there are other reasons for the great differences in 100% detection depth from the test sites and the 11× line commonly observed at GPOs, which include:

- Targets whose signatures are shadowed by nearby clutter or background that display large, strong anomalies.
- Operation of the sensor system at less than optimum performance. The effects of large platform noise, improper data leveling, excessively low or high detection threshold, and large track separation are all evident in the test sites data.

Optimum operation is an obvious goal in a munitions response, and the wide variance in system performance at the Standardized Sites underscores the importance of implementing an effective QA/QC strategy.

Two types of misses were considered: those targets that are commonly missed even among the better demonstrators and those that were detected by most demonstrators, but were missed by one or more of the better demonstrators (targets they “should have”

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[2] The NAEVA raw data was not processed in time to be included in the failure analysis portion of the standardized site analysis. From their dig list, we found that nearly 60% of the UXO NAEVA missed were also missed by other demonstrators.

detected). A table providing detailed results by performer and ordnance type is included in Appendix A.

Targets with overlapping signatures, where an ordnance item signature is shadowed by a more prominent nearby object, are the most commonly missed. A target-by-target analysis shows that the same items are often missed by many demonstrators. The 81 mm mortar shown in Figure 5-13 was detected by 3 of 21 demonstrators at APG and by none of the better demonstrators. Figure 5-14 shows another such example, a faint 40 mm projectile screened by a nearby clutter object. In nearly all cases, the nearby large clutter object is detected, but the fainter 40 mm projectile is overlooked.

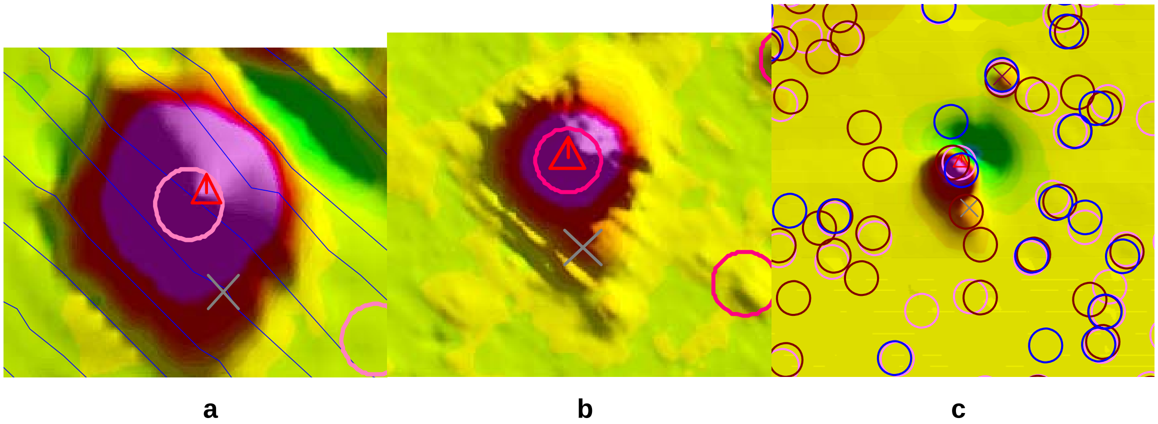

Figure 5-13. An 81 mm mortar at 42 cm depth screened by a large clutter item. The gray X is the location of the mortar and the red triangle indicates the location of the clutter item. The circles have radii of 0.5 m and are centered on the alarms picked by each demonstrator. Panel (a) is from a single time gate from the TTFW EM61. Panel (b) is GEM3 data from NRL GMATDS. Panel (c) is zoomed out and contains alarms from three magnetometers. The gridded data and pink circles in (c) are from the MTADS magnetometer array dig list. The dark blue and brown circles are from two different the mag-and-flag surveys. Notice that one mag-and-flag survey (HFA) "found" the mortar, but at the cost of many more false alarms.

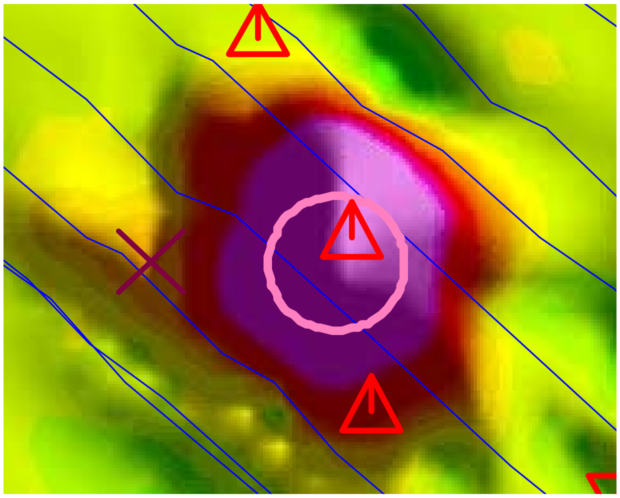

Figure 5-14. Example of overlapping signatures. A 40 mm projectile at 0.4 m (marked with the X) is 1.5 m distant from an approximately 1 kg clutter item at 0.05 m depth marked with the red triangle).

As a practical matter, it is not clear whether a shadowed item counted as a miss by the Standardized Site scoring system would be found during an excavation of the clutter item at the dig list location. In the field, after an excavation, resurveying the dig location with a sensor of the same sensitivity as the original survey sensor will overcome the screening effect of the item that caused the original alarm.

After shadowing, the next most common reason for a missed detection was that the alarm that appears to correspond to an emplaced item was placed farther away than the allowable miss distance of 0.5 m. In these instances, the missed target was not near any other emplaced clutter or ordnance. An anomaly nearby was marked as an alarm, but it was outside the scoring halo. Some of the alarms scored as misses using a 0.5 m halo were only a few centimeters outside the scoring halo. In many instances, the horizontal extent of the target signature was larger than the scoring halo, and it is possible that if the dig list were excavated, the target would be found.

Figure 5-15 shows geophysical data from one of the better demonstrators that had the greatest incidence of this type of miss. This demonstrator also had the greatest spacing between survey tracks. In the case of this example, the ordnance fell within a particularly wide gap in track spacing, and the gridded data appear to have mispositioned the anomaly location.

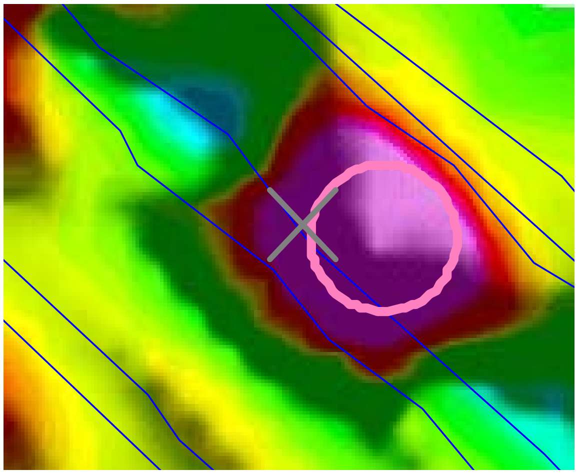

Figure 5-15. 81 mm mortar buried at 0.22 m. X indicates the location of the mortar, circle indicates the picked location, and blue lines are the sensor survey tracks.

When attempting to translate standardized scoring into real-world response action, misses such as these are less of a concern than shadowing. It is likely that, even though the dig list coordinates were outside the scoring halo, an excavation crew would have reacquired the anomaly and found the large target shown in Figure 5-15. Nevertheless, geolocation technology and target-selection methods exist to support more accurate anomaly location. If implemented, these improvements could ease the cost and manpower burden of target reacquisition.

The other common missed targets are those nearly as deep as the 11× line. In these instances, the targets had a very low amplitude signals. Figure 5-16 shows an example of a 155 mm projectile buried at 1.6 m (the 11× depth is 1.7 m). The signal amplitude at the location of the projectile is not perceptibly different from the surrounding background fluctuations, and no anomaly is identified within several meters of its location.

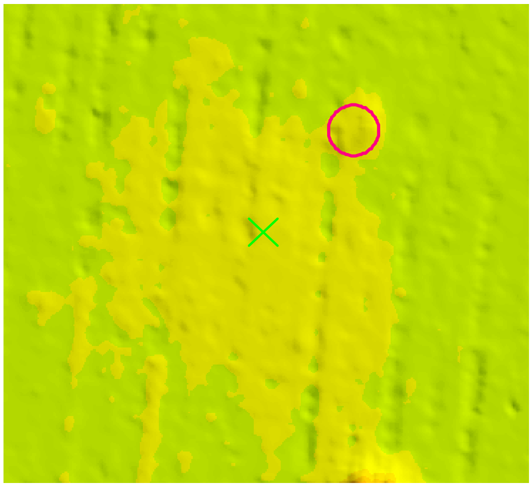
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Figure 5-16. Better demonstrator miss of a 155 mm projectile at depth 1.6 m (marked with X). The item is just less that 11× its diameter in depth, and the nearest alarm (circle) is several meters away.

The NRL MTADS magnetometer was included in this analysis to illustrate the performance differences between magnetometers and EMI systems. Of the optimum demonstrators, the NRL MTADS magnetometer array had the most difficulty finding 20 mm projectiles, despite having a very narrow survey track separation of 25 cm. However, the MTADS magnetometer array missed none of the 105 mm or 155 mm projectiles shallower than the 11× line. This is consistent with the difference in theoretical response between magnetic and electromagnetic induction detectors: magnetometers are more sensitive to large deep targets than EMI systems.

Poorly Performing Demonstrators at the Standard Test Sites

Several demonstrators fared far worse than the better performing demonstrators, despite using the same geophysical equipment. Figure 5-17 gives examples of data from two of the poorer performing demonstrators. The demonstrator on the left used an EM61, but experienced much higher noise than better performing demonstrators using the same equipment. As a result, the site was peppered with false alarms and the probability of detection was universally lower. The noise is so severe in the data shown on the right that the site is virtually covered with false alarms. Determining real detections, as opposed to fortuitous matches of emplaced item locations with one of the demonstrator’s alarms, is nearly impossible.

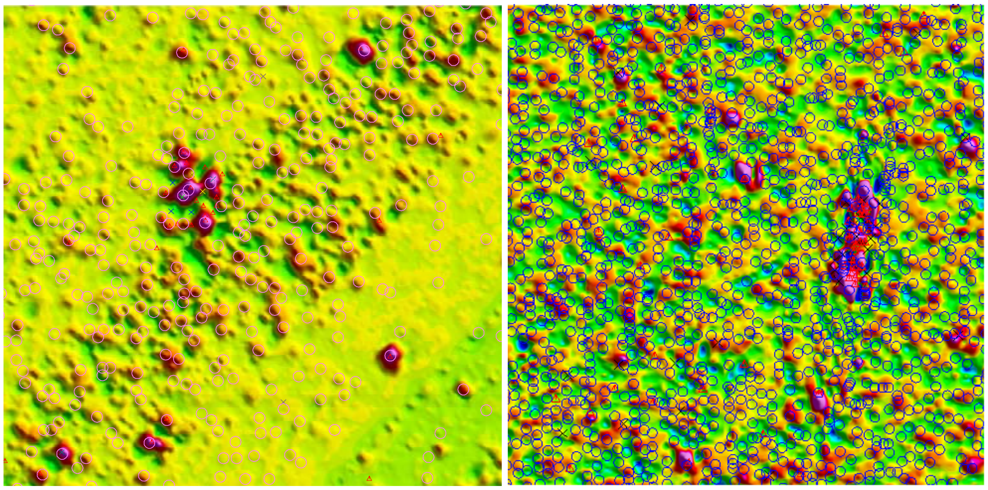


Figure 5-17. Sample data from poorly performing demonstrators at the test sites.

Figure 5-18 shows two sets of magnetometer data. In the image on the left, systematic errors are evident by the striping in the data. The demonstrator on the left achieved a much lower probability of detection than the demonstrator on the right, but had a lower false-alarm rate.

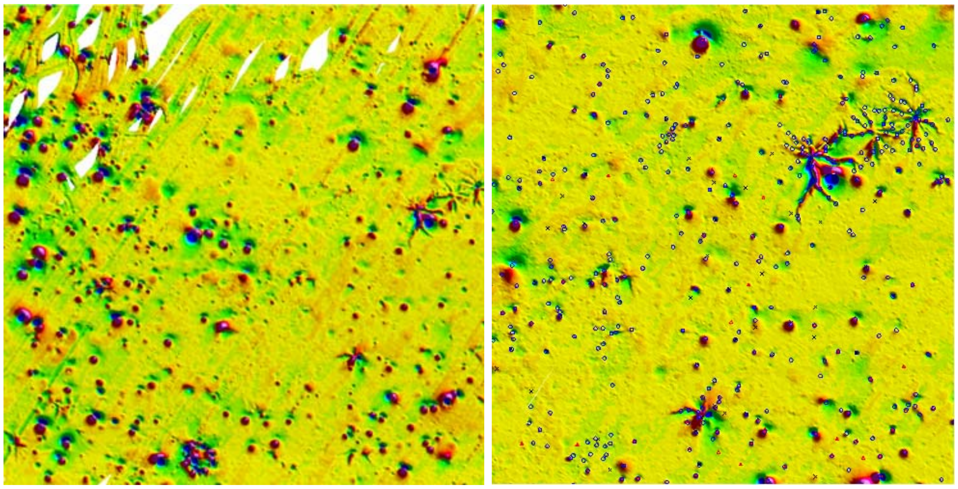


Figure 5-18. Magnetometer data from two demonstrators at YPG. The figure on the left shown data with residual noise of about 10 nT along the survey track. This can be contrasted with the much quieter magnetometer data from the demonstrator on the right.

5.4 Case Studies from Recent Geophysical Surveys and UXO Response Action Projects

5.4.1 Detection by Ordnance Type—GPOs

Figures 5-19 to 5-22 give summary results from the GPOs reviewed in the form of bar and whisker charts. Each chart shows all the available instrument test results for a specific ordnance type (or similar ordnance types with the same diameter). The bar represents the 100% detection depth for each instrument test. The whisker indicates the maximum detection depth for each instrument test. Below the bar and whisker diagram, two detection rates are shown, the overall Pd for the ordnance type and the Pd for those seed items shallower than the 11× depth.

5.4.1.1 Small Ordnance—20 mm

The results are far less consistent than the standard test sites. Some demonstrators on GPOs found all the 20 mm in some GPOs. This is in contrast to the standard test sites, where even the better demonstrators found only about 70% of the 20 mm projectiles emplaced. Possible explanations for this difference include the following: On the GPOs with 20 mm projectiles present, target selection methodologies and field procedures are tailored to find them; GPOs are commonly designed to avoid overlapping targets or clutter, which could mask small items.

5.4.1.2 Medium Ordnance—60 mm

For most sites, the depths of interest are fairly shallow. On these sites, 100% detection depths are fairly consistent with the better demonstrators at APG, where the values were about 50–60 cm. Two sites looked at much greater depths. Some performers detected 100% of the 60 mm mortars to depths of approximately 90 cm, which was not seen at the standard test sties.

5.4.1.3 Large Ordnance—155 mm

For most sites, the 100% detection depth of the 155 mm projectiles is constrained by the maximum burial depth. On the GPOs that contained deeper targets, the mag-and-flag systems detected 100% of the 155 mm projectiles to a depth greater than 2 m. This is in contrast to a 100% detection depth of less than 1 m for mag and flag on the standard site. Only one other demonstrator detected 100% of the 155 mm projectiles to a depth greater than 1.5 m. This also contrasts with the standard sites, where all the better DGM demonstrators achieved greater than 1.5 m detection depths.

5.4.2 Detectability versus Depth GPOs

As in the standard test sites analysis, the better performers with each instrument type were selected in an attempt to construct an operating envelope for the sensor. These plots are shown in Figures 5-23–5-27. The data were more limited in the GPOs, both in terms of number of encounters and seeding depth, so attempts to fit the probability of detection as a function of depth to the function used for the standardized sites were not successful. Instead, the curves derived from the standard test sites were superimposed on the GPO data points to determine similarities and inconsistencies.

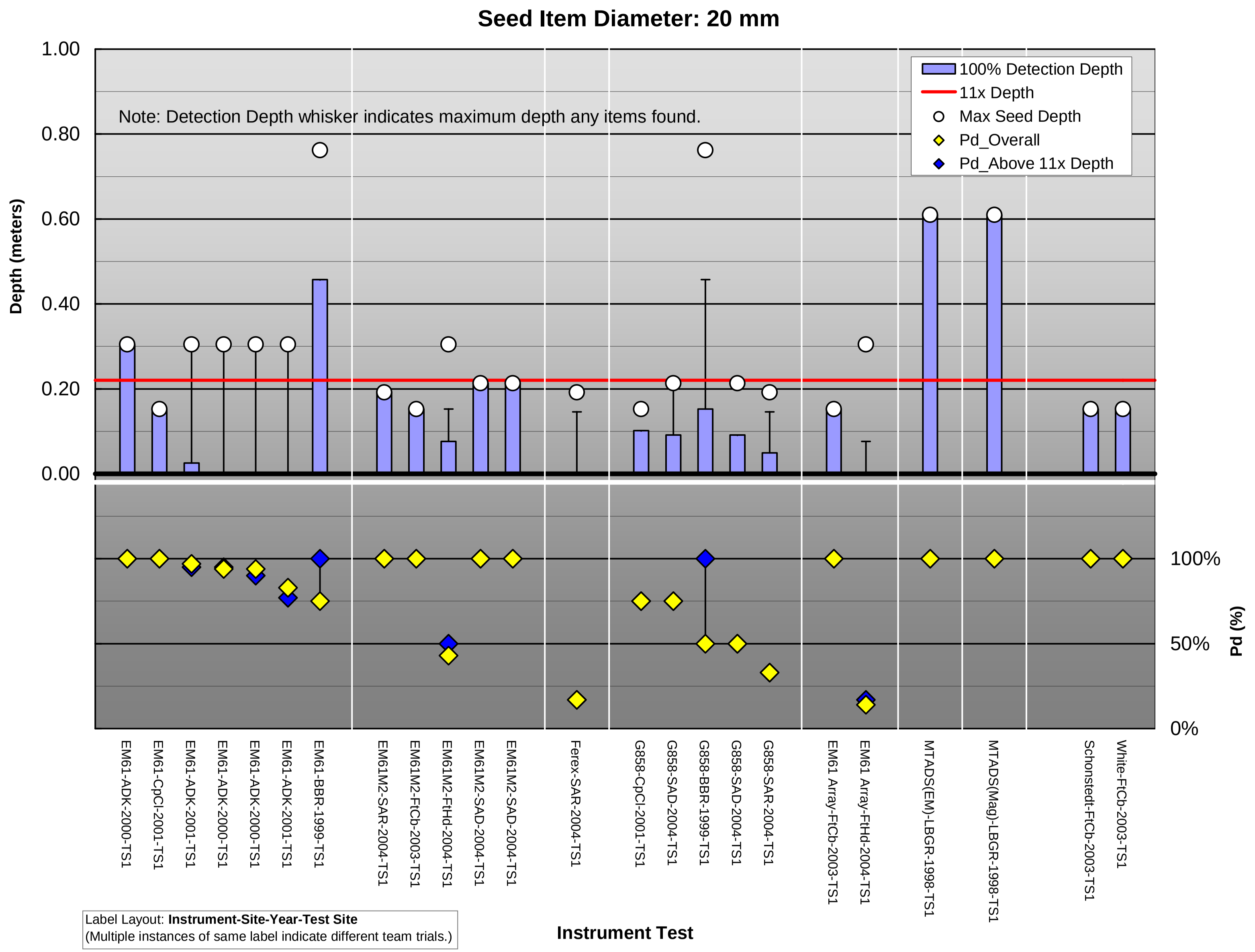


Figure 5-19. GPO 100% detection depth and detection rates for 20 mm projectiles—sorted by instrument.

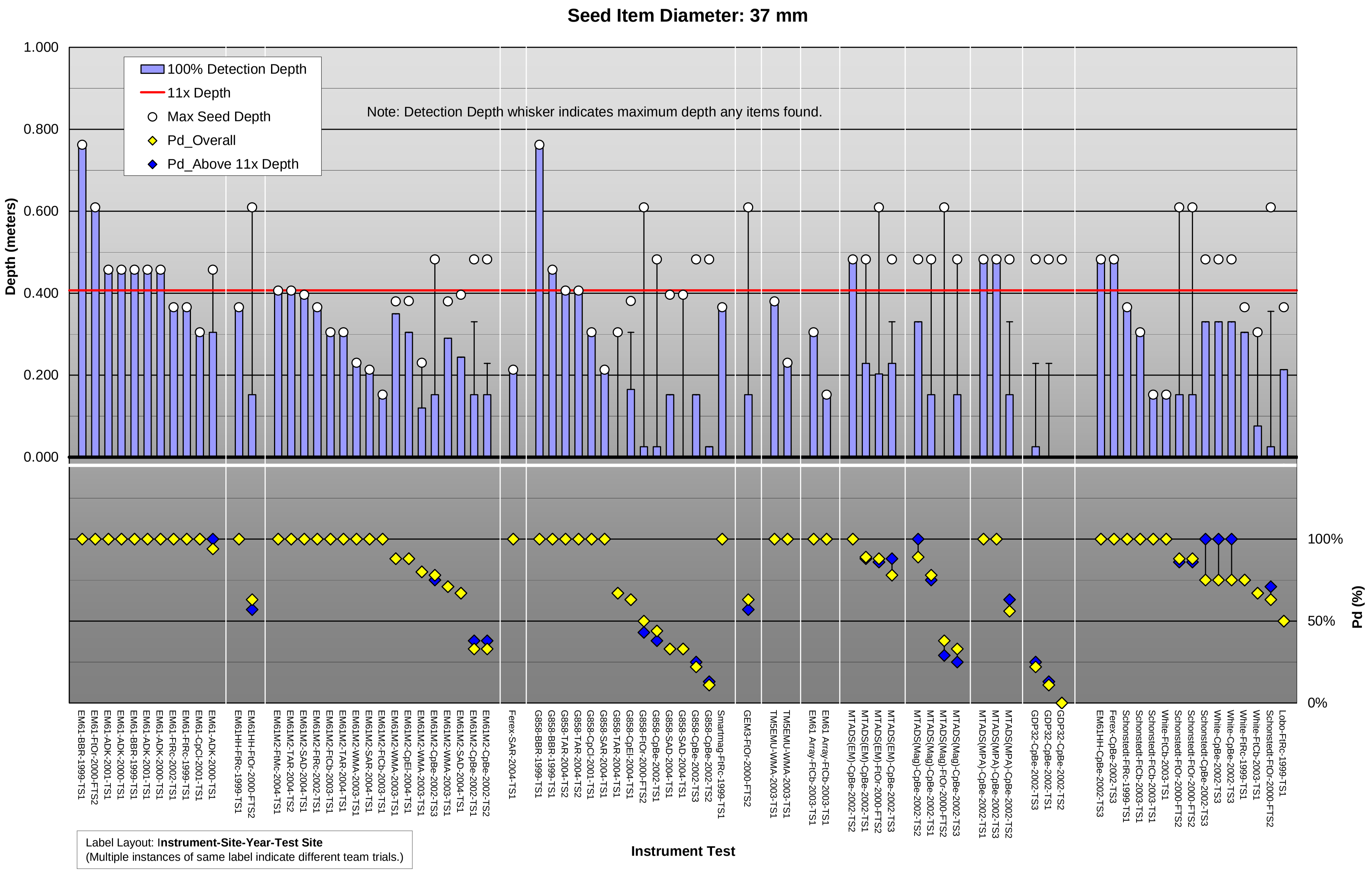


Figure 5-20. GPO 100% detection depth and detection rates for 37 mm projectiles—sorted by instrument.

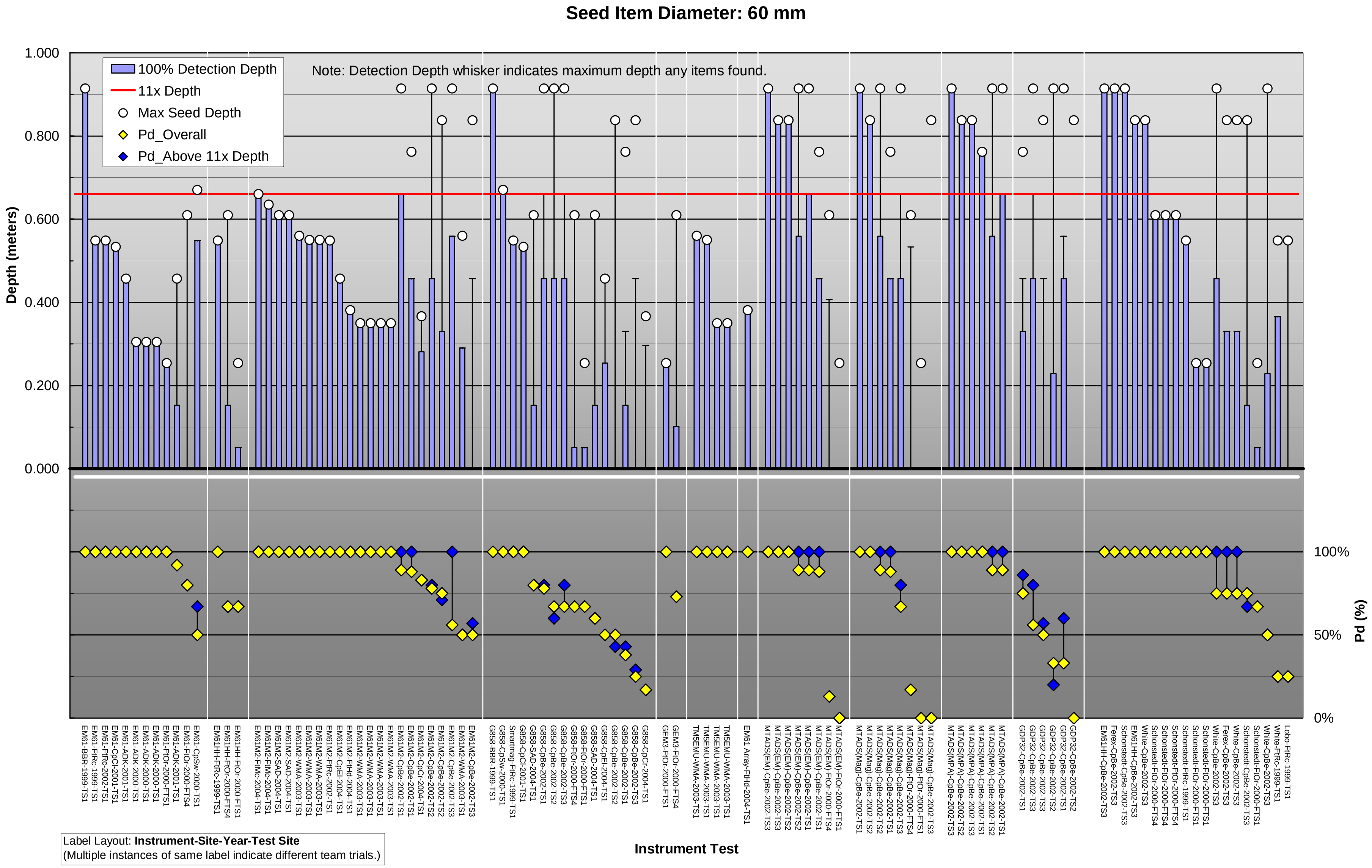


Figure 5-21. GPO 100% detection depth and detection rates for 60 mm mortars—sorted by instrument.

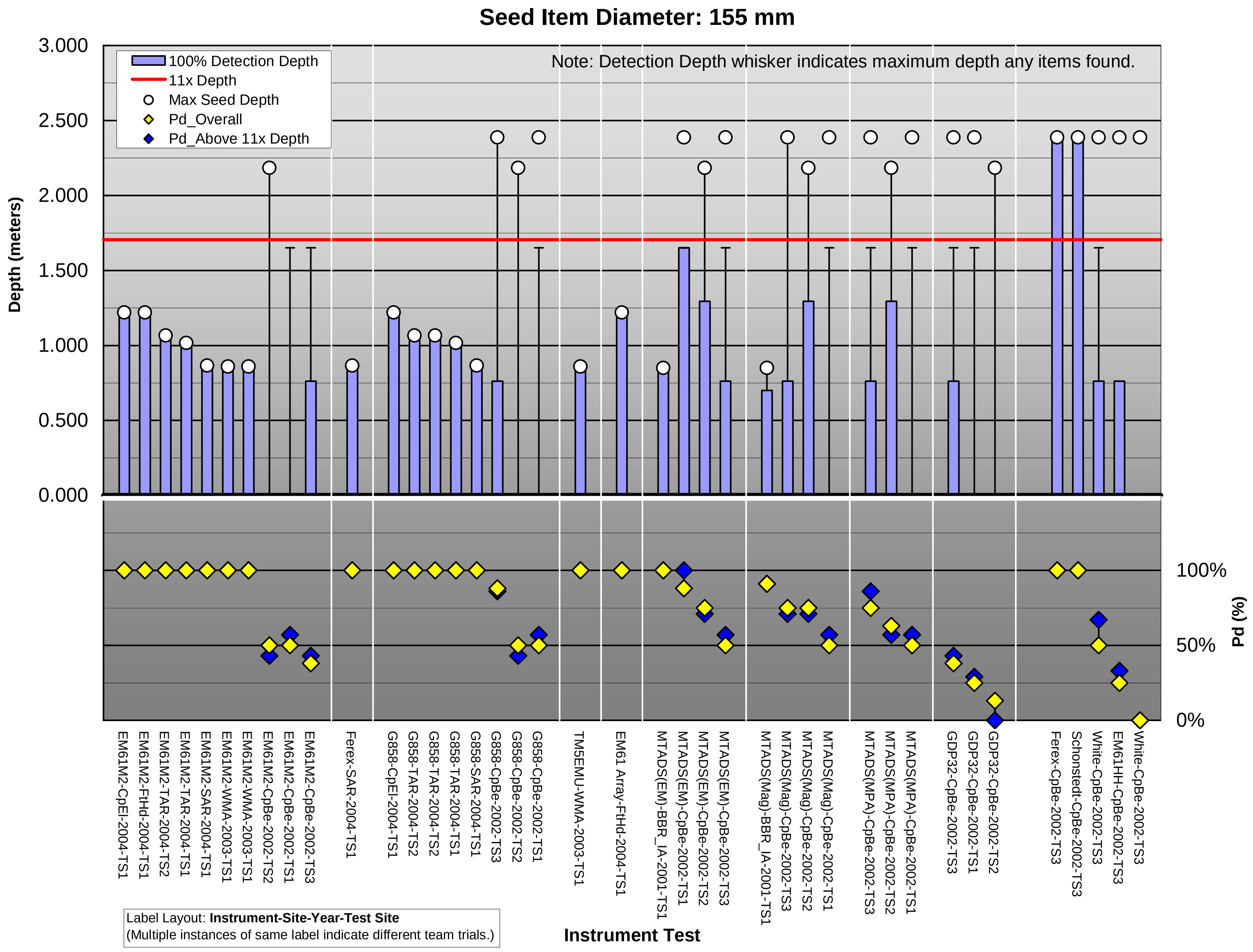
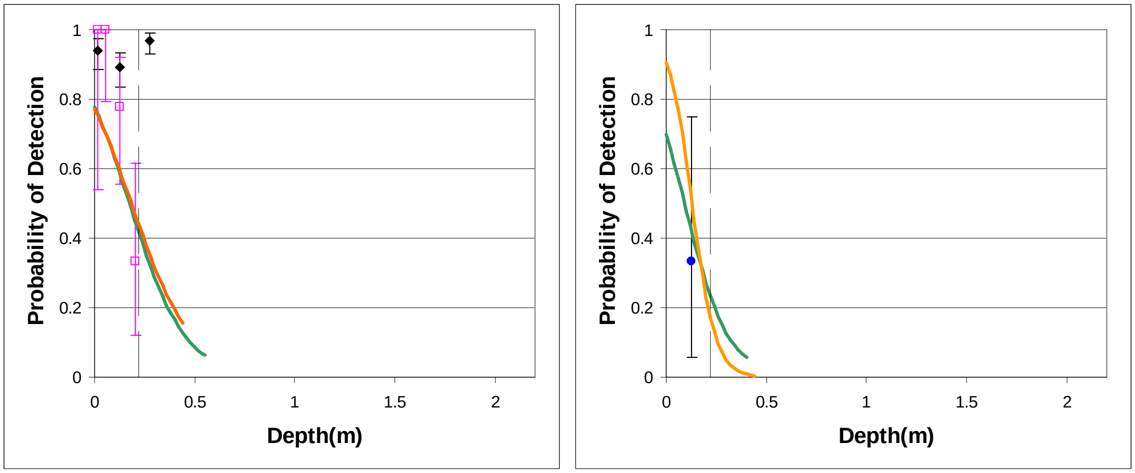
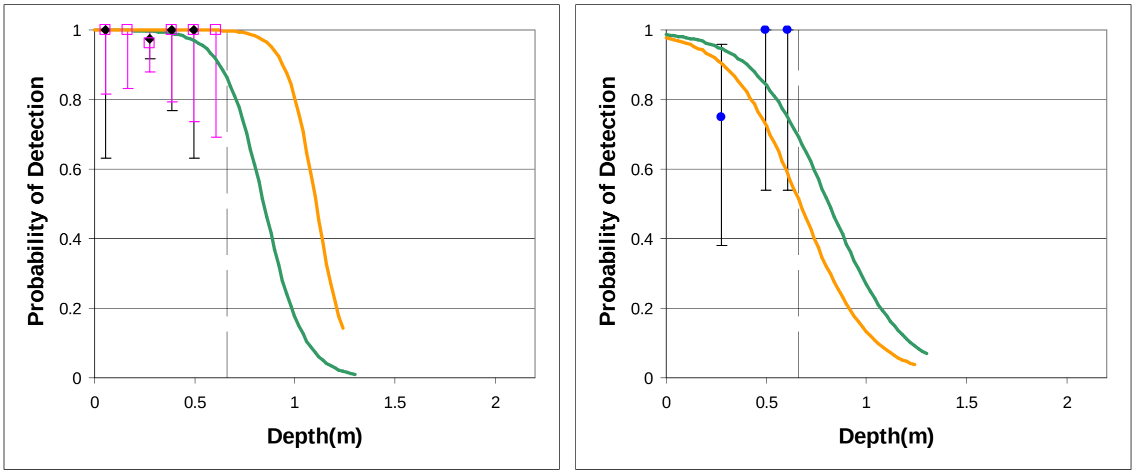


Figure 5-22. GPO 100% detection depth and detection rates for 155 mm projectiles—sorted by instrument.



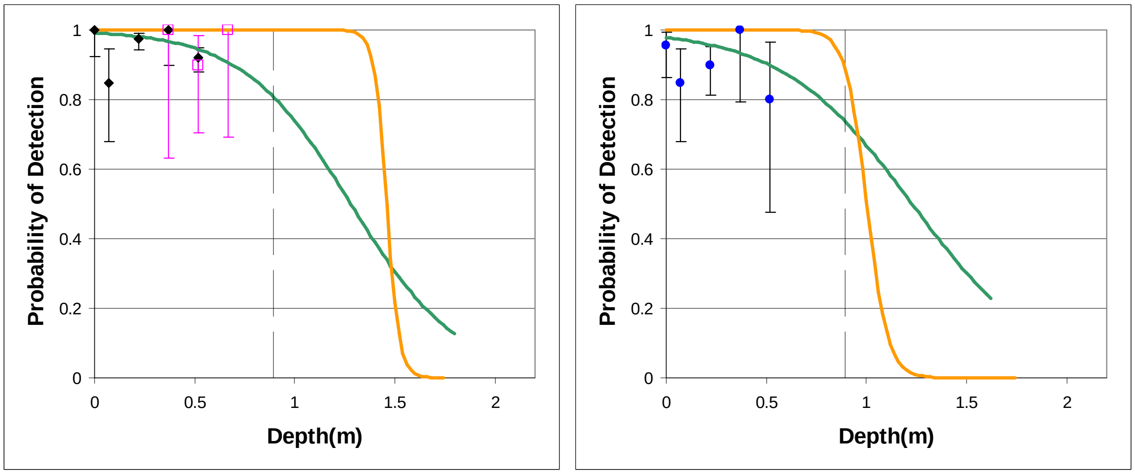
(a) **(b)**

Figure 5-23. Detectability versus depth for 20 mm projectile for better performing magnetometer and EM sensors at selected GPOs. The lines are fits to the Pd-by-depth data from the Standardized Test Sites: green = APG, orange =YPG. (a) shows the EM61Mk1 (black) and EM61 Mk2 (pink); (b) shows the magnetometers. The dashed vertical line indicates the 11× depth.



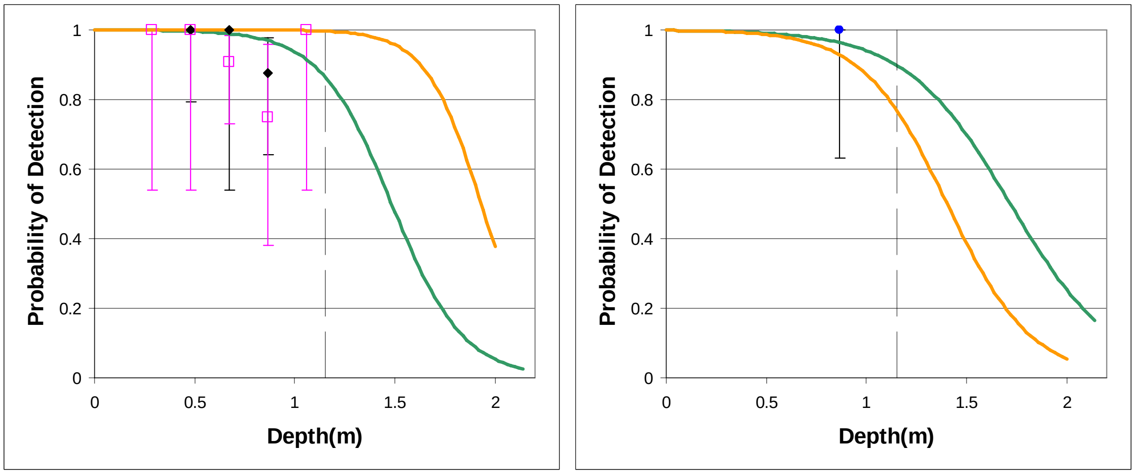
(a) **(b)**

Figure 5-24. Detectability versus depth for 60 mm mortar for better performing magnetometer and EM sensors at selected GPOs. The lines are fits to the Pd-by-depth data from the Standardized Test Sites: green = APG, orange =YPG. (a) shows the EM61Mk1 (black) and EM61 Mk2 (pink); (b) shows the magnetometers. The dashed vertical line indicates the 11× depth.



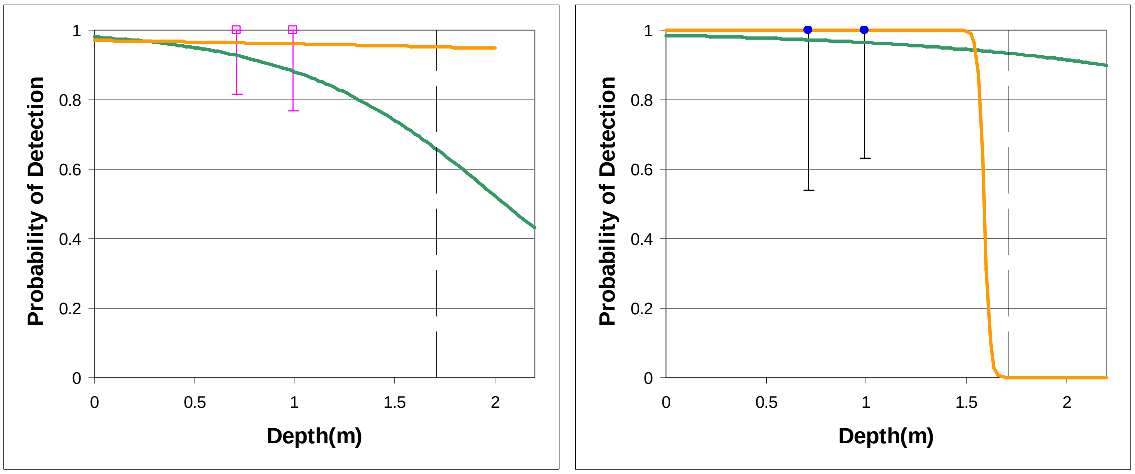
(a) **(b)**

Figure 5-25. Detectability versus depth for 81 mm mortar for better performing magnetometer and EM sensors at selected GPOs. The lines are fits to the Pd-by-depth data from the Standardized Test Sites: green = APG, orange =YPG. (a) shows the EM61Mk1 (black) and EM61 Mk2 (pink); (b) shows the magnetometers. The dashed vertical line indicates the 11× depth.



(a) **(b)**

Figure 5-26. Detectability versus depth for 105 mm projectile for better performing magnetometer and EM sensors at selected GPOs. The lines are fits to the Pd-by-depth data from the Standardized Test Sites: green = APG, orange =YPG. (a) shows the EM61Mk1 (black) and EM61 Mk2 (pink); (b) shows the magnetometers. The dashed vertical line indicates the 11× depth.



(a) (b)

Figure 5-27. Detectability versus depth for 155 mm projectile for better performing magnetometer and EM sensors at selected GPOs. The lines are fits to the Pd-by-depth data from the Standardized Test Sites: green = APG, orange =YPG. (a) shows the EM61Mk1 (black) and EM61 Mk2 (pink); (b) shows the magnetometers.

5.4.2.1 20 mm

For the EM61 MK1, the detection rates on the GPOs are generally higher to greater depth than the standard test site curve would predict. The EM61 MK2 data follow the curve more closely, but there are few data points and they exhibit large error bars. There is not sufficient magnetometer data to draw any conclusions.

5.4.2.2 Medium and Large Items

For the 60 mm mortar, 81 mm mortar, 105 mm projectile, and 155 mm projectile, the GPO data terminate at depths shallower than the depth at which the curve from the standard test site falls off:

- 60 mm—At depths for which there are data, the GPO results are consistent with the test site results.
- 81 mm—At depths for which there are data, the GPO results are consistent with the test site results for the EM systems, but the magnetometer data show lower probabilities of detection at shallow depth on the GPOs than the standard sites.
- 105 mm—At depths for which there are data, the GPO results are consistent with the test site results for the EM systems. For the magnetometer, there is not sufficient data for comparison.
- 155 mm—At depths for which there are data, the very limited GPO results are consistent with the test site results.

5.4.3 Best and Worst Performers

Because each GPO tends to have many site-specific issues affecting the results, it is difficult to make definitive conclusions about performance of the various instruments tested. Certain qualitative observations can be made, however, especially when looking at instruments within the context of each site. These observations are tied to the results from the test site analysis wherever possible. In general, they tend to validate what is known about these instruments.

Overall, the most tested instrument was the EM61 and its variants and, with the exception of certain sites, it appeared to perform the best for most ordnance items. In many instances, it ranked at or near the top when comparing instruments within GPOs. In the majority of tests, EM61 instruments located 90–100% of the seed items buried for most ordnance types from 37 mm to 155 mm. Note, however, that many items were not seeded as deep as the 11× depth. The EM61 MK2 had its worst performance at two sites: Waikoloa Maneuver Area and Camp Beale. The probabilities of detection at these sites for many ordnance types varied from 50% to less than 85%. The reasons for these performance drops are site specific. The data tend to show detection to the maximum seeded depth, which is often above the 11× line, suggesting that the instruments may have depth-sensing ability greater than was tested in the various GPOs.

The G-858 tended to not do as well for the smaller items and generally ranked behind the EM61s for munitions with smaller diameters. As can be seen in Figure 5-20, which shows the 37 mm data, the G-858 showed much greater variability, with many of the probabilities of detection for the G-858 falling below 67%. This is also reflected in the gaps, or whiskers, above the 100% detection bars, suggesting a drop-off in the detection capability. For larger items (>81 mm) at depth, the situation changes, and the G-858 probabilities of detection improve significantly. Ranking changes as well, with the G-858 performing equal to or better than EM61 variants and other instruments.

Both the EM61 and G-858 systems had trouble with smallest items. The EM61 variants, however, always outperformed the G-858’s when in direct comparison in the GPO analysis. The EM61 usually had high probabilities of detection (94% to 100%), but at one site (Adak), the 100% detection depth values indicated some shallow misses.

Other DGM instrument systems tested included the Foerster Ferex, TM-5 EMU, and the Zonge nanoTEM, but they were only used at one or two sites each. The Ferex, which was tested in digital mode at Spencer Artillery Range, detected all the 37 mm projectiles (3), 60 mm mortars (1), 2.36-inch rockets (1), and 155 mm projectiles (2) present. It found only one of six 20 mm projectiles and none of the 81 mm mortars (1) or 105 mm projectiles (2). The TM-5 EMU did very well at Waikoloa, detecting all the items (37 mm projectiles, 60 mm mortars, 2.36-inch rockets, 81 mm mortars, 105 mm projectiles, and 155 mm projectiles) seeded at two test areas. It outperformed the EM61 MK2 also tested at those sites. The Zonge nanoTEM was tested at the three Camp Beale test areas and generated probabilities of detection ranging from 11% to 75% for ordnance items from 37 mm to 155 mm.

Various analog instruments were also tested, but at fewer sites than the digital instruments. Analog instrument data were analyzed at three sites: Camp Beale, Fort

Campbell, and Fort Ritchie. At Camp Beale they were only tested to verify their ability to perform safety and reacquisition tasks. The instruments types included two Schonstedts, four White's metal detectors, a Lobo metal detector, and analog-mode versions of the EM61 HH and Foerster Ferex. The Schonstedt produced mostly 100% detection from 37 mm through 155 mm. The deepest item detected was a 155 mm at 2.39 meters. The Foerster Ferex detected all items from 37 mm to a 155 mm buried at 2.39 meters. The EM61 HH detected all items through 60 mm, but missed increasing numbers from 81 mm to 155 mm. The deepest item found was a 105 mm at 0.97 meters. The White's did reasonably well detecting smaller items (up to 81 mm) at Fort Campbell, but did not perform well at detecting 105 mm there or at the other two sites. The Lobo EM at Fort Ritchie showed very limited performance.

5.4.4 Background Alarm Rate

The background alarm rate was examined for the GPO sites where it was available. Table C-4 in Appendix C presents the results of this analysis. The background alarm rate is defined as the number of nonordnance targets picked divided by the area surveyed. Also, to allow comparison of results between instruments tested under the same conditions, a relative background alarm rate (rBAR) ranking was calculated based on the lowest background alarm rate at a particular test area. Note that some of the background anomalies picked may be actually be blind seeds placed in the GPO test area by the USACE.

There is a trade-off between BAR and Pd. Indeed, in cases where there are large differences in probability of detection (e.g., 90% versus 50%), the system with the lower probability of detection generally reported a much lower background alarm rate, indicating the target picking threshold is likely set too high. For example, at Camp Beale (SWA), three demonstrators had Pd less than 0.50, and all had significantly lower background alarm rates compared with the systems that had Pd greater than 90%. Similar performance is seen by the demonstrators at the other two Camp Beale GPOs. Likewise, at Camp Croft the demonstrator with the higher probability of detection (85%) had a background alarm rate 60% higher than the demonstrator with a probability of detection of 15%.

Among systems with generally high probability of detection (>90% on the same site), however, no such clear trend emerges. For example, in the Adak 2001 tests, both sensors scored Pd of 98%, but the false-alarm rate between the two differed by nearly a factor of 2. Similarly, at Fort Campbell, three demonstrators scored a Pd of 91%. The two that used DGM systems had background alarm rates that differed only by about 20%, but the demonstrator using an analog system suffered a much higher background alarm rate.

Waikaloa represents the exception, where the highest probability of detection is accompanied by the lowest false-alarm rate for both GPO areas. In both cases, this was achieved by the TM-5 EMU instrument.

6.0 INTERPRETING AND APPLYING DETECTION SYSTEM PERFORMANCE

The detection capability of the geophysical instrument is one of the most important pieces of information needed by a project manager or regulator to evaluate the appropriateness of detection technology. Results from the standard test sites summarized in Chapter 5 show that current equipment used properly can detect items of interest to depths of interest. The analysis in Chapter 5 indicates that instrument sensitivity should not be an issue at most sites. However, the range of performance seen on the test sites shows that geophysical instruments with adequate sensitivity can produce suboptimal results for a variety of reasons. This chapter illustrates how the results in Chapter 5 can be used in evaluating technologies for specific objectives and explores some of the factors that can degrade performance and how they can be managed or mitigated.

The probability of detecting any given target will be a function of the type of ordnance, sensor type, object depth and orientation, sampling density, crew capability, and target-selection strategy. Thus, a percentage detected on an ensemble of targets and depths is not very illuminating. This metric will be greatly influenced by the relative distribution of types and depths of munitions emplaced in the test, which may or may not be representative of the distributions on the site. Detection systems may achieve an acceptable overall probability of detection (Pd), for example 90% of the emplaced items, but may consistently miss one particular munition type at specified depths of interest. Our analysis has relied largely on the detectability curves and individual item detection analysis presented in Chapter 5.

The results from the standard test sites are useful for defining basic detection capabilities of instruments under particular site conditions. Note, however, that a probability of detection cannot be taken from any one study and expected to be replicated on other sites with different conditions, deployment platforms, personnel and objectives. In addition to obvious physical differences that may be encountered in geology, terrain and vegetation, there are myriad design and execution considerations that are critical.

Fundamentally, real-world performance is a function of quality. Obtaining the required performance will require scrutinizing each of the critical components of the geophysics, and the performance achieved will be determined by the weakest link. We consider the following basic process steps: instrument selection, survey design, execution, data reduction, and target-selection methodology, which are discussed as applicable in the following sections. Proper data collection, processing, and analysis must be selected to achieve project objectives for detection while avoiding the costs associated with excessive false alarms. Proper use of detection instruments, anomaly interpretation, and reacquisition are important for improving the probability of detection and ultimately the amount of ordnance removed from the site.

Finally, there is always a tradeoff between detection rate and the background (false) alarm rate. That is, detections may always be increased by lowering the threshold for selecting targets, but doing so will have the inevitable consequence of selecting more anomalies. These additional anomalies, which may correspond to metallic clutter or geology or, if the threshold is lowered far enough, instrument noise, will all require investigation, which is a major cost driver on projects.

First, we summarize the major conclusions of the analysis in Chapter 5. Second, we walk through a few example scenarios to draw out the specific information and illustrate how it is used. Finally, we summarize some real-world conditions that can influence performance.

6.1 Summary of Major Conclusions from the Standard Test Site and Geophysical Prove-Out Analysis

The analysis of the standard test site and Geophysical Prove-Out data in Chapter 5 tells us specific things about the fundamental capability of the sensors, as well as the performance achieved in various deployment configurations. Here, we summarize the basic conclusions.

6.1.1 Detection Sensitivity

Under the highly controlled conditions of a test grid where the locations of potential targets were known, *both EM-61 and GEM-3 EMI systems were capable of detecting all targets seeded in the standardized site to a depth of 11 times (11×) their diameter*. This is a standard frequently used by the CoE for the required depth of detection. The best performing systems detected more than 90% of the distribution of targets on the test grids at APG and YPG, even when all depths were considered. Magnetometer systems generally scored lower aggregate probabilities of detection on the Blind Grid.

This performance was achieved by only the best performing demonstrators. Many demonstrators performed far worse, even those using systems based on the same sensor technologies. *These results suggest that most targets exhibit sufficient signal strength to be detectable to depths of interest by currently available technology. Failures of similar systems to achieve equivalent performance suggest that poor field technique or improper target selection can negate a sensor's inherent capabilities.*

6.1.2 Detecting Targets in an Open Field

The best demonstrators detected 90% or more of the munitions at depths not exceeding 11× their diameter in the open field, where potential target locations were unknown. Difficulties in maintaining planned survey routes to achieve 100% site coverage and inaccuracies in geolocation are expected to have a degrading effect on performance compared with the Blind Grid, and observed decreases in detection rates are consistent with this expectation.

Specifically:

- *Most undetected targets in the standard test sites' open field by the better demonstrators are understandable through detailed analysis of their sensor data.* Common causes of missed targets include masking from nearby objects that exhibit stronger signals, location inaccuracy in excess of the 0.5 m requirement to be credited with a detection, or targets at depth that exhibit low amplitude signatures. Signal-to-noise ratio (SNR) is generally not limiting, except for a small number of items near the 11× depth.
- *The results from YPG show relatively higher Pds compared with APG.* This is at least in part attributable to the fact that the depth distributions at YPG were shallower due to difficulties burying targets deeply in the desert environment. However, even when items deeper than 11× are removed, the YPG Pds are higher.
- Although the groups of demonstrators and APG and YPG were not identical, *among common demonstrators, those that performed better at YPG for the most part also performed better at APG.*

6.1.3 Detectability Versus Depth by Ordnance Type

The 20 mm projectile, 60 mm mortar, and 155 mm projectile were studied in detail as examples of small, medium, and large munitions types. Details are found in section 5.4.3, and results of other munitions types are found in Appendix X. A summary follows.

6.1.3.1 Small ordnance

All demonstrators experienced difficulty detecting 20 mm projectiles. The depths to which 100% of the 20 mm projectiles are detected are far shallower than the 11× rule of thumb. Even the better demonstrators detected only about 70% of small items shallower than 11×. However, nearly all demonstrators detected at least some 20 mm projectiles at depths significantly deeper than 11×. This suggests that these items are not inherently undetectable by the sensors, but that the field procedures and target selection methodology, which were likely selected to detect the larger targets, were not suitable to their reliable detection.

6.1.3.2 Medium ordnance

For 60 mm mortars, the 100% detection depth of about 0.5 m approaches, but does not reach, the 11× rule of thumb for the better demonstrators, which included EM61 and GEM-based systems. This seems a reasonable estimate of the depth at which detectability falls off. Several demonstrators, including those using EM61 and magnetometer systems, detected at least one 60 mm mortar to depths in excess of 1 m.

6.1.3.3 Large ordnance

The 155 mm projectile is detected up to and beyond the 11× rule-of-thumb depth for the better demonstrators. The deepest 100% detection depths were achieved by systems using magnetometer sensors.

6.1.4 Data Collection and Analysis Procedures Matter

Demonstrators using the same sensors show significantly different results. This is observed at the top-level analysis of probability of detection on the suite of targets at the test sites, as well as in the detailed analysis of individual munitions. Demonstrators with 100% Pd on the Blind Grid used the EM61 and the GEM array. Other demonstrators using the same equipment experienced both vastly greater false alarms and much lower Pds.

The difference between the depth at which 100% of the items are detected and the deepest item detected is consistent with the conclusion that missed targets are not due to inherent limitations in the instruments. Although it is possible to detect all of the studied items much deeper than the observed 100% detection depths, these depths were not consistently achieved using current procedures and target-selection methodology employed at the test sites.

The gap between observed and theoretical performance is even greater. Likely contributors to the inability to achieve theoretical detection limits include more complex issues such as geologic noise and site clutter, as well as the effects of site survey coverage on data quality. Many other factors likely contributed to these differences:

- Platform implementation and associated noise.
- Choice of geolocation equipment and its implementation.
- Planned line spacing and along track data density.
- Correct field implementation of the work plan.
- Data processing steps to remove noise, time lags, and the like.
- Target selection threshold and further analysis procedures.

The difference between theoretical and observed performance suggests the need for additional research. Further, *this difference is a reminder that the performance achieved by one demonstrator using a particular sensor should not be used to predict performance of systems based around that sensor in general*.

6.1.5 Electromagnetic Induction versus Magnetometer Instruments

The best Pd on the ensemble of targets at the standard sites for a magnetometer is somewhat lower than the Pds of the better EM demonstrators. The appropriate choice will depend on the munitions of interest on a given site. Detectability of specific items must be considered as follows:

- For small items, both sensor types performed similarly.

- For medium munitions, the deepest items were more consistently detected by magnetometer-containing systems. However, depths to which magnetometers detected all the targets were shallower than for EM systems. The most appropriate technology will depend on the cleanup objective.
- For large munitions, magnetometer-containing systems detected 100% of the items to deeper depths. However, the deepest single items detected by magnetometers were at depths no greater than those for EM systems. Particularly for larger ordnance, however, the burial depths at the test sites may have been too shallow to show real differences.

6.1.6 DGM versus Mag and Flag Processes

*Mag and flag and EM and flag demonstrators achieved lower maximum Pds than the best demonstrators of DGM technologies. The mag and flag demonstrators experienced much higher false-alarm rate*s.

- For small items, DGM and mag and flag performed similarly in detection, but mag and flag false-alarm rates overall were higher.
- For medium items, the 100% detection depths for the DGM and mag and flag were comparable, but the deepest items detected were consistently deeper for DGM systems.
- For large items, both the 100% detection depths and the deepest items detected were at greater depths for the DGM systems.

For the munitions types and scenarios represented in the standard test sites, DGM consistently outperforms mag and flag. But in very high clutter environments such as the centers of impact areas, which are not represented in the standard test sites, mapping is not useful for the detection of individual munitions. Alternatives such as mechanical sifting or locating and removing a large fraction of the metal items with mag and flag should be considered before attempting DGM.

6.1.7 Translation to Geophysical Prove-Out Results

Overall, the most tested instrument was the EM61 and its variants, which appeared to perform the best for most ordnance items, except at certain sites. In many instances, it ranked at or near the top when comparing instruments within Geophysical Prove-Outs. In the majority of tests, EM61 instruments located 90–100% of the seed items buried for most munitions types from 37 mm to 155 mm.

For all except the 20 mm, the detectablity-versus-depth plots for the Geophysical Prove-Outs were consistent with the results observed for the standard sites. On the Geophysical Prove-Outs, 20 mm projectiles were consistently detected to deeper depths at higher Pds. It is likely that on Geophysical Prove-Outs where detection of 20 mm projectiles was paramount, the data collection and target selection were tailored to this munition to achieve better results. It is generally not clear from the Geophysical Prove-

Out results what penalty in added false alarms is incurred to ensure detection of 20 mm projectiles.

6.2 Impact of Major Findings on Munitions Response Projects

Table 6-1 summarizes the major findings and captures their impact on the executing a munitions response project. These considerations may be used as a guide to making decisions on how a project will select and deploy detection technologies.

6.3 Implementation Considerations

In this section, we consider the application of test site results to real-world situations. Three scenarios are presented, each designed to illustrate how the information from test-site performance evaluations might be used to select and evaluate technologies for specific applications. These scenarios show how the reader can comb through the performance data in chapter 5 to select the metrics relevant to a specific munitions response site.

These discussions are constructed assuming that the technologies are used in an optimum manner to achieve the results of the best performers at the test sites. As can be seen by the tremendous variation in test results from various contractors, even using the same equipment, results depend on proper field techniques to achieve the objectives of the project. The failure analysis offers important lessons in the investigation of the reasons for demonstrators using the same equipment performing poorly. This analysis is used to explore what can go wrong in the application of technologies to specific scenarios, as well as how instances of systematic errors can be identified, minimized, and corrected. Finally, the conditions at the standard test sites are relatively benign compared with a typical munitions response site conditions. As more difficult sites are encountered, maintaining the performance seen here is likely to be challenging.

The performance results are also relevant to establishing and evaluating quality control and quality assurance plans. Typically, some portion of the site is re-sampled in both steps to verify system performance. To be effective, the sensor and deployment configurations used for quality control and quality assurance must have a capability against the munitions of interest that both meets the project objectives and is at least as good as the survey sensor. These detailed performance results can be used to evaluate candidate sensors and sampling strategies.

6.3.1 Scenario 1—Mortar Range

Scenario Description—The munitions response site is a former mortar range. Both 60 mm and 81 mm mortars are known to have been used at the site. The range was constructed with a single firing point and multiple targets sited throughout a central impact area that was approximately 100 acres. Moderately dense munitions contamination is present immediately around identified target areas; contamination of a lower density can be found throughout the remainder of the impact area. The site has been surface cleared and is free of large trees or other obstructions. The initial investigations have shown no evidence of munitions use other than mortars. Soil conditions are such that the depth of penetration for mortars is not expected to exceed 0.5 m.

Technology Considerations—Looking at the 100% detection depths in Figure 5-7, the three best performers in detecting 60 mm mortars used EMI in towed-array configurations, with two using EM61s and one using a GEM-3 (demonstrators 3, 4, and 1). These three demonstrators all had 100% detection depths in excess of 0.5 m. If employed correctly, these systems are capable of detecting the mortars of interest with high probability to the depths of interest.

If deeper items were expected at the site, the magnetometer systems would also merit consideration. The deepest items detected bar on Figure 5-7 shows that for the most part, magnetometer-based DGM systems (demonstrators 11–17) are able to detect the 60 mm to depths of more than 1 m but, as deployed at the test sites, did not do so consistently. Although the magnetometer systems had similar 100% detection depths of about 0.3 m in both the mag and flag (demonstrators 19 and 20) and DGM applications, the deepest items detected were consistently deeper for the DGM systems. If only shallow targets of 0.3 m or less are of interest, the mag and flag systems would also be capable of detecting the mortars in this scenario. However, from the Pd versus BAR plot in Figures 5-4 and 5-5, it is evident that this would be at a cost of considerably greater false alarms.

For items in the medium-size range such as mortars, one of the most common reasons for missed detections at the test sites was the presence of a nearby item with a larger signature that masked the item of interest. Where the density of munitions and metallic clutter is high, this can occur on a response action project. Figure 6-1 shows an example of two nearby items in the data of two demonstrators. The demonstrator on the left, with higher data density, detected two targets, and the geophysics data were analyzed to estimate target parameters for both. The demonstrator on the right flagged only a single target at the location of the strong signal from the shallow clutter item, missing the deeper nearby mortar.

Good data quality can help mitigate the problem of shadowing targets, but the data quality objectives must be established and verified to ensure that the data can reveal subtle features as well as discrete, isolated targets. As can be seen in Figure 6-1, masking failures can be very difficult to detect in a sparse data set. Data parameters that merit consideration include line spacing, along-track data density, location accuracy, and sensor noise. In addition, data processing, such as filtering or gridding, can either enhance or smear subtle features. These effects should be understood for the targets of interest, and specific procedures or end-of-process data requirements should be established. Finally, the target picking and characterization methodology will ultimately determine which targets are dug.

Table 6-1. Practical Applications of the Findings Regarding Munitions Detection Systems

Major Finding Summary	Performance Supporting Data	Impact on Project	Uses and Applications	Reference to Detailed Analysis
All systems have trouble isolating single items when anomaly signatures overlap.	Numerous examples of missed individual munitions when signatures are shadowed by prominent nearby objects.	Even with careful surveys and high-quality data, items of interest may be masked.	Care should be taken to ensure that all objects of interest within an anomaly footprint are removed.	Figures 5.4, 5.5, and Section 5.3.5.
DGM achieved higher Pd and lower FAR than mag and flag.	DGM is more consistent in detecting deeper medium and large items and has deeper 100% detection depths for large items.	Where site conditions allow, DGM should be preferred to mag and flag.	DGM is applicable to flat terrain, low vegetation, and modest anomaly density. Mag and flag may be the only choice on steep terrain, dense vegetation, and as a first pass in areas of high anomaly density.	Figures 5-4, 5-5 and 5-7, and Section 5.5.3, best and worst performers of report.
Rule of thumb that items are detectable to depths approximately 11× their diameter is reasonable for currently available sensors.	For larger ordnance (60, 81, 105), Pd at 11× is ~80–90% and falls off sharply beyond this point. This is true only for better demonstrators; many fared far worse.	Even for well-executed surveys, a sharp drop in detection capability with depth can be expected.	The 11× rule could be applied as a quality-control parameter to alert Program Managers and regulators of possible deficiencies in contractor work.	Figures 5-8 to 5-13.
System noise is generally not the limiting factor in detectability of munitions.	Distance between 100% detection depth and deepest item detected indicates that deeper items can have sufficient SNR to be detected, but that they are not reliably detected with the field procedures and analysis strategies used.	Implementation matters—field work, processing, and analysis will all govern detection capability. Even where these factors are considered, items at depth could be missed.	Detectable items can be missed due to clutter, poor field technique, or improper target selection.	Figure 5-7 and Section 5.4.5 on failure analysis.
All systems have trouble detecting smaller items. Smaller items are more likely to be missed at shallower depths than larger items are.	Spread between 100% detection depth and deepest item detected is proportionally much greater than for larger items. Small items at depths of interest are detectable if the sensor element passes closely enough.	When smaller items are of interest, survey data quality objectives must be set up specifically to look for these items. • Narrower line spacing. • Lower sensor height. • Tailored target picking.	When reliable detection of small items is essential, single-pass, detection-driven approaches may not be sufficient. Multiple passes or mechanical means, such as sifting, may be required.	Figures 5-7, 5-8, 5-9, and 5-19.

Major Finding Summary	Performance Supporting Data	Impact on Project	Uses and Applications	Reference to Detailed Analysis
There is no clear winner in magnetometer versus EMI for all munitions types and depths		Sensor selection requires consideration of munition types of interest and response action objectives.	For complex, mixed-use sites, more than one sensor type may be necessary.	
• Magnetometers generally have lower Pds on an ensemble of mixed targets than EM devices; Pds are lower for small ordnance, but magnetometers are better at detecting deeper medium and large ordnance.	100% detection depths for 60 mm and 105 mm are consistently greater for systems containing a magnetometer component.			Figures 5-4, 5-5, 5-7.
• EM61 typically performs best for most ordnance items in Geophysical Prove-Outs with mixed ordnance types.	EM61 typically locates 90–100% of seed items buried for most ordnance types from 37 mm to 155 mm.			Figures 5-19 to 5-22.
Aggregate Pds against ensembles of target types and depths provide limited information to support decisions.	Differences in sensor capabilities to detect munitions varies by size, depth, and local clutter environment (among other factors)	Understanding sensor performance for specific project objectives requires detailed study of the detection of munitions of interest and investigation of the root causes of any failures.	Pd on an ensemble of targets is not optimal as a Geophysical Prove-Out metric for acceptable performance.	Figures 5-3 to 5-6, 5-19 to 5-22, and Section 7-3.
Only magnetometer and EMI sensors have demonstrated robust performance detecting buried munitions. Alternative sensors have not demonstrated comparable capability.	Standard test site and GPO data demonstrate magnetometer and EM detection capability. R&D projects exploring alternative sensors do not indicate comparable performance.	Proposals to use alternative technologies on MR projects should be carefully scrutinized.	For MR sites that challenge magnetometer and EM technologies, alternative technologies are not likely to provide better detection ability.	Figures 5-3 to 5-6, 5-19 to 5-22, and Section 7-3

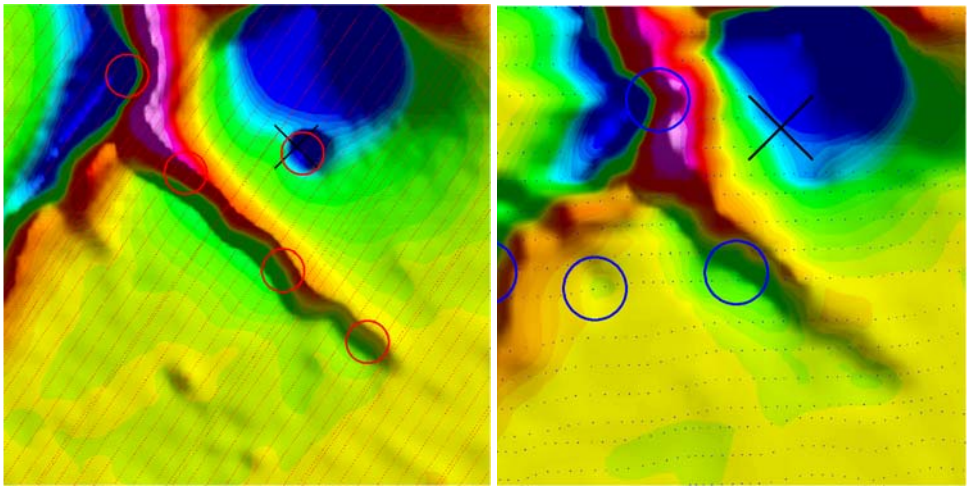


Figure 6-1. The target marked by the X is a mortar. The demonstrator on the left, with closer track spacing, is able to resolve the target of interest from the nearby large clutter object and marks it with a circle. The demonstrator on the right, with larger line spacing, is not.

This type of failure also has implications for reacquisition and quality assurance/quality control. For the demonstrator with better data, where both targets are detected and well located, the flagged positions could be dug and both items recovered. For the demonstrator with sparser data, one item could be missed if the single flag were dug and a small search radius strictly employed. In this case, the entire area covered by the anomaly should be checked when digging to ensure that there are no items too weak to be seen in the footprint of the larger anomaly.

6.3.2 Scenario 2—Aerial Gunnery Range

Scenario Description—The munitions response site is an aerial gunnery range impact area with a combination of 2.75-inch rockets, and 37 mm, 20 mm, and .50 cal. projectiles. Several targets located in a central impact area were heavily used. Dense munitions contamination is present out to about 50 m from each target center, with moderate- to low-density contamination across the remainder of the site. The site has been surface cleared and is largely free of vegetation, save some isolated trees and large shrubs. Terrain is for the most part flat, with some rolling hills and a steep wash through the center of one target on the site. The .50 cal. munitions are ferrous, consisting of a copper jacket covering a solid steel projectile, and present no hazards. During initial site investigations, maximum penetration depths for 2.75-inch rockets and 20 mm and 37 mm projectiles were determined to be 2 m, 0.25 m, and 0.50 m, respectively. Clearance to the depth of the 20 mm and larger munitions is required for planned development.

Technology Considerations—The 2.75-inch rocket is reliably detected by many instruments and does not present a significant challenge to current DGM or mag and flag technology. But reliable detection of the 20 mm and 37 mm projectiles to depth will require special consideration. The results from the test site, where the ordnance mix spanned a wide range of sizes, suggest that these items were not reliably detected using field procedures typically used for larger items, procedures followed by most demonstrators.

All systems detected at least some of the 20 mm and 37 mm items to deeper depths, which suggests that these items have signals that are not below the detection limits. These signals are small in amplitude and limited in spatial extent, however, and the sensor must pass very close to the item to detect it. Figure 6-2 illustrates this problem.

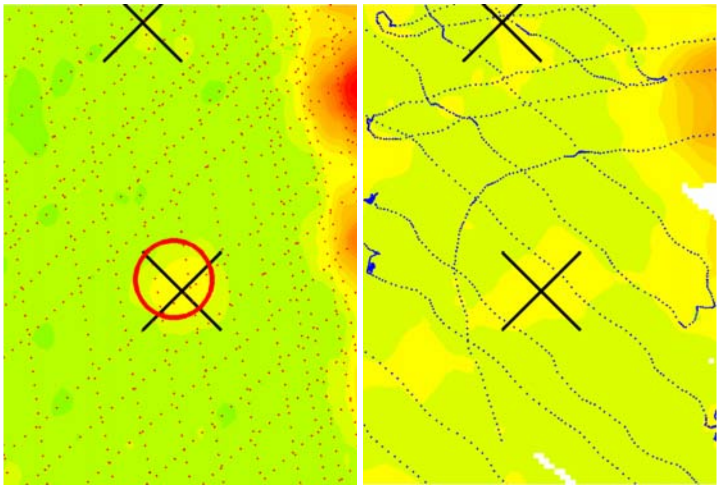


Figure 6-2. The 20 mm projectile is indicated by the center X. The demonstrator on the left, with closer, regular track spacing detected the relatively weak signal of this target, but the demonstrator on the right, with much lower data density, did not.

To reliably detect small items such as 20 mm or 37 mm projectiles, alternative field procedures must be considered. One approach is to employ narrower line spacing in the geophysical survey. Simply increasing the number of towed or man-portable sensors in an array configuration will correct the problem of limited spatial extent of the anomaly as shown in Figure 6-2. The line spacing and along-track data density of the mapping survey should be selected to allow for a sufficient minimum number of sensor readings above the background noise threshold for the weakest anomaly of interest, in this case the deepest item of interest at the maximum possible offset.

Another approach would be lowering the sensor height, which will preferentially increase the signal amplitudes of small shallow items. This strategy has worked on fields with mixed bombs and 20 mm projectiles (CH2M Hill 2005). Note that this practice will also increase the system response to small, shallow clutter and metallic debris.

The highly concentrated areas on this site may not be initially tractable with DGM. On the other hand, the test site results suggest that mag and flag likely misses the larger deep items, and ensuring 100% coverage with this method is always problematic. Thus, an approach utilizing mass removal by either mag and flag or sifting with heavy equipment, followed by DGM, may be appropriate.

Isolated sections of the site, near trees and in the wash that are not accessible by towed arrays, will require an alternative approach using a different mapping platform. To maintain consistent performance, the data quality objectives for platforms deployed to these areas should closely mimic those developed for the rest of the site in terms of data density, location accuracy, and system noise. Still, the realities of maneuvering a platform in rough terrain where DGPS accuracy may not be attainable will often require compromises in project objectives and expectations for these portions of the site.

6.3.3 Scenario 3—Artillery Range

Scenario Description—The munitions response site consists of a former artillery range used for 105 mm and 155 mm projectiles. Again, a single firing point was used, and multiple target areas are present in a central impact area. There are four known high-density target centers, and lower density munitions and fragments can be found throughout the impact area. The impact area is level and grassy with good sky view for GPS, and the site geology is benign. Clearance to depth is required to support future development plans. It is desired to remove all detectable munitions.

Technology Considerations—The 100% detection depths for 155 mm projectile shows two things clearly. First, the depth to which mag and flag detects 100% of these items is much shallower than that achieved by magnetometer-based DGM. The former barely exceeds 1 m (demonstrators 19 and 20), but the latter are approximately 2 m for the better demonstrators (13 and 14) and may in fact be deeper because results from the sites are limited by the deepest item buried. Second, the DGM systems that used magnetometers had the two deepest 100% detection depths for 155 mm projectile, and these were both deployed on towed arrays. Since the primary objective is to remove all detectable ordnance and the site is suitable for magnetometer systems, the magnetometer towed array is clearly the platform of choice.

Several EM61 systems (demonstrators 3, 4, and 6) and the GEM towed array achieved 100% detection depths near or in excess of 1.5 m. For similar sites where response action objectives are not as deep or projectile penetration depths are limited by site geology, these systems could also be suitable alternatives.

On many artillery sites, there is also a concern with bursters and fuzes. These are potentially hazardous components of artillery that must also be detected and removed. If this is the case, selecting equipment and protocols based solely on the detection performance for large intact items will not be appropriate. Because bursters and fuzes are not represented in the test sites, data specific to these items are not available. Comparably sized items must be examined for comparison. Here, the towed magnetometer arrays that were most successful in detecting the large, deep items did not fare as well as EM towed arrays for medium-sized munitions, and none of the systems as demonstrated achieved reliable performance against 20 mm munitions. If the response action objective includes bursters and fuzes, multiple approaches may need to be considered.

6.4 Additional Factors to Consider

The conditions at the standard test sites are relatively benign compared to typical munitions response site conditions. As conditions become more difficult, additional consideration of site coverage, data quality, and the like will be needed, and quality control checks may have to be more stringent. Table 6-2 summarizes some of the conditions that are likely to degrade performance and the impact that those conditions are likely to have.

Table 6-2. Real-world effects on geophysical system performance.

Real-World Challenge	Impact
Geologic noise	Decreased probability of detection and detection depth. Increased false-alarm rate.
Terrain	Motion noise. Accessibility. Difficulty in achieving 100% coverage. Difficulty for navigation systems.
Vegetation	Accessibility. Difficulty for navigation systems.
Crew experience and skill	Poor field technique will compromise data quality.
Complex mixed use ranges	Compromises in field procedure and analysis strategy to detect multiple diverse target types may not be optimal for any one munition of interest.
Extensive metallic debris and clutter	Performance or efficiency suffer. Targets with overlapping signatures make data analysis difficult.
Instrument malfunction	Unexpected noise sources or data gaps.
Processing and analysis procedures	Improper data leveling. Geolocation problems. Improperly set thresholds.
Reacquisition and excavation procedures	Improper procedures can result in recovery of objects other than those intended from the geophysical analysis. For example, geophysics indicates large deep item, but nearby small, shallow clutter item is dug instead.

Some of the items listed in Table 6-2 can be mitigated through proper quality-control procedures, but other are largely unchangeable, and their effect on realistic performance expectations should be addressed in setting project objectives. The most difficult of these factors to control and mitigate is the effect of geologic noise. Specialized data processing has been developed and successfully applied at sites with particular geologic challenges. However, at many sites, lower detection capability, in terms of the size and depth to which items can be detected, and higher false alarms arising from geology will be inevitable. Filtering of geologic noise is currently the subject of R&D.

Other real-world factors, such as field technique, instrument function, overall data quality, or target selection, are readily mitigated by careful quality assurance and quality control. Depending on the specific concern, this may come in the form of frequent instrument function tests, oversight of field procedures, careful checks of data products, or random field resampling.

7.0 ADVANCED DETECTION AND DISCRIMINATION

Current research and development efforts typically focus on hardware and algorithms to improve either the detection performance or discrimination capability (or both) over that available from today's systems. In this context, we define detection and discrimination:

- Detection—the ability to extract a signal arising from an object of interest from the noise.
- Discrimination—the ability to separate detected anomalies into two classes, (1) munitions and (2) clutter items, which do not require removal.

Successful discrimination requires that we make the false-negative rate (munitions items incorrectly classified as clutter) vanishingly small while simultaneously reducing the total number of the detected anomalies that must be dug. In addition, we need to understand the limitations of discrimination technology so that we can intelligently manage risk. The current approach combines digital geophysical data and discrimination algorithms to positively identify clutter items that can be left in the ground.

This section reviews ongoing efforts in these areas.[1] Because magnetometer and EMI systems have proven to be the most useful sensors for both these tasks, they are the focus of current research. However, other technologies, particularly for discrimination, have been researched, and we briefly catalog some of those. Finally, we summarize recent efforts in the emerging areas of underwater surveys and wide-area assessment to delimit munitions-contaminated areas from clean areas. Table 7-1 lists some areas of detection and discrimination that are challenging to current sensors and the focus of much of the ongoing research and development efforts. Detection of medium and large munitions to the 11× diameter depth in benign geology and topology is achievable by current technology, so research is focused on the more difficult detection situations. Discrimination performance is not as advanced as detection capability, so much discrimination research focuses on understanding data requirements for successful discrimination.

7.1 Detection

As is clear from Standardized Test Site results presented in Section 6, the detection capability of current equipment is far ahead of its ability to discriminate munitions from items that would not have to be dug in a response action. Nevertheless, we would like improved detection performance even in benign situations. Beyond that, there remain many detection issues worthy of study and advancement, including detection of

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[1] This section reflects the status of advanced technologies as of the writing of this document in June 2006. As research continues to evolve, this material will become obsolete. The reader is directed to the various program offices referenced herein for the most up-to-date information.

munitions in highly cluttered or geologically active backgrounds, detection of small munitions close to the surface, and detection of large, deep objects.

Table 7-1. Detection and discrimination research and development challenges

Task	Challenge
Detection	Adverse geology or topography Heavily cluttered environments Small munitions (<60 mm) Deep munitions (>11× diameter) Underwater munitions Multiple anomaly identification and separation
Discrimination	Sensor requirements definition • Frequency/time-gate coverage • SNR requirements • Single vs. multiple transmit/receive axes • Sensor orientation effects Accurate DGM data geolocation Reliable classifiers with quantified false-negative rates Geology/topography/clutter effects Survey-based discrimination

There is significant synergy in ongoing efforts focused on improved detection and those focused on improved discrimination. Improving detection essentially requires improving the signal-to-noise ratio (SNR) for targets that are not currently detected reliably, such as those deeper than 11× their diameter. This may be approached by increasing the signal by increasing the transmit moment or sampling part of the decay curve that is difficult to reach but provides a stronger target response. Alternatively, improving SNR may be approached by reducing noise through the development of new sensor elements or advanced processing to filter noise. Regardless, the improvements in SNR that increase detections will also produce better data for discrimination.

Research has shown that successful discrimination requires a significantly higher SNR than simple detection. For that reason, new sensors aimed at discrimination are designed to provide better SNRs than current systems, and hence better detection performance. Emerging dual-mode sensors, which combine the advantages of magnetometers and EMI sensors, offer the possibility for improved detection performance against all targets. Magnetometers detect only ferrous metal such as steel but typically are more sensitive to deeply buried objects; EMI sensors generally perform better for detecting small, shallow objects, are sensitive to all metals, and are more immune than magnetometers to geologic noise. Dual-mode systems also offer significant promise for improving discrimination through cooperative inversion, where magnetometer data are used to constrain an EMI classification algorithm. Many techniques are similar in that they offer benefits in both arenas. This section discusses only those efforts solely focused on detection improvement, leaving discussion of devices, models, or algorithms with applications to both areas for section 7.2 on discrimination research. Table 7-2 summarizes the efforts discussed and provides references.

Table 7-2. Detection technology research and development examples.

Study	Objectives	Reference
Improving Detection and Discrimination of UXO in Magnetic Environments	Understand the geologic origins and physics of soil magnetization, develop protocols for characterizing site magnetization, establish procedures for removing soil effects from magnetic measurements, and establish methods for preprocessing EM data.	Li 2004
Multi-Channel EM Data Processing Algorithms for Target Detection in Magnetic Soils	Use multichannel EM sensor to detect munitions in magnetic soils by taking advantage of the decay differences in the response of soils and munitions.	NAEVA Geophysics 2001
Sub-Audio Magnetics (SAM)	Simultaneously acquire the magnetic and electromagnetic response of subsurface munitions with a cesium-vapor magnetometer using a large loop on the ground (tens of meters diameter) to provide the pulsed magnetic field.	G-tek 2003
Man-Portable Simultaneous Magnetometer and EMI System	Develop a man-portable system that simultaneously collects total field magnetometer and time-domain EMI data to provide the benefits of the merged technologies in munitions detection and discrimination.	SAIC 2006

7.1.1 Detection Modeling and Algorithm Development

From a pure detection standpoint, major problems occur in areas where local geology is magnetic. A classic example is the cleanup effort at Kaho'olawe, Hawaii, where magnetic soil rendered magnetometers almost useless and greatly reduced the effectiveness of EMI devices. Two current studies are focused on understanding the effects of geology and improving performance in unfavorable conditions.

The Colorado School of Mines leads a team that is attempting to understand the geologic origins and physics of soil magnetization (Li 2004). The team is developing models capable of characterizing site magnetization and is exploring signal-processing methods and procedures for removing soil-response effects from magnetic measurements. In two projects, Geophysical Associates employed multigate, hand-held EMI sensors and utilized the difference in decay characteristics between munitions and magnetic geologic features to improve detection performance in magnetic backgrounds. Figure 7-1 shows the results of applying this processing technique at Camp Croft, where geology significantly hampers detection. The image on the left is the result of standard processing of EM-61 Mk2 data. The decay analysis reduced the number of items to dig from 8,000 targets, with the EM61 Mk2, to just over 1,400 (D. Smith, personal communication, 28

March 2006). Geologic returns mask detection of desired targets and create false targets, as seen by the large number of detection calls, shown by triangles on the figure. When the decay analysis was applied to the data, the result was the image on the right. A survey on a 5-acre site at Camp Croft resulted in several thousand anomalies per acre, which needed to be dug within a 2-week scheduled period. Reanalysis of the existing data using the chi-squared analysis markedly reduced the geologic anomalies, as can be seen in the figure, allowing the Corps of Engineers to complete the excavation within the allotted work window.

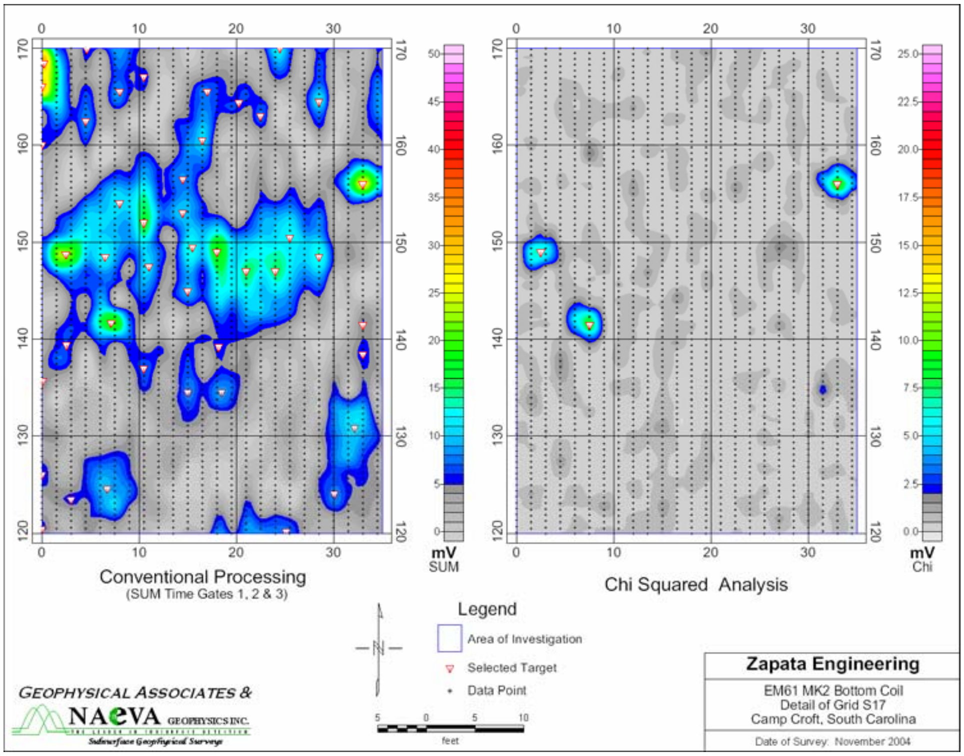


Figure 7-1. Camp Croft EM data showing conventional processing (left) and the GPA chi-squared analysis (right).

7.1.2 Advanced Detection Systems Development

Almost all the current sensor-development programs have the dual objective of improving detection and discrimination performance; Section 7.2 provides details of those systems. Here we note that the Sub-Audio Magnetics dual-mode sensor utilizes a very large loop on the ground (generally tens of meters on a side) to provide a more uniform and more deeply penetrating field for EMI detection. It is developing an improved pulsed transmitter to provide better detection performance. Similarly, new pulsed transmitters being developed under two other SERDP projects produce higher currents along with sharper cutoff times to allow better sampling of the large, early-time response from targets, while maintaining a sufficient late-time response for discrimination.

7.2 Discrimination

The first requirement in a cleanup operation is that all detectable munitions be removed. But experience has shown that digging all detected anomalies often results in removing a hundred scrap items for every munitions item dug—an extremely expensive process. The costs associated with digging nonhazardous items motivates a search for methods to differentiate munitions from scrap based upon geophysics data. This is termed "discrimination." For the most part, the physics-based discrimination that has been the subject of recent research has seen limited field use to date. The instances where it has been successfully applied are described below. However, most projects practice some form, whether formalized or not, of anomaly discrimination. This is often simply the selection of the threshold below which targets are not picked. But target selection is sometimes based on the geophysicical interpretation of the size and shape of the anomaly, or filters are employed to remove large-scale geological responses.

The Defense Science Board Task Force on Unexploded Ordnance noted in its 2003 report that 75% of the total cost of a current response action is spent on digging scrap. Reducing the number of scrap items dug per munitions item from 100 to 10 could reduce total response action costs by as much as two-thirds. Discrimination efforts focus on technologies that can reliably differentiate munitions from items that can be safely left undisturbed.

Discrimination only becomes a realistic option when the cost of identifying items that may be left in the ground is less than the cost of digging them. Because discrimination requires detection as a precursor step, the investment in additional data collection and analysis must result in enough fewer items dug to pay back the investment. Even with perfect detection performance and high SNRs, successfully sorting the detections into munitions and nonhazardous items is a difficult problem but, because of its potential payoff, one that is the focus of significant current research. Emerging discrimination algorithms typically take advantage of the fact that most munitions are axially symmetric, cylindrical objects, and their electromagnetic characteristics are different from those of irregularly shaped scrap items. Issues under investigation in developing and applying discrimination techniques include the signal-to-noise ratio required for reliable discrimination, the number and diversity of the distinct looks (i.e., different geometries of transmitted and received field directions) required to adequately define the object's properties, and the value that multiple frequencies or time gates bring to the discrimination problem. A connected problem, arising because most current EM systems use a single-axis transmit and receive coil, is how accurately relative position must be known for data where multiple sensor positions are used to provide illumination diversity.

As noted above, evolving discrimination algorithms require the anomaly to be illuminated from multiple directions. To date, the requirement for carefully controlled and precisely located data-collection points over an anomaly has made cued discrimination necessary. That is, an anomaly is detected on an initial survey, its position is noted, and the data required for discrimination is collected on a separate, second survey. Work is ongoing to improve geolocation technologies, but currently some guide such as a physical template must be used to achieve required accuracies. Figure 7-2 shows one such approach from a cued data collection by AETC at the DuPont, Bridgeport, Conn., site. In this case, a template is used to accurately position the EM-61HH to provide quality data for inversion. The template data were used to remove 584 nonmunition items from a list of 694 possible detections on a cart-based EM-61 MkII survey.

Figure 7-2. Cued identification of anomalies using an EM-61HH and template.

As is obvious from the figure, cued identification using templates is not efficient. The template must be placed for each anomaly, and then data must be collected in a set pattern at each template position. Improved efficiency would be obtained on cued data collection for discrimination if the sensor head position could be accurately determined and recorded, removing the need for a template. Efforts to achieve that goal, where a head-mounted laser target or inertial measurement unit is used to sense head position and orientation, are a focus of research (Bell 2004, Foley 2005). The goal is to provide sufficient relative position accuracy between data points to allow successful data inversion for discrimination.

Maximum efficiency would be achieved with survey-based discrimination because it would completely eliminate the need for a second survey. Towed arrays offer a partial solution to the navigation problem, as the sensor-to-sensor spacing is accurately known. However, accurate down-track geolocation is required, and track-to-track geolocation knowledge is required in cases where anomaly signatures exist across multiple tracks. Requirements for location accuracy are significantly reduced if the survey instrument can produce multiple illumination directions from a single point. That is a focus of current research described in more detail in section 7.2.2.1. Summaries of the discrimination efforts, along with references, are provided in Table 7-3.

Table 7-3. Discrimination technology research and development examples.

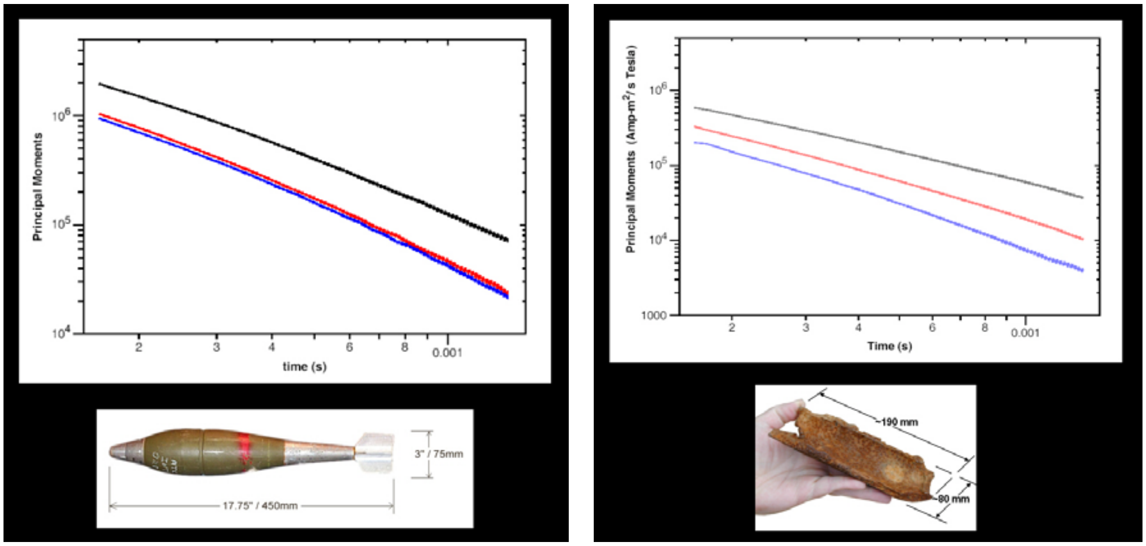
Study	Objectives	Reference
Efficient, Realistic Physics-Based Modeling for Buried UXO Based on Time-Domain Electromagnetic Scattering Signatures	Deliver software suitable for transition to time-domain EMI sensors that provides an efficient, high-fidelity, physics-based model for realistic target shapes to be used in forward modeling and inversion for discrimination.	Weichman 2005
UXO Discrimination by Mid-Frequency Electromagnetic Induction	Perform basic research on sensor development signature possibilities in the 25 kHz to 300 kHz band to provide additional options in discriminating munitions from clutter and reduce false-alarm rates.	O'Neill 2002
Model-Based, Robust Methods for UXO Discrimination from Time and Frequency Domain EMI	Refine and enhance discrimination and signal-processing algorithms, develop frequency-domain and time-domain signature libraries, and validate the algorithms.	Miller 2004
Statistical and Adaptive Signal Processing for UXO Discrimination for Next-Generation Sensor Data	Exploit and refine phenomenological models to predict target signatures for the new sensor modalities, develop physics-based statistical signal-processing approaches and quantify the data needs, develop the theory of optimal experiments to guide the design and deployment of discrimination algorithms, and develop graph-based kernel algorithms for target classification.	Collins 2005
UXO Classification Using a Static TEM Antenna Array	Develop and test an apparatus based on the concept of acquiring static, broadband, multi-axis, EMI measurements with an antenna array for classification of munitions.	Zonge 2003
Multisensor System for the Detection and Characterization of UXO	Demonstrate a multisensor EMI system to discriminate munitions from clutter that can perform target characterization from a single position of the sensor platform above a target. Goal is to exceed detection capabilities of existing sensors.	Gasperikova 2005
Modification and Testing of the Very Early Time Electromagnetic System, and the Tensor Magnetic Gradiometer System for UXO Detection, Imaging and Discrimination	Improve detection, imaging, and discrimination of munitions using existing magnetic and EMI prototype systems originally designed for other geophysical applications. Goal is to demonstrate that a combination of modified instrumentation and new interpretation algorithms can result in high probability of detection with reduced probability of false alarm.	Wright 2004
EMI Sensor Optimized for UXO Discrimination	Develop and produce a prototype munitions-specific EMI sensor optimized for detection, classification, and identification.	NRL 2005

7.2.1 Discrimination Modeling and Algorithm Development

Recent discrimination modeling has focused on the electromagnetic response differences between munitions and other metallic objects. Discrimination algorithm development has basically followed two paths. The first, model-based discrimination, focuses on comparing measured data to a physics-based model of munitions-like responses and evaluates fits to those models. The second, feature-based discrimination, may use physics to guide feature selection, but it focuses on the use of training data to discern the differences between munitions and other objects in a multidimensional feature space.

7.2.1.1 Model-Based Discrimination

Model-based discrimination exploits the fact that the typical munition is an axially symmetric, cylindrical object with a reasonably large aspect ratio, while many scrap objects are irregularly shaped. The simplest of model-based discrimination algorithms makes use of the fact that munitions are expected to have one large polarizability moment associated with the major axis and two smaller and equal moments associated with the minor axes, as shown from a Lawrence Berkley National Lab model of the response from an 81 mm mortar in Figure 7-3a. Scrap is more likely to have three unequal moments as shown in Figure 7-3b.



a. 81 mm mortar. **b. piece of scrap.**

Figure 7-3. Lawrence Berkley National Lab model results for the principal polarizability moments as a function of decay time calculated for a munitions item and a piece of scrap.

Note that the curves of Figure 7-3 cover a time scale from about 100 μs to about 2 ms after transmitter turn off, as the response from the target decays. Simple models based on polarizability moments could make use of a single time-gate EMI measurement sampling a small portion of the decay curve to determine whether the target appeared to be axially symmetric. However, the detailed shape of the curves is dependent on the target size, material composition, and wall thickness. More sophisticated modeling efforts underway are aimed at understanding the detailed decay characteristics of munitions versus other buried items and using that information to improve discrimination. BAE Systems has developed fast, approximate prediction algorithms for use in real-time inversion. A CRREL-led group has developed both exact and approximate solutions to guide model-based discrimination.

Emerging Discrimination Tools: UX-Analyze

Model-Based Analysis

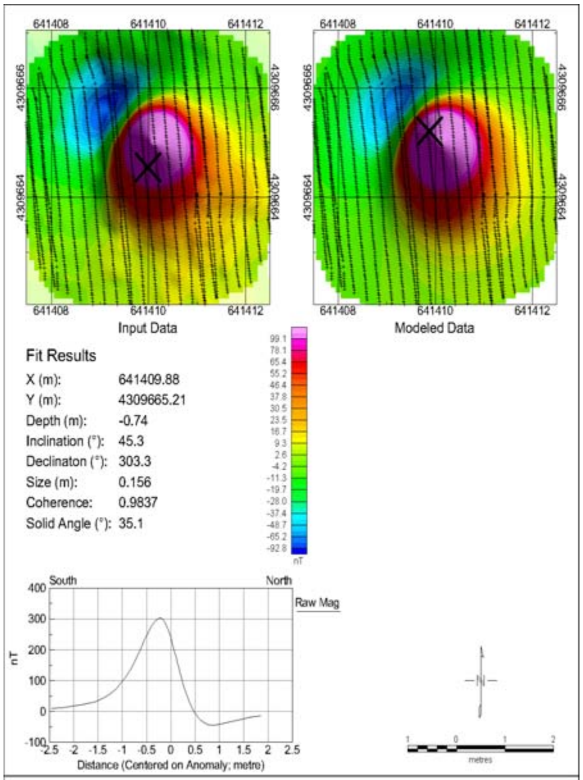
UX-Analyze has been developed as a module to run in the Oasis Montaj platform. It allows the analyst to select targets for analysis from a graphical user interface that displays a map of geophysical data. EM or magnetometer data associated with the selected target can be inverted using physics-based models to estimate intrinsic target parameters such as size, depth, and polarizability, which may be used to determine whether the selected target is similar to the munitions of interest.

Feature-Based Discrimination

Following the extraction of target parameters, the analyst has the option to choose from a number of advanced signal-processing algorithms to evaluate the likelihood that the signal corresponds to a target of interest.

Documentation

As indicated in the output, the program stores the measured data and the fitted parameters and graphically displays the results for use by the project team.



```
Fit Results
X (m):              641409.88
Y (m):              4309665.21
Depth (m):          -0.74
Inclination (°):    45.3
Declinaton (°):     303.3
Size (m):           0.156
Coherence:          0.9837
Solid Angle (°):    35.1
```

MTADS vehicle magnetic data - Anomaly 118

7.2.1.2. Feature-Based Discrimination

Much of the feature-based discrimination work has used an appreciation of the underlying physics to design algorithms, so too sharp a division between it and the model-based methods is misleading. Nevertheless, feature-based methods generally apply training data to learning algorithms to distinguish munitions from items not of interest. Figure 7-4 shows a ROC curve based on GEM-3 data collected at Jefferson Proving Ground. Out of 202 total anomalies, 16 were munitions. The mag and flag curve is based simply on signal amplitude. The vendor performance is the result of standard GEM-3 processing. Duke University applied two different learning classifiers (support vector machine and generalized likelihood ratio test) and gained the discrimination improvements shown. That earlier work is now being extended by Duke under another project whose goal is to develop advanced statistical and adaptive signal-processing algorithms for discrimination that take advantage of the richer data set from new sensors in development.

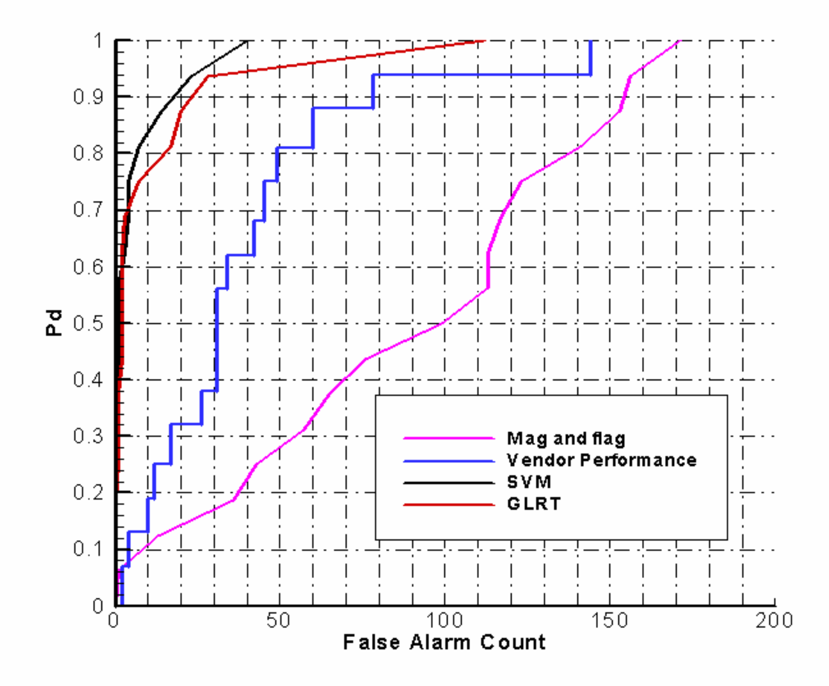


Figure 7-4. Duke University discrimination results using GEM-3 data collected at Jefferson Proving Grounds.

7.2.2 Advanced Discrimination Systems Development

As a result of associated modeling and measurement efforts supported by SERDP, the research and development community has reached the consensus that successful discrimination generally requires target interrogation from enough different directions that detectable responses from the three orthogonal axes of a target are excited. Successful discrimination also requires knowledge of data point relative positions in the 1 cm accuracy range. For that reason, systems that provide multiple illumination directions at a single measurement point are of great interest. Cooperative inversion, where magnetometer data are used to determine the depth and size of the anomaly and those data are then used to constrain an EMI solution, has proven to be more stable and accurate than inversion from multigate EMI data alone (AETC 2004). Research is underway on joint algorithms, where the two data sets are fused; those techniques may eventually provide better results than cooperative inversion. Because dual-mode systems that can provide simultaneous magnetometer and EMI data aid either cooperative or joint inversion, they are an area of research interest.

7.2.2.1 Multiaxis Systems

Systems that provide multiple illumination directions from a single survey location significantly reduce precise geolocation problems, potentially provide more rapid data acquisition, and may allow accurate discrimination to be performed in a survey mode. These potential advantages make multiaxis systems a topic of significant current research. Some examples are summarized below.

Zonge Engineering is developing a cued identification system, but one that can collect all required data from a single sensor position. Three orthogonal transmitter coils are pulsed sequentially to provide diverse target illumination. Multiple triaxial receiver coils are used to sense all components of the decay field from the anomaly.

The group at Lawrence Berkley National Lab has developed an active electromagnetic system, optimized to determine the size, shape, orientation, shell thickness, and metal content of a target using survey data. The resulting system, shown in Figure 7-5, is configured with three orthogonal transmitter coils and multiple receivers to record sufficient data in a single measurement to calculate the intrinsic target parameters of interest. Field testing is planned for 2006.

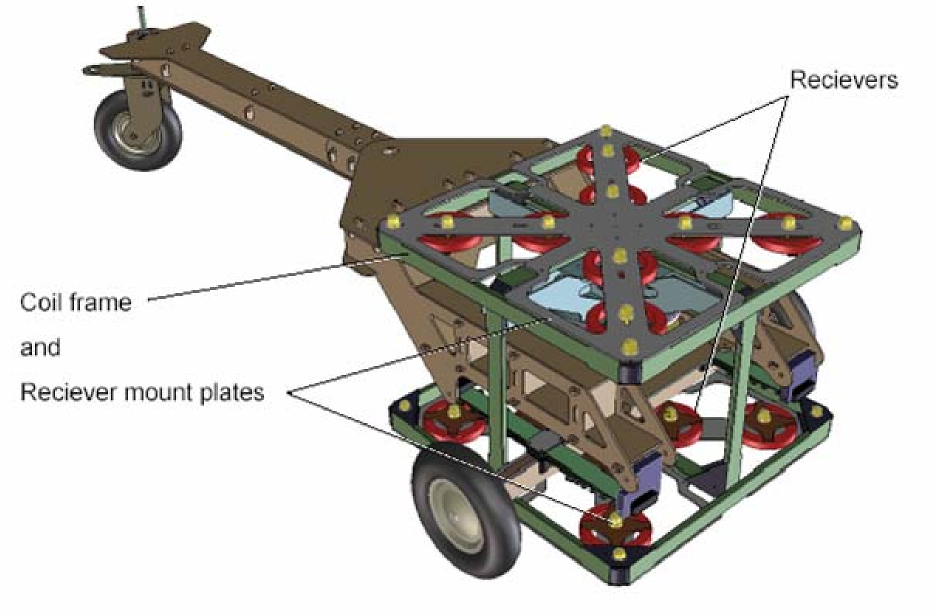


Figure 7-5. Field prototype of multisensor active electromagnetic system.

A team led by the U.S. Geological Survey is developing the ALLTEM system, which also uses three orthogonal transmit coils and multiple receive coils. Rather than using a pulsed waveform, however, this device uses a sawtooth waveform and receives while the primary field is transmitting. Modeling efforts are underway to exploit additional discrimination information available from this configuration.

7.2.2.2 Dual-Mode Systems

UXO site characterization is typically conducted using a single sensor technology, almost exclusively employing either magnetometry or electromagnetic induction sensors. The two sensors have complementary detection and discrimination capabilities, suggesting the potential for dual-mode surveys to improve performance. The simultaneous deployment of these two technologies on a single platform is difficult due to the active nature of EM technology, which generates electromagnetic fields that are picked up as noise by magnetometers operated close to each other. Recent investments have been made in dual-mode sensor technology to increase the probability of detection, minimize false detections, and improve discrimination.

SAIC (formerly GeoCenters) has developed the capability to simultaneously acquire five channels of total field magnetometer data and three channels of EM-61 Mk 2 data on the Vehicular Simultaneous EMI and Magnetometer System (VSEMS) platform (see Figure 7-6). The project team developed and integrated electronics for interleaving data collected by these two sensors and designed a new nonmetallic proof-of-concept towed platform. The multisensor STOLS first was deployed in November 2002 at the APG standardized test site. In May 2003, STOLS supported a geophysical assessment at the Former Lowry Bombing and Gunnery Range in Aurora, Colo. The objective was to detect, locate, and discriminate all subsurface objects that were K941 ferrous shipping containers (also known as PIGs), which might be associated with chemical-warfare material. STOLS covered about 70% of this area at a production rate of nearly 10 acres per day.

Figure 7-6. Multisensor STOLS system.

The SAIC team is currently developing a new version of the interleaved magnetic and EM hardware for use on a man-portable platform by reducing the size, weight, and power consumption requirements of the STOLS system.

AETC, Inc has also been developing a dual-mode survey instrument. The hand-held system (see Figure 7-7), initially constructed using an EM73, was field tested at the Blossom Point test facility near La Plata, Md., and at the ERDC test facility in Vicksburg, Miss. The system was too heavy for a deployable hand-held sensor. System improvements in the next phase of the project have included using a GEM-3 sensor with a magnetometer, which significantly increases the ergonomic feasibility of the sensor, as well as adding multifrequency capability and compensation for EM-induced offsets in the magnetic data.

Figure 7-7. Dual-mode sensor survey at ERDC Vicksburg Test Facility.

Geophysical Technologies Limited (GTEK) has developed a system called Sub-Audio Magnetics (SAM), which can simultaneously acquire total field magnetic and total field electromagnetic induction responses from munitions. EM excitation is provided by a 40 m by 100 m transmitter loop laid out in a square surrounding the survey area. A bipolar, pulsed waveform is transmitted through the loop using a typical repetition rate of between 5 and 30 Hz and on/off times of 10–30 ms. The operator covers the area within the loop with multiple parallel, straight-line traverses while carrying the TM-6 receiver and an array of four Cesium vapor magnetometers. The system has been tested on the Standard Test Sites and at real-world sites in Montana to quantify the performance and limitations of the system.

7.3 Unsuccessful Technologies for Detection and Discrimination

Munitions response contractors all currently use magnetic or electromagnetic methods for detecting and discriminating munitions from metallic scrap. A number of other technologies have been investigated, but none has yet matched the performance of state-of-the-art magnetometer and EMI systems. Technologies tested include ground penetrating radar (GPR), sonar, acoustic, and seismic sensors. Sonar (discussed separately in section 7.5) appears to offer benefits in the underwater survey environment. Table 7-4 summarizes alternative technologies that have been researched and tested. The table includes the technology name, work completed, and a performance assessment. Because none of those efforts were carried forward, detailed discussion is not provided, but the interested reader can obtain further information from the referenced reports.

Table 7-4. Technologies investigated for munitions detection/discrimination.

Name of Technology	Documented Performance and Comments	Reference
Seismic Ordnance Detection System	Testing with a 155 mm shell in a sandy soil without significant vegetation. Varying degrees of false targets on image displays. Performance was limited by reverberation and soil inhomogeneity.	BBN Technologies 1998
Ultra-Wideband, Fully Polarimetric Ground-Penetrating Radar	Demonstrations took place at four sites. GPR operated between 10 MHz and 810 MHz. Objective was to distinguish munitions-like targets from irregularly shaped objects. 90% correct identification of munitions-like objects, with 80% FAR. With current capabilities, technology would not be applied.	O'Neill 2005
Spectral Analysis of Surface Waves Seismic Test for Discrimination of UXO and Clutter	Proof-of-concept data collected on four objects buried in a soil bin. Frequency and spatial resolutions (50 Hz and 10 cm) insufficient to resolve the pattern or obtain quantitative estimates of reflection coefficients. Not able to evaluate munitions/clutter discrimination.	Bell et al. 2001
Assessment of Microgravity for UXO Detection and Discrimination	Modeled gravity anomaly signatures of 10 munitions ranging from 105 mm projectiles to 2,000 lb bombs. Only five items, 1,000 lb bomb and larger, were detected at depths of less than 0.5 m and only the 16-inch projectile was detected at a depth of 1 m. Conclusion was that microgravity surveys are not a viable technique for detection and discrimination of munitions.	Butler 2000
Detection of Ordnance Exploiting Trace Explosive Chemical Signatures	Project investigated the explosive signature associated with munitions and the background common to ranges. Explosive-filled munitions were not found to have reliable residual explosive signatures; inert-filled munitions were found to occasionally exhibit residual explosive signatures; and ranges have been found through multiple studies to have highly inhomogeneous explosive background levels, due to low-order detonations. The use of trace explosives to detect and discriminate live rounds on ranges was not pursued.	Phelan et al. 1998
UXO Detection by Enhanced Harmonic Radar	Project investigated whether harmonics generated by interior junctions could be used to detect ordnance and suppress clutter encountered in the transmitting band when using traditional radars. Harmonic radar is not a viable MR sensor as it misses many munitions items not having robust harmonic generation.	Kositsky 1999

7.4 Wide-Area Assessment

Millions of acres of base realignment and closure and formerly used defense sites land potentially require cleanup. It is likely, however, that only a small percentage of those acres contain concentrated areas of munitions that require response actions. Thus, techniques that can cover large areas of land rapidly and delimit areas that require cleanup or further assessment can be valuable in defining the magnitude of the clearance problem and focusing resources on the correct areas. With development of statistical survey tools, integration of multiple sensor modalities, and demonstrations to assess the state of the technology, wide-area assessment (WAA) has become a focus area of ESTCP.

Because of the vast size of many sites of interest, a major goal of WAA is to identify areas having no indication of previous munitions-related activity, as well as those where more extensive investigations are required. Historical records provide some information, but they have generally proved inadequate for locating all contaminated areas on many ranges. Current efforts are taking a layered approach to surveys for WAA. Table 7-5 summarizes the individual layers and the appropriate sensors for each layer, which are described in more detail below.

Table 7-5. Wide-area assessment layers and applicable technologies.

Layer/Sensor	Goal	Expectations	Limitations
High Airborne Ortho-photography Lidar Synthetic aperture radar Hyperspectral imaging	Identify areas for more extensive investigation.	Identify features (craters, spectral changes, surface metal) as marker for impact zones.	Heavily vegetated areas may be difficult. Time may obscure features. Not all techniques sufficiently validated.
Helicopter Magnetometer array	Detect areas of subsurface contamination. Mark areas as free of subsurface ferrous metal.	Detect ferrous targets. Pd a function of target size, depth, and platform altitude.	May not be applicable to mortars and small projectiles in unfavorable geology. Terrain limitations on coverage.
Ground Systems Magnetometer arrays EMI arrays	Detect all surface and subsurface ferrous metal larger than 20 mm.	Detect all ferrous targets larger than 20 mm. Characterize individual anomalies.	Terrain limitations on coverage. Cost limitations on total coverage

Aircraft are able to survey thousands of acres per day using optical and radar sensors that can identify features that might be related to munitions but are not capable of detecting buried objects. These technologies are proving very useful in pinpointing areas of concerns that require additional investigation (Foley 2005, Tomczyk 2005). A helicopter-borne magnetometer array flying a few meters above the surface will detect concentrations of ferrous scrap or munitions at typical burial depths, but will not reliably detect individual small munitions. Helicopter-borne magnetic gradient and EMI systems are also being investigated. Helicopters can cover hundreds of acres per day, but because of sensor sensitivity restrictions, are limited to areas where they can fly very close to the surface (ORNL 2005, Nelson et al. 2005). Towed-magnetometer and EMI arrays reliably detect all munitions of concern, but can cover only tens of acres per day and have significant terrain limitations. Because of coverage rate constraints, on large sites, ground-based sensors are limited to surveying transects that may cover a very small percentage of the total area of concern. In current testing, each of these layers is being evaluated for what its sensors can bring to the overall WAA problem solution and how the information from multiple sensors can be combined to enhance the solution.

As noted, ground-based systems provide the best detection performance, but they must often be used in surveys that do not cover the entire area of concern. In an effort to provide a statistically defensible survey planning tool, Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratory (SNL) developed separate, statistics-based sampling protocols that use knowledge of weapons deployed at a site and their dispersion characteristics to allow high-confidence location of areas of munitions contamination (Pulsipher et al. 2006). PNNL and SNL are cooperating in a joint project to extend and transition the earlier work. These methods have been programmed into Visual Sample Plan, a multiagency-sponsored tool for statistical sampling design and analysis. Consistent with a data-quality objectives approach, the software can devise an optimal survey scheme that ensures a high probability of detecting a target area of a specified size, shape, and anomaly density. Methods for evaluating the performance of a meandering pathway also have been developed.

Once targets are identified, other established geostatistical and Bayesian methods can support mapping of anomaly density or obtain probability maps depicting the probability of at least one munitions item or anomaly at all locations. Other statistical methods for determining the number of geophysical transects required to confidently demonstrate that no or very few munitions remain at a site after remediation also have been developed. These new algorithms are currently being tested in the ESTCP-sponsored WAA demonstrations.

The WAA demonstrations are collecting data at the Pueblo Bombing Range, La Junta, Colo.; Victorville, Calif.; and Kirtland PBR, N.M., using a number of different survey techniques and instruments, including airborne magnetometer surveys with the Naval Research Lab-developed MTADS helicopter shown in Figure 7-8. Figure 7-9 provides a residual magnetic field map from a 2003 survey at Isleta Pueblo, N.M. (Nelson et al. 2004). The position of the original bombing bull’s-eye is easily discernible on the figure, as are more scattered anomalies away from the bombing target. The helicopter magnetometer surveys, along with ground-based magnetometer and EMI surveys, aerial photography, and other airborne sensors, are being evaluated for their capability to identify target areas and for the benefit they bring to the overall WAA problem.

Figure 7-8. NRL Airborne MTADS magnetometer system.

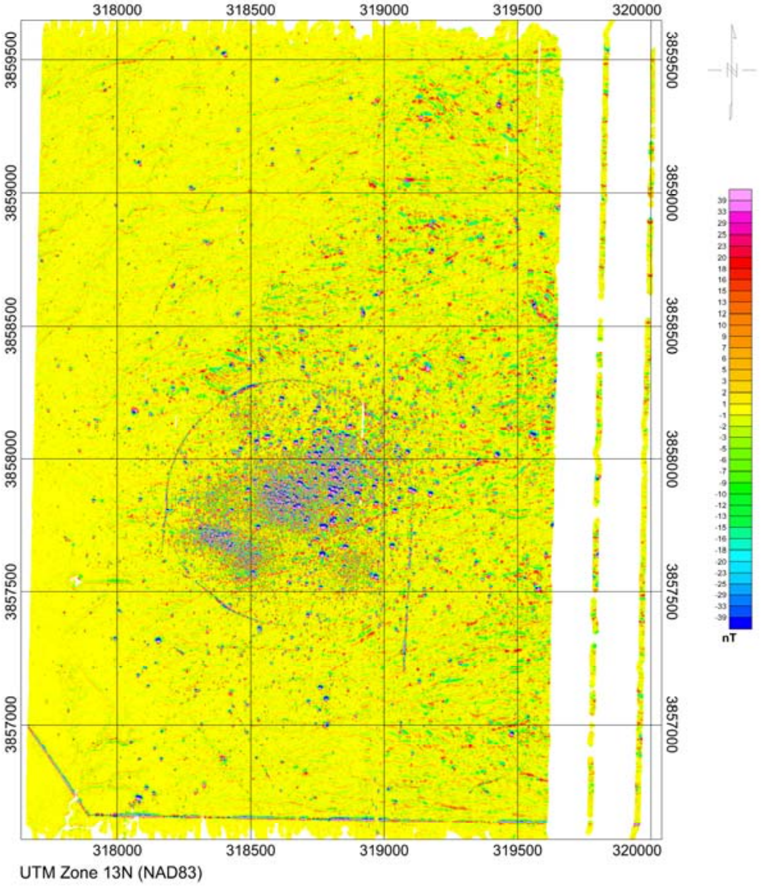


Figure 7-9. Airborne MTADS residual magnetic field map of the Isleta Pueblo, N.M., survey area.

7.5 Underwater Survey and Response Action

Historically, most munitions response actions have been on land. However, response actions for underwater areas will become more important in the future, and current research efforts are focused on improving technology available for such actions. Currently, SERDP and ESTCP have three efforts focused on different aspects of the underwater munitions detection and classification process.

In one effort, the Navy Facilities Engineering Service Center is studying the mobility and burial of underwater munitions (Sugiyama 2004). Particularly in coastal regions, munitions are likely to move and to be buried and uncovered by the action of waves, tides, and currents. This effort is validating a hydrodynamics-based mobility model intended to help chart likely munitions locations and burial conditions as a function of local underwater topography, bottom type, and water forces.

For munitions that are sitting on the bottom or not deeply buried, sonar holds promise for detection and discrimination. Several SERDP projects are investigating the phenomenology of underwater munitions and adapting acoustic sensor performance models developed for mine countermeasures purposes to support munitions response (Lim 2004, Bucaro 2006, Lavely 2006, Carroll 2006). Models are being validated using data measured in tanks and ponds and in offshore test areas maintained by NSWC (Lim 2004).

In previous limited underwater testing, magnetometers and EMI devices have shown the best detection performance, just as they have in testing on land. A team led by AETC has constructed and tested a towed 4 m array, shown in Figure 7-10, that contains eight cesium vapor magnetometers, a time-domain EMI transmit coil, and four receiver coils. The tow body contains a depth-control system capable of maintaining accurate tow body depth above the bottom or below the surface. First system demonstrations were held in May 2005 in Currituck Sound west of the Former Duck Naval Target Facility, N.C. Figure 7-11 shows a magnetometer map of detected anomalies in the sound (McDonald 2005).

Underwater detection technology is several years behind the technologies used for terrestrial sites, both in development and performance characterization. There does not exist a series of comprehensive tests, comparable to the standardized test sites analysis in Chapter 5, for the underwater environment. The AEC has created a freshwater test site, but few systems have been demonstrated and scores are not available at this time. Furthermore, systematic surveys of underwater ranges have never been performed, in large part because until recently no technology with the capability to do so existed, so the characteristics of these sites are not well understood. This is a subject of current research data-collection efforts.

Figure 7-10. Assembled marine sensor platform shown floating beside the tow boat.

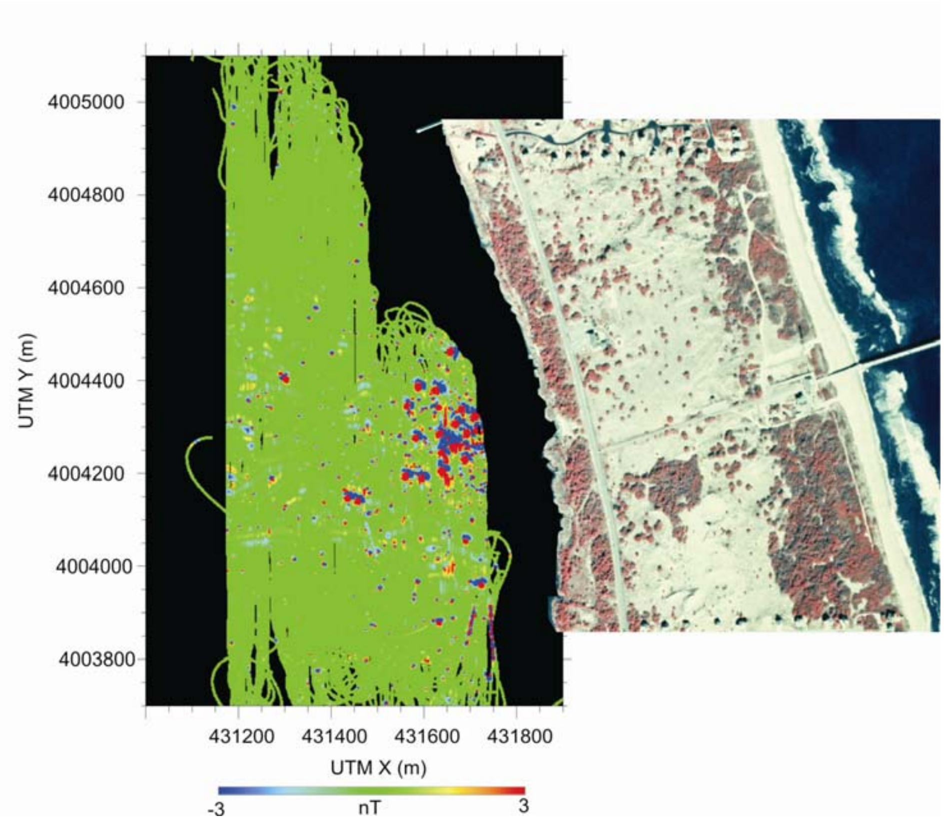


Figure 7-11. Magnetic anomaly image map of the magnetometer survey. An aerial photograph of the adjacent Duck, N.C., land area is superimposed for reference.

8.0 FILLER MATERIAL IDENTIFICATION TECHNOLOGIES

Munitions used for training by the military Services come in many different configurations, depending on their intended uses. Training munitions may (1) be completely inert, (2) have a live fuze or a "spotting charge" but no explosive filler, or (3) have a complete fuzing system and high-explosive filler. All these conditions may be encountered at a single site. Because of the myriad munition and nonmunition items that may be present, every suspect item encountered at a munitions response site must be inspected and assessed by appropriate personnel. Note that only military explosive ordnance disposal (EOD) personnel or contractor UXO technicians are trained and qualified to identify the nature of, and hazards associated with, a particular munition item. In some instances, even they cannot make a definitive determination of the munition item's contents based on only an external visual inspection.

When visually determining a munition item's contents is not possible, various technological means may be used to identify the filler if there is a need to do so, but in most cases, unidentified items are simply blown up. In populated areas, however, where evacuations may be needed to obtain unencumbered explosive safety quantity-distance (ESQD) safety arcs, determining the contents can avoid unnecessary detonations. In any case where technological means are used, the false-negative rate for filler identification must be essentially zero. That is, it is unacceptable to misidentify any dangerous munitions as inert.

One simple approach to identifying the internal filler is to drill a hole to permit visual inspection. A variation is to use an explosive perforator to blow a small hole through the item. Both methods are used in special cases when there is high confidence that the item has an inert filler. The hole allows inspectors to confirm that the item does not contain explosives. If the item does contain explosive filler, a perforator induces a detonation and the item is destroyed.

Trace chemical signatures of munitions are not discussed here for several reasons. Studies of the source term associated with HE-filled munitions, as well as background contamination on ranges, suggest that trace chemical signatures will not be reliable indicators of HE fill. Some rounds that are inert exhibit trace residue because they are stored with HE rounds. Other rounds that contain HE do not exhibit trace contamination. Finally, a large and inhomogeneous background signature—from items that have either functioned as intended or experienced low-order detonations—can be present on sites where ordnance activities have taken place. (Phelan, Webb, Leggett, and Jury 1998)

8.1 Nuclear Techniques

Nuclear techniques have shown promise for nondestructive elemental characterization. Neutron reactions produce characteristic gamma rays that can be used to identify elements present in bulk quantities of unknown material. The Idaho National Laboratory has developed a system that has been used since 1992 to detect nerve agents, blister agents, explosive fills, military screening smoke, compressed gases, and other hazardous material. The Portable Isotropic Neutron Spectroscopy (PINS) system is a nondestructive field tool for identifying the contents of munitions and chemical storage containers. PINS irradiates an item using a radioisotopic source. A high-resolution spectrometer measures the characteristic gamma-ray signature of the item, and the system deduces the fill compound or mixture from the elemental data. More than 20 PINS systems are used around the world, including systems in Australia, Egypt, Greece, Japan, and the United Kingdom. In the United States, PINS has been used at over 40 different sites. (Idaho National Laboratory Fact Sheet 2001)

The PELAN (Figure 8-1), in contrast, uses a neutron generator tube for the source. This produces higher energy neutrons, which allow the system to access reactions not achievable from isotopic sources, where lower energy neutrons dominate the distribution. Separate gamma-ray spectra from fast-neutron, thermal-neutron, and activation reactions are accumulated and analyzed to determine elemental ratios. Automated data analysis is performed to determine the fill in the munition. The PELAN system was demonstrated during a 2-week period in 2002 and again in 2003 and found to have some capability to characterize larger muntions. Following an assessment of 232 different ordnance items, filler materials, and soil types, PELAN resulted in a 3% false-negative rate and a 22% false-positive rate for shells 90 mm and larger. When smaller shells were included, the false-negative rate increased to 19%, with the same 22% false-positive rate. (Womble 2004) Additional research work is ongoing.

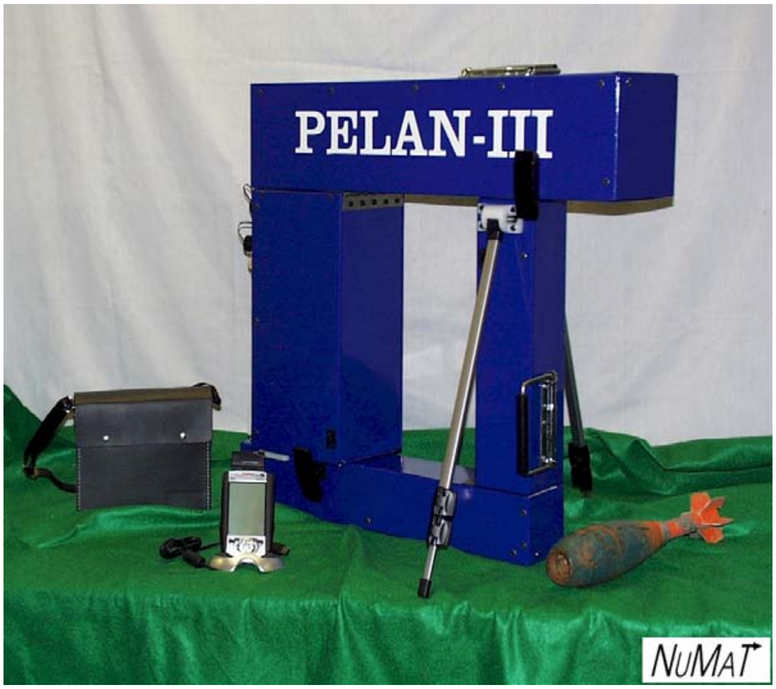


Figure 8-1. PELAN system.

8.2 X-ray Techniques

X-ray imaging technology can be used to nondestructively evaluate munitions. Several manufacturers offer portable systems that typically include an X-ray source, an imager, and supporting computer hardware and software. Although the images taken by these systems can offer indications of type of fill and fuzing systems that the munition may have, they do not provide definitive "proof" that a munition contains either an explosive or inert filler. In addition, using the X-ray systems requires moving the potentially hazardous, explosive-filled munition so that it can be imaged. Because of these shortcomings, the technology is seldom used for conventional munitions either by military EOD personnel or by the contractor UXO technicians; however, X-ray technology is used with other technologies such as PINS to develop multiple lines of evidence in characterizing rounds with chemical fill.

8.3 Research and Development Efforts—Acoustic Techniques

A current project in the SERDP program is investigating acoustic waves to identify filler material inside closed munitions. Acoustic waves are propagated through the filler material while sensors attached to the outside walls measure the attenuation in the filler material and the sound velocity at selected frequencies. The signal is compared to signals in a database of properties for known explosive and inert filler materials.

In one test, attenuation and acoustic-velocity measurements were taken at various points on two projectile bodies with different filler materials to determine if the fillers could be identified. Figure 8-2 shows the clusters of these data points for attenuation and velocity. The shaded ovals indicate the scatter for each filler and projectile body (±2 standard deviations). Each filler material resides in a specific area of the cluster plot. All the filler materials tested could be discriminated inside the projectile bodies. Additional testing of different munition bodies with unique filler materials is planned, as is optimization of the sensor to handle a wider variety of body types (Cobb 2004).

8.4 Munition Cutting and Venting Technologies for Filler Identification

As previously mentioned, two techniques are used to identify the filler: explosive venting or mechanical opening. Explosive venting of a munition case involves (1) obtaining Service approval of the approach and approval to increase the ESQD safety arc needed to accommodate the potential resulting detonation (this is necessary because the unknown filler may be composed of energetic material—the technique employed usually imparts sufficient energy to detonate the energetic material); (2) venting the case with an explosive shaped charge; and (3) examining the filler and determining its composition using visual or field screening test kit means. Mechanical opening of a munition case involves (1) obtaining Service approval of the approach and approval to increase the ESQD arc needed to accommodate the potential resulting detonation; (2) opening the case with a remotely operated drill, saw, or waterjet cutter; and (3) examining the filler and determining its composition using visual or field screening test kit means. Table 8-1 describes these methods and gives the advantages and disadvantages of utilizing each technology.

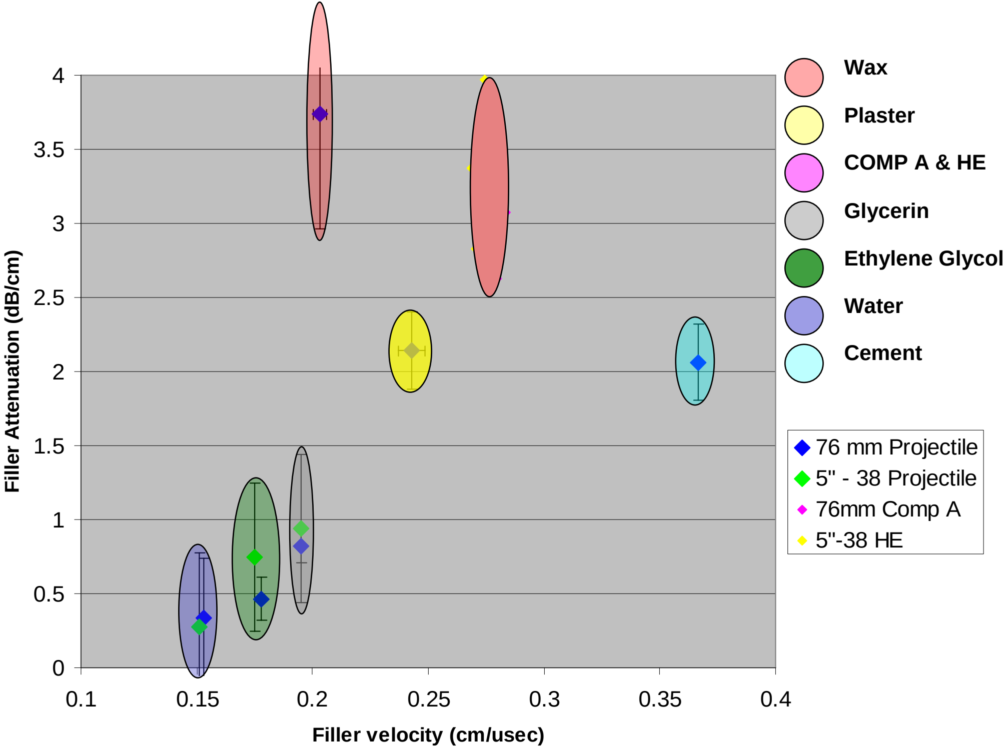


Figure 8-2. Attenuation versus acoustic velocity cluster plot.

Table 8-1. Methods for Filler Identification

Technology	Description	Advantages	Disadvantages
Explosive venting	Munitions to be vented are placed in a demolition pit, and the demolition material is placed to ensure total venting of the items. Blasting caps and perforators are used during venting operations. A detonation cord is used to link perforators.	Inexpensive to operate (jet perforators cost a few dollars each). More efficient as setup and operating time is minimal and no equipment teardown is required. No filler analysis if munition detonates.	The Services will likely require greater EQSD arcs than for mechanical opening techniques. Small jet perforators may not be capable of venting munitions with heavy, thick casings.
Drilling	The bomb or projectile is strapped to a jig and the drill is set up to penetrate the bomb casing. The drill operator controls the drilling operation from a remote location using television cameras. Once the drilling is complete, a UXO technician examines the drilling fines and the exposed filler to determine the filler material. This determination may be accomplished using visual methods or a field screening test kit.	Quick and easy, this approach has the capability to examine over 100 projectiles or bombs per day.	The size of the drilled hole is limited by the diameter and length of the drill bit, thus limiting the amount of material examined.
Cold saw cutting	This cutting tool holds and rotates the bomb while a rotary saw blade cuts through only the thickness of the casing. Then the bomb breaks in half and the filler can be easily removed from the casing by the same machine.	Properly lubricated, produces no sparks.	The technology is still under development. Present technology is inefficient.
Abrasive waterjet systems	The abrasive waterjet system safely sections munitions and explosives of concern shapes (e.g., bombs and rockets) and collects the water and residual materials in a hold-and-test tank. This is analyzed and later disposed of by an approved contractor. There are two systems: (1) entrainment or convection abrasive water-jet system (higher pressures and lower flow rates) and (2) slurry-jet system (lower pressures and higher flow rates). The mechanism of abrasive water-jet cutting consists of high-pressure water first being expelled through an orifice and forming a high velocity jet. This water jet is then passed through a venturi, where industrial abrasive is entrained within the water jet. The combined water and abrasive forms a low-temperature, low-impact cutting tool that has proven to be safe on almost 1 million high-explosive projectiles.	Various munition items have explosive components that are inaccessible for removal by conventional means. By utilizing abrasive waterjets, it is feasible to separate these components and open them for removal. A conventional water jet system can cut between 50 to 100 projectiles per day (40 mm, 60 mm, 76 mm, 81 mm, 105 mm, Mark 80 series bombs, and Harpoon motors). Can reuse water in the slurry jet system.	Issues with performance and maintenance with slurry jet system. (These have little impact if the slurry jet system is not entered into full-scale production.) The grit in the system gets stuck in the valves and must be cleaned out in a slurry-jet type unit; operator must be very skilled.

9.0 REMOVAL TECHNOLOGIES

The various removal technologies employed by the munitions response industry fall into three general categories: manual, mechanized, and remote control. The removal technology, which is determined on a site-by-site basis, depends on the characteristics of the targeted munitions, burial depth, soil type, and number of munitions slated to be removed. The employed technology will always consider the safety of site workers and the public above cost and project duration.

9.1 Individual Item Removal

The most common method of munitions removal is manual, using picks, shovels, or trowels. Manual-removal techniques are generally used for isolated munitions at shallow burial depths, where they can be easily reached.

When geophysical instruments can distinguish discrete munitions separated from one another, these items are judged to be relatively close to the surface, and the soil is easily dug, the UXO technician will commonly use hand tools to remove and recover them. The safest approach is to dig with a shovel beside the point indicated by geophysical instruments to a depth level with the item. The UXO technician then switches to a hand trowel and cautiously approaches the item from the side. This technique avoids striking any sensitive fuzing with a force sufficient to cause the item to function.

Mechanized removal techniques are usually employed at sites where the munitions are found in soil too deep or too hard for hand excavation, where munitions occur in clusters or masses, or where metallic clutter makes detecting munitions problematic. An excavator or backhoe can be used. The backhoe operator digs beside the point indicated by geophysical instruments to a depth level with the item, then uses a shovel or trowel to gain lateral access to the item. Equipment operators must be protected behind Plexiglas or Lexan shields, the thickness of which is dependent on the munitions with the greatest fragment distance (MGFD) expected to be encountered.

9.2 Bulk Item Removal

When high densities of munitions and other ferrous material are present, mechanical excavators and mechanical screens are often employed. The excavators remove large quantities of target-laden soil and place it in hoppers. The hoppers feed screens of various sizes, each intended to filter objects larger than the screen opening. The smallest screen must preclude the smallest munitions item from getting through. For example, soil contaminated with 20 mm projectiles requires use of a 3/4-inch screen.

Some existing mechanized equipment designed for landmine clearance also has applicability to munitions removal. Landmines are typically found at shallower depths than munitions. They have thin bodies that can be crushed or processed through grinders. In a report summarizing mechanized munitions response removal technology for the U.S. Army

Corps of Engineers in 2001, Foster Wheeler Environmental Corporation identified six categories of equipment—earth grinders/rippers, front-end scrapers, rotating bucket attachments, excavators, armored bulldozers/armoring kits, and screening kits—from the landmine community that could be easily modified or used as is for munitions removal (Foster Wheeler Corporation 2001).

Each removal operation is unique, depending on the site terrain, ordnance found on site, and project-specific objectives. Mechanized removal is suitable when the terrain has less than a 20% slope, on-site vegetation is sparse, areas are not environmentally sensitive, weather effects on the equipment are minimal, and soils are noncohesive and siftable. Mechanized removal is typically more cost effective in areas with high densities of military munitions at depths of less than 0.5 m. The improved site conditions will also lead to more efficient digital geophysical mapping following excavation.

Soil may also be removed in bulk and searched for individual ordnance items using a metal detector. This method was employed at the Training Annex and on a series of berms during site cleanup at the Former Lowry Bombing and Gunnery Range (FLBGR) in Aurora, Colorado. At the range, the sites were initially surveyed with Schonstadt metal detectors and cleared of any suspected near-surface anomalies. Then the areas were excavated to 2 feet and the bulk soil spread out on clean ground in 6 inch lifts. Schonstadt metal detectors were again used to identify any anomalies in the excavated soil.

9.2.1 Bulk Item Removal Technology Examples

The Air Force Research Laboratory (AFRL) has been working on a robotic excavator known as the Advanced Automated Ordnance Excavator (A-AOE) as part of its Active Range Clearance (ARC) system. The ARC consists of the A-AOE (see Figure 9-1), a remote sifter or screener, an All-Purpose Robotic Transport System (ARTS) for moving munitions to a safe area for disposal by EOD technicians, and a mobile command center. The A-AOE was used by the Army Corps of Engineers to clear an impact site at Camp Croft, South Carolina. The command center during this operation was 270 ft. from the impact area boundary. A remote-controlled bulldozer pushed topsoil to a collection area so the A-AOE could scrape the topsoil into a screener. The ARTS system moved all munitions and oversize items to a safe area for disposal. Over 150 munitions were recovered using this method. Using the remote-operated vehicles reduced the clearance time from an estimated 90 weeks to 12 weeks (AFRL Web site 2005).

Figure 9-2 shows the Range Master, an excavation system currently in development and testing. The Range Master builds on the commercially available Caterpillar 633d Scraper. An integrated screening system filters items that are too large to pass through the screen into a wire mesh hopper at the back of the system. The operator controls hydraulic dumping of the screened objects for examination by UXO technicians. The system has the capability to remediate items up to 0.3 m below ground surface, which will expand the safety and efficiency of conventional shallow mechanical sifting operations or manual techniques.

Range Master has been armored to withstand detonations of munitions up to 105 mm projectiles, and fitted with a remote-control capability.

Figure 9-1. The A-AOE robotic system, a modified Caterpillar 325L excavator.

Figure 9-2. The Range Master system.

The first demonstration of Range Master was conducted at Fort Ord, Calif., in February 2004 to assess its ability to excavate test plots safely and effectively. This controlled test site was seeded with known munition-like targets and clutter objects. The manually operated system successfully demonstrated an integrated excavator and screening unit. Geophysical surveys conducted before and after the excavation documented removal of the emplaced items.

9.2.2 Safety

When the removal operation will likely result in rough handling of the munitions, such as with excavators or mechanical screening equipment, some or all of the equipment may be controlled remotely. Care must be taken to ensure that a UXO technician can observe all operations and activate emergency-stop switches. Both nonessential and essential personnel must be protected from the unintentional detonation of munitions encountered during cleanup projects. Safe separation of nonessential personnel from munition excavation and removal actions is achieved by ensuring that these actions are a minimum ESQD arc away from inhabited buildings and public transportation routes. Shielding can be used to reduce the ESQD arc for essential personnel. Shielding can be clear, using material such as Plexiglas or Lexan. Clear shields allow technicians and operators to observe soil excavation or mechanical screening operations from distances that are significantly less than the normal ESQD arc. Concrete and metal shields can also be erected at sites where it is operationally important to protect personnel and equipment at distances less than the normal ESQD arc. When using this approach, operators are located in a protected area, where they operate the equipment using cameras and remote-control links. In addition, when mechanized equipment of any type is used, there must be approved procedures for identifying and safely removing any munition that may become lodged in the equipment.

Portable shields achieve the same purpose, but at a fraction of the weight. The miniature open front barricade (MOFB), a portable shield made of aluminum, is open at the front and is used by the UXO technician to defeat primary fragments in three directions only. It is not designed to mitigate effects from blast overpressure and noise. The MOFB is assembled in the shop and carried to the munitions response project site. The basic MOFB can provide protection against smaller munitions. By adding aluminum plates at the site, protection can be achieved for larger munitions. The basic barricade weighs approximately 100 pounds, with each additional 1/4 inch of aluminum plates adding another 100 pounds. The required thickness of aluminum is based on the munitions with the greatest fragment distance for the site.

10.0 DETONATION AND DECONTAMINATION TECHNOLOGIES

This chapter discusses the technologies used to detonate or neutralize whole munitions and the decontamination technologies that can be applied to the scrap metal left over from the detonation or neutralization. Many variables need to be taken into consideration before selecting any of these treatment technologies: the type of munition; whether or not it is fuzed, and if fuzed, whether or not the munition is armed; the munition size; etc. Additional tradeoffs include safety for the nearby population and the UXO technicians doing the work, availability, cost, effectiveness, potential for residual contamination, need for environmental permits, and noise. For example, while a consolidate-and-blow operation and the contained detonation chamber are capable of destroying munitions that are less dangerous to move, the latter is better suited to sites where inhabited buildings or public traffic routes are nearby or where noise is an issue.

10.1 Detonation Technologies

The objective of detonation is the instantaneous and complete destruction of ammunition and explosives. How an item is detonated depends on the munition and the site. Munitions may be moved off site for destruction, or if EOD technicians determine it is unsafe to move the munitions, they may be detonated in place.

10.1.1 Blow in Place

Blow-in-place (BIP) operations, which require very little preparation of the ammunition and explosives, allow the items to be detonated in place. Disposal by detonation is accomplished by placing demolition charges or other explosive materials on the munition, priming the charges, and initiating the detonation from a safe distance.

BIP procedures can employ electric or nonelectric initiation. The electric firing system consists of an electric blasting machine, a firing wire, and an electric blasting cap. A nonelectric system consists of a fuse igniter, time blasting fuse, and nonelectric blasting cap. With BIP, each munition is individually destroyed, and destruction is individually verified for QC/QA. Figure 10-1 shows an example of a BIP operation.

For some types of explosives, detonation is the quickest method of disposal (particularly in emergencies), as long as the effects of the blast and shock wave are acceptable to nearby inhabited buildings, public transportation routes, and the environment. The techniques are field proven, and the tools and equipment are transportable. The technique can usually be employed in the area where the munition is found, and engineering controls can reduce blast overpressure and fragments. BIP operations can be manpower intensive, however, and costs can increase in areas of high population densities or where public access must be monitored or controlled. Finally, handling of resultant waste streams must be addressed in BIP operations planning.

Figure 10-1. Item detonated during Munitions Response at Camp Hale, Colorado.

10.1.2 Consolidate and Blow

Consolidate and blow also uses detonation. Munitions determined to be safe to move are collected in a common area and destroyed in a single action. Figure 10-2 shows a consolidate-and-blow operation. Consolidate-and-blow procedures generally employ the same techniques, tools, and equipment as BIP, but they require a larger area and greater controls. Like BIP, consolidate and blow can be manpower intensive and may require heavy equipment for large-scale operations. The disposition of resultant waste streams must be addressed, and a larger EQSD arc is required.

Another consideration is the possible kick-out of unexploded munitions fuzes, boosters, bursters, etc., which presents a secondary hazard. Kick-outs are possible since, unlike the BIP of a solitary munitions item, the consolidate-and-blow operation involves treatment of multiple items of various sizes and configurations. When dealing with large quantities of munitions where donor charges are only placed on the outer layer, the shock wave may not propagate to the inner munitions layers. In some instances, undetonated munitions on a lower layer may be driven down into the ground or sideways into the crater wall; in other instances they may be kicked out. Military EOD and contractor UXO standard operating procedures call for them to search the area in and around the site of the consolidate-and-blow operation for kick-outs. This may occur immediately, or may take place several hours or a day after the operation. If kick-outs are located, each is inspected and evaluated to determine whether it is safe to move. If the kick-out is not safe to move, it is blown in place. Otherwise, it is consolidated with other kick-outs and the process is repeated until all items are destroyed.

Figure 10-2. Preparing a consolidated ordnance detonation "shot" on Kaho'olawe Island, Hawaii. (Photo courtesy of U.S. Navy.)

10.1.3 Contained Detonation Chambers—Mobile

A method of munitions destruction in the field is the transportable contained detonation chamber, a closed chamber in which technicians can detonate ammunition. The chamber captures all the fragments, a side chamber reduces the blast, and a bag house captures fugitive emissions. These chambers successfully contain the hazardous components in the unit. They are commonly used for fuzes and smaller explosive components but, compared with stationary facilities, have a greatly reduced EQSD arc. Mobile facilities may require permits, and a small amount of construction may be required. Other concerns are the service life of the unit and its maintenance requirements. Mobile facilities require additional handling of military munitions compared with BIP. System cleaning and maintenance usually requires personal protection equipment (PPE) and worker training.

The contained detonation chamber is designed to fully contain blast overpressure and debris from intentional detonations. The model T-10 detonation chamber (Figure 10-3) is limited to one HE-filled 81 mm mortar plus donor charge with the total explosive weight less than 13 lbs of TNT. The T-30 model can handle less than 40 lbs of TNT. Both the T-10 and T-30 are transportable (D. Murray, personal communication, 31 October 2005). Other chambers are being designed and tested, but no performance data are currently available.

10.1.4 Laser Initiation

Laser-initiation systems, which are still in development, are currently deployed in Iraq and Afghanistan for testing. Test results have been positive for 81 mm and smaller munitions, with successes on munitions up to 155 mm.

Figure 10-3. T-10 mobile detonation chamber. (Photo courtesy of DeMil International.)

The laser initiation generally produces a low-order detonation, which can potentially result in very high environmental contamination from unconsumed munitions constituents. Targets must be exposed and on the surface for attack by the directed beam. This system is not useful when the munition is buried or otherwise concealed by intervening structures, topography, vegetation, etc. A fiber-optic-delivered version does not require line-of-sight access within approximately 100 m, but it does require placement of the fiber-optic cable within about 2.5 cm of the round to be engaged. According to the Army, laser-initiation systems greatly reduce manpower, increase transportability, and offer improved safety because of the significant standoff distances allowed compared with traditional BIP. Laser-initiation systems have been demonstrated but are not currently being used in the munitions response industry.

ZEUS–HLONS is a solid-state laser-initiation system, with an effective standoff engagement range of up to 300 meters. ZEUS–HLONS focuses energy on the outer casing of the target, heating the munition until it is destroyed by internal combustion. The laser system includes a color camera for locating targets and a visible laser for targeting the co-boresighted, invisible, high-power laser on an aim point. The ZEUS–HLONS is mounted on an uparmored high-mobility multipurpose wheeled vehicle (NAVEODTECHDIV 2004).

10.2 Decontamination Technologies

Decontamination technologies are used to remove hazardous explosive material from an item and decontaminate the munition. Thermal or chemical processing is the most effective way to ensure complete decontamination.

10.2.1 Shredders and Crushers

Shredders and crushers render small arms, fuzes, and other components inoperable by mechanical action. The residue will typically require additional treatment to achieve higher decontamination levels. Most systems are stationary facilities. The knife blades are high-maintenance items.

An example system is the Shred Tech ST-100H. A hydraulic-powered shredder mounted on a roll-off platform, it is suitable for on-site waste reduction and materials processing. The roll-off system features a transportable, self-powered shredder that is powered by a diesel motor. A folding conveyor discharges the shredded material into a waste container. By shredding materials on site, transportation costs are lowered and handling is reduced.

10.2.2 Shearing Operations

The Department of Defense encourages recycling of all range scrap once it has been inspected, certified, verified as inert or free of explosives or related materials, and demilitarized. Hydraulic shears have proved to be a safe, effective means of demilitarizing concrete-filled practice bombs. Shearing opens and mutilates the casing, thus satisfying demilitarization requirements. Shearing also separates the steel from the concrete so both components can be readily recycled. Figure 10-4 shows a bomb-shearing operation.

Figure 10-4. Processing MK 80-series practice bombs. (Photo courtesy of FACT, International.)

10.2.3 Oxyacetylene Cutting Torches

Cutting torches are used for demilitarizing practice bombs. Oxyacetylene torches can cut steel approaching 1.2 cm in thickness, but doing so would take up to 1 hour to make the two longitudinal cuts required to split a bomb open. Although mobile and mechanically simple, with readily available supplies, cutting torches require a high level of manual labor and have very low throughput. Detonation can also occur if an item is misidentified as inert when it is HE filled or there is mechanical (steam) pressure buildup. The Defense Reutilization and Marketing Office (DRMO) allows use of oxyacetylene cutting torches, but the Navy prohibits using them for demilitarization procedures (D. Murray, personal communication, 24 October 2005).

10.2.4 Chemical Decontamination

Chemical decontamination can be used to remove and destroy munitions constituents (e.g., propellants, pyrotechnics, explosives). These processes can generate additional waste streams that may be considered hazardous and require additional processing. The chemical treatment may also require emission controls. The specialized workers performing chemical decontamination will typically require training and PPE.

UXB International has developed a chemical decontamination process that uses sodium hydroxide. In this process, contaminated range scrap is continuously fed to a shredder and then to a heated tank containing a solution of sodium hydroxide (about 10% by weight). The tank is equipped with a perforated basket for removal of the scrap after treatment. The tank is filled and the mixture is allowed to soak for 1 hour to ensure complete destruction of all energetic material. The basket is raised from the tank, drained, and placed into a second tank containing water, which rinses any remaining caustic from the scrap. The water is adjusted to a pH between 6 and 9 with hydrochloric (muriatic) acid before the scrap is removed. At the end of the process, the scrap is wet, and the water will contain a small amount of sodium chloride (table salt).

The initial tank fills of hydroxide solution and rinse water can process over 100 tons of scrap before tank replenishment is required. At the end of the project, both solutions are neutralized to a pH between 6 and 9 and disposed of as nonhazardous waste. Any remaining nonmetallic solid matter (dirt or plastics) is allowed to dry before being properly disposed of. The process is capable of treating all types of metal, plastics, wood, and paper, although aluminum and magnesium are rapidly degraded. In a recent test, the UXB system successfully neutralized the spotting charges for a number of practice bombs (UXB International 2006).

10.2.5 Flashing Furnaces

Flashing furnaces are designed to thermally treat and contain hazardous components. Because of safety concerns, flashing furnaces have low feed rates. They produce additional hazardous waste streams, and cleaning and maintenance usually requires PPE for the workers. Furnaces may also require a permit. Examples of thermal treatment include rotary kiln incinerators, explosive waste incinerators, transportable flashing furnaces, fireworks disposal trailers, hot-gas decontamination, and hot fire flashing in pans.

In hot-gas decontamination, workers load materials into a large chamber, which fills with air. The heat (ranging from 500 to 700 °F) vaporizes the explosives. A fan draws the vapors into a second chamber known as a thermal oxidizer, where temperatures of 1,800 °F destroy the explosive vapors in about 2 seconds. The exhaust contains no trace of explosive compounds, and the entire process usually takes less than 8 hours. (USAEC Web site 1997) The furnace has a volume of 270 cubic feet and can accept a maximum of 3,000 pounds of contaminated materials containing less than 1 pound of total explosives. Up to four batch runs can be processed every 24 hours. The system requires a two to three person crew and is skid mounted. (USAEC Web site 2005)

El Dorado Engineering's transportable flashing furnace is 5 feet high, 7 feet wide, and 17 feet long (see Figure 10-5). The furnace cycle time is 45 to 90 minutes, depending on load size, and the ceramic wool insulation allows for rapid heating and cooling. Temperature recording enables verification of each load's temperature. Up to 10,000 pounds of material can be loaded in a single batch, and a typical operation is 5,000 pounds per hour. In a recent demonstration, a combined heat-and-soak time of 50 minutes resulted in temperatures throughout an instrumented load of 650 °F or higher. Fifty explosive-spiked coupons distributed throughout 10 loads all returned results below the detection threshold in laboratory testing (El Dorado Engineering 2005).

Figure 10-5. El Dorado Engineering flashing furnace for treatment of range scrap.

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GLOSSARY

Anomaly. A geophysical signal above geological background from a detected subsurface object.[8]

Anomaly reacquisition. The process of returning to a location identified as having an anomaly, reproducing a geophysical response at that location, and marking the location for excavation by UXO technicians.

Archives search report. An investigation to report past ordnance and explosives (OE) activities conducted on an installation.[2]

Background Alarm Rate (BAR). Background alarms are locations where a demonstrator indicates a geophysical anomaly, but no object is emplaced. The BAR is the number of background alarms divided by the area surveyed.

Bin. Statistical category to facilitate analysis.

Blow-in-place. Method used to destroy military munitions, by use of explosives, in the location the item is encountered.[6]

Buried munitions. Munitions that have been intentionally discarded by being buried with the intent of disposal. Such munitions may be either used or unused military munitions. Such munitions do not include unexploded ordnance that become buried through use.[6]

Caliber. The diameter of a projectile or the diameter of the bore of a gun or launching tube. Caliber is usually expressed in millimeters or inches. In some instances (primarily with naval ordnance), caliber is also used as a measure of the length of a weapon's barrel. For example, the term "5 inch 38 caliber" describes ordnance used in a 5-inch gun with a barrel length that is 38 times the diameter of the bore.[6]

Casing. The fabricated outer part of ordnance designed to hold an explosive charge and the mechanism required to detonate this charge.[6]

Clearance. The removal of military munitions from the surface or subsurface at active and inactive ranges.[6]

Closed range. A range that has been taken out of service and either has been put to new uses that are incompatible with range activities or is not considered by the military to be a potential range area. A closed range is still under the control of the military.[8]

Clutter. Munitions-related scrap and other common metallic field debris that can mask signals of interest or generate signals not of interest, thereby affecting sensor performance.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). CERCLA, commonly known as Superfund, is a Federal law that provides for the cleanup of releases from abandoned waste sites that contain hazardous substances, pollutants, and contaminants.[6]

Department of Defense Explosives Safety Board (DDESB). The DoD organization charged with promulgation of ammunition and explosives safety policy and standards, and with reporting on the effectiveness of the implementation of such policy and standards.[6]

Depth of Interest. Depth to which a munition type must be detected. This can be determined by the depth to which removal is required, the depth to which the munitions are expected to be found, or other project-specific objectives.

Destruction of military munitions. Generally means thermal treatment process such as incineration, open burning and open detonation, but could also include chemical treatment.[9]

Detonation. A violent chemical reaction within a chemical compound or mechanical mixture evolving heat and pressure. The result of the chemical reaction is exertion of extremely high pressure on the surrounding medium. The rate of a detonation is supersonic, above 3,300 feet per second.[6]

Digital Geophysical Mapping (DGM). Any geophysical system that digitally records geophysical and positioning information.

Discarded Military Munitions (DMM). Military munitions that have been abandoned without proper disposal or removed from storage in a military magazine or other storage area for the purpose of disposal. The term does not include unexploded ordnance, military munitions that are being held for future use or planned disposal, or military munitions that have been properly disposed of consistent with applicable environmental laws and regulations 10 U.S.C. 2710 (e)(2).[5]

Discrimination. The ability to distinguish ordnance from fragments and other non-ordnance materials based solely on the geophysical signature.[6]

Electromagnetic induction. Physical process by which a secondary electromagnetic field is induced in an object by a primary electromagnetic field source.

Excavation of anomalies. The excavation and identification of a subsurface anomaly.[6]

Explosive. A substance or mixture of substances, which is capable, by chemical reaction, of producing gas at such a temperature, pressure and rate as to be capable of causing damage to the surroundings.[6]

Explosive filler. The energetic compound or mixture inside a munitions item.[6]

Explosive ordnance disposal (EOD). The detection, identification, field evaluation, rendering-safe recovery, and final disposal of unexploded ordnance or munitions. It may also include the renderingsafe and/or disposal of explosive ordnance that has become hazardous by damage or deterioration, when the disposal of such explosive ordnance is beyond the capabilities of the personnel normally assigned the responsibilities for routine disposal. EOD activities are performed by active duty military personnel.[6]

Explosives safety. The implementation of appropriate training, policies, and procedures to minimize the unacceptable effects of an ammunition or explosives mishap.

False negative. When the geophysical sensor indicates no anomaly present when one actually exists and should have been detected.

False positive. When the geophysical sensor indicates an anomaly and nothing is found that caused the instrument to detect the anomaly.[6]

Filler Identification. Identification of a substance in an ammunition container such as a projectile, mine, bomb, or grenade. A filler may be an explosive, chemical, or inert substance.[3]

Formerly Used Defense Site (FUDS). Real property that was under the jurisdiction of the Secretary and owned by, leased by, or otherwise possessed by the United States (including governmental entities that are the legal predecessors of Department of Defense [DoD] or the Components) and those real properties where accountability rested with DoD but where the activities at the property were conducted by contractors (i.e., government-owned, contractor operated [GOCO] properties) that were transferred from DoD control prior to 17 October 1986.[13]

Fuze. 1. A device with explosive components designed to initiate a train of fire or detonation in ordnance. 2. A nonexplosive device designed to initiate an explosion in ordnance.[6]

Geophysical Prove-Out (GPO). Before conducting a geophysical survey of an entire munitions response site, a site-specific geophysical prove-out is conducted to test, evaluate, and demonstrate the geophysical systems proposed for the munitions response. Information collected during the prove-out is analyzed and used to select or confirm the selection of a geophysical system that can meet the performance requirements established for the geophysical survey.[7]

Gradiometer. Magnetometer configured for measuring the rate of change of a magnetic field in a certain direction.[6]

Ground-penetrating radar. A system that uses pulsed radio waves to penetrate the ground and measure the distance and direction of subsurface targets.[6]

Habitat management. Management of an ecosystem to create environments which provide habitats (food, shelter) to meet the needs of particular species of wildlife, birds, etc.

Handheld. Instruments operated using the hand to collect either mag and flag or digital geophysical mapping data.

Hand carried. Another way of referring to handheld platforms.

Inert. Ordnance, or components thereof, that contain no explosives, pyrotechnic, or chemical agents.[4]

Mag and flag. A geophysical survey process whereby field personnel use hand-held geophysical instruments to manually interpret anomalies and surface-mark them with non-metallic flags for excavation.

Magnetometer. An instrument for measuring the intensity of magnetic fields.[6]

Man-portable. Any geophysical system that can be deployed manually, either by carrying, pushing or towing.

Military munition. All ammunition products and components produced for or used by the armed forces for national defense and security, including ammunition products or components under the control of the Department of Defense, the Coast Guard, the Department of Energy, and the National Guard. The term includes confined gaseous, liquid, and solid propellants, explosives, pyrotechnics, chemical and riot control agents, chemical munitions, rockets, guided and ballistic missiles, bombs, warheads, mortar rounds, artillery ammunition, small arms ammunition, grenades, mines, torpedoes, depth charges, cluster munitions and dispensers, demolition charges, and devices and components thereof. The term does not include wholly inert items, improvised explosive devices, and nuclear weapons, nuclear devices, and nuclear components, other than non-nuclear components of nuclear devices that are managed under the nuclear weapons program of the Department of Energy after all required sanitization operations under the Atomic Energy Act of 1954 (42 U.S.C. 2011 et seq.) have been completed (10 U.S.C. 101 (e)(4).[5]

Military Munitions Response. Response actions, including investigation, removal and remedial actions to address the explosives safety, human health, or environmental risks presented by unexploded ordnance (UXO), discarded military munitions (DMM), or munitions constituents.[5]

Munition constituents. Any materials originating from unexploded ordnance, discarded military munitions, or other military munitions, including explosive and nonexplosive materials, and emission, degradation, or breakdown elements of such ordnance or munitions. (10 U.S.C. 2710 (e)(4)).[5]

Munitions and Explosives of Concern (MEC). This term, which distinguishes specific categories of military munitions that may pose unique explosives safety risks, means: (1) Unexploded ordnance (UXO); (2) Discarded military munitions (DMM); or (3) Munitions Constituents (e.g. TNT, RDX) present in high enough concentrations to pose an explosive hazard. Formerly known as Ordnance and Explosives (OE).[5] This document concerns the first two but not munitions constituents.

Munitions response. Response actions, including investigation, removal and remedial actions to address the explosives safety, human health, or environmental risks presented by unexploded ordnance (UXO), discarded military munitions (DMM), or munitions constituents.[5]

Munitions Response Area (MRA). Any area on a defense site that is known or suspected to contain UXO, DMM, or MC. Examples include former ranges and munitions burial areas. A munitions response area is comprised of one or more munitions response sites.[5]

Munitions Response Site (MRS). A discrete location within a MRA that is known to require a munitions response.[5]

Noise. Noise is commonly divided into sensor noise and environmental noise. Sensor noise is the fluctuation in sensor output in the absence of an external signal and is generally dominated by noise in the sensor electronics. Environmental noise captures other external sources that also compete with the signal of interest. These sources can include electromagnetic interference, geological noise, or other types of clutter. In the case of munitions detection, environmental noise is generally the dominant contributor to the overall noise of the system.[7]

Noise Floor. The measure of the signal created from the sum of all specified noise sources. For geophysics applications, the noise level varies depending on the munitions response site and the type of geophysical sensor applied at the site.

Open burning. The combustion of any material without (1) control of combustion air, (2) containment of the combustion reaction in an enclosed device, (3) mixing for complete combustion, and (4) control of emission of the gaseous combustion products.[6]

Ordnance. Weapons of all kinds including bombs, artillery projectiles, rockets and other munitions; military chemicals, bulk explosives, chemical warfare agents, pyrotechnics, explosive waste, boosters, and fuzes.[4]

Preliminary assessment (PA) and site inspection (SI). A PA/SI is a preliminary evaluation of the existence of a release or the potential for a release. The PA is a limited-scope investigation based on existing information. The SI is a limited-scope field investigation. The decision that no further action is needed or that further investigation is needed is based on information gathered from one or both types of investigation. The results of the PA/SI are used by DoD to determine if an area should be designated as a "site" under the Installation Restoration Program. EPA uses the information generated by a PA/SI to rank sites against Hazard Ranking System criteria and decide if the site should be proposed for listing on the NPL.[6]

Probability of Detection (Pd). A statistically meaningful parameter that describes the probability of detecting an item of interest. Pd is estimated as the number of emplaced munitions detected divided by the number emplaced. A true probability is calculated on a statistically significant population of items that all have the same chance of being detected and captures the random processes that affect detectability.

Probability of False Alarms (Pfa). The probability that a non-munition is declared as a munition.

Production Ground Survey. Detailed geophysical characterization and mapping to detect and locate individual military munitions.[10]

Projectile. An object projected by an applied force and continuing in motion by its own inertia, as mortar, small arms, and artillery projectiles. Also applied to rockets and to guided missiles.[6]

Quality Assurance (QA). A process that provides oversight to quality control and involves an audit/review of the quality control process.[1]

Quality Control (QC). A process that monitors and checks the design process to ensure that the product will meet agreed-upon requirements of the customer, is on schedule, and within budget.[1]

Range. Means designated land and water areas set aside, managed, and used to research, develop, test and evaluate military munitions and explosives, other ordnance, or weapon systems, or to train military personnel in their use and handling. Ranges include firing lines and positions, maneuver areas, firing lanes, test pads, detonation pads, impact areas, and buffer zones with restricted access and exclusionary areas. (40 CFR 266.601) A recent statutory change added Airspace areas designated for military use in accordance with regulations and procedures prescribed by the Administrator of the Federal Aviation Administration. (10 U.S.C. 101 (e)(3)).[6]

Receiver Operator Characteristic (ROC) Curve. A diagram used to communicate expected MEC detection rates. Typically, ROC curves are used to communicate MEC detection rates as a function of the expected number of non-MEC items that will be excavated in order to achieve those rates (i.e. a plot of Pd vs. Pfa).

Remedial action. A type of response action under CERCLA. Remedial actions are those actions consistent with a permanent remedy, instead of or in addition to removal actions, to prevent or minimize the release of hazardous substances into the environment.[6]

Remedial investigation and feasibility study (RI/FS). The process used under the remedial program to investigate a site, determine if action is needed, and select a remedy that (1) protects human health and the environment; (2) complies with the applicable or relevant and appropriate requirements; and (3) provides for a cost-effective, permanent remedy that treats the principal threat at the site to the maximum extent practicable. The RI serves as the mechanism for collecting data to determine if there is a potential risk to human health and the environment from releases or potential releases at the site. The FS is the mechanism for developing, screening, and evaluating alternative remedial actions against nine criteria outlined in the NCP that guide the remedy selection process.[6]

Removal action. Short-term response actions under CERCLA that address immediate threats to public health and the environment.[6]

Resource Conservation and Recovery Act (RCRA). The Federal statute that governs the management of all hazardous waste from cradle to grave. RCRA covers requirements regarding identification, management, and cleanup of waste, including (1) identification of when a waste is solid or hazardous; (2) management of waste — transportation, storage, treatment, and disposal; and (3) corrective action, including investigation and cleanup, of old solid waste management units.[6]

Seeded target. Munition or clutter item buried at a known location used to assess the detection capability of a geophysical system at test sites, geophysical proveouts, and/or as a quality control or assurance tool during production surveys. Seeded target is also referred to as a seeded munition.

Seeded munition. Another way of referring to a seeded target.

Signal-to-Noise Ratio (SNR). The signal strength and system noise are often combined in the SNR. The target's signal strength and the noise are reported in the operating units of the instrument, i.e., nanoteslas (nT) for a magnetometer and millivolts (mV) for an EM instrument. The SNR is the ratio of these two metrics (target strength divided by noise level) and is a dimensionless quantity. In general, SNRs of a minimum of 2–3 are required for reliable detection.[7]

Site preparation. This process typically includes an MEC surface clearance to remove any MEC potential hazards to the survey team, removal of surficial metallic objects to eliminate potential interference, vegetation clearance, and establishment of survey grids and control points.[7]

Standardized test site. Established technology demonstration sites at both Aberdeen Proving Ground and Yuma Proving Ground for users and developers to define the range of applicability of specific UXO technologies, gather data on sensor and system performance, compare results, and document realistic cost and performance information.[11]

Survey technologies. Geophysical instruments used during munitions response efforts.

Sweeping. The act of field personnel systematically moving over a specified area to conduct munitions response operations, with or without the aid of a geophysical instrument.

Target. Target is typically used to denote two different concepts: (1) the individual munitions item that one is attempting to detect and (2) the aim point of a weapons system at which large concentrations of munitions are typically found (i.e., an aiming circle for aerial bombing). In this document, "target" refers to definition 1.

Transferred ranges. Ranges that have been transferred from DoD control to other Federal agencies, State or local agencies, or private entities (e.g., formerly used defense sites, or FUDS). A military range that has been released from military control.[8]

Transferring ranges. Ranges in the process of being transferred from DoD control (e.g., sites that are at facilities closing under the Base Realignment and Closure Act, or BRAC). A military range that is proposed to be leased, transferred, or returned from the Department of Defense to another entity, including Federal entities.[8]

Unexploded Ordnance (UXO). Military munitions that (1) have been primed, fused, armed, or otherwise prepared for action; (2) have been fired, dropped, launched, projected, or placed in such a manner as to constitute a hazard to operations, installations, personnel, or material; and (3) remain unexploded whether by malfunction, design, or any other cause (10 U.S.C. 101 [e][5]).[5]

Wide Area Assessment (WAA). Rapid assessment of large tracts of potentially contaminated land to identify those areas with concentrated military munitions that require detailed characterization.[10]

11× diameter. Empirical formula developed by the U.S. Army Corps of Engineers to determine how deep existing magnetic and EMI sensor technology should be able to detect ordnance items. A simplified expression for maximum depth of detection is calculated as:[12]

$$\text{Estimated Detection Depth (meters)} = 11 * \text{diameter (mm)}/1{,}000$$

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ACRONYMS

AEC	Army Environmental Center
AFRL	Air Force Research Laboratory
APG	Aberdeen Proving Ground
ARC	Active Range Clearance system
ARTS	All-Purpose Robotic Transport System
ATC	Aberdeen Test Center
BAR	Background Alarm Rate
BG	Blind Grid
BIP	Blow-In-Place
BRAC	Base Realignment And Closure
CEHNC	Army Corps of Engineers, Huntsville Center
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (commonly known as Superfund)
COE	Corps of Engineers
CSM	Conceptual Site Model
DAS	Data Analysis System
DGM	Digital Geophysical Mapping
DGPS	Differential GPS
DMM	Discarded Military Munitions
DoD	Department of Defense
DQO	Data Quality Objective
DR	Detection Rate
EE/CA	Engineering Evaluation/Cost Analysis
EMI	Electromagnetic Induction
EOD	Explosive Ordnance Disposal
EPA	Environmental Protection Agency
EQT	Environmental Quality Technology program
ERDC	US Army Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program

FDEM	Frequency-Domain Electromagnetic System
FLBGR	Former Lowry Bombing and Gunnery Range
FS	Feasibility Study
FUDS	Formally Used Defense Sites
GIS	Geographical Information System
GPO	Geophysical Prove-Out
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
GX	Geosoft Executable
HE	High Explosive
IDA	Institute for Defense Analyses
INS	Inertial Navigation System
ITRC	Interstate Technology Regulatory Council
MC	Munitions Constituents
MEC	Munitions and Explosives of Concern
MMRP	Military Munitions Response Program
MOFB	Miniature Open Front Barricade
MR	Munitions Response
MRA	Munitions Response Area
MRS	Munitions Response Site
MTADS	Multi-sensor Towed Array Detection System
NRL	Naval Research Laboratory
OE	Ordnance and Explosives
OF	Open Field
PA/SI	Preliminary Assessment/Site Investigation
P_{ba}	Probability of Background Alarm
P_d	Probability Of Detection
PDA	Personal Digital Assistant
PELAN	Pulsed ELemental Analysis with Neutrons
PINS	Portable Isotropic Neutron Spectroscopy
PPE	Personal Protective Equipment

QA	Quality Assurance
QC	Quality Control
R&D	Research and Development
RA	Remedial Action
RCRA	Resource Conservation and Recovery Act
RD	Remedial Design
RI	Remedial Investigation
ROC	Receiver Operating Characteristic
SERDP	Strategic Environmental Research & Development Program
SNR	Signal-to-Noise Ratio
TDEM	Time-Domain Electromagnetic System
USACE	US Army Corps of Engineers
UXO	Unexploded Ordnance
YPG	Yuma Proving Ground

Appendix A—Standardized Test Site Results

A.0 Standardized Test Site Analysis

A.1.1 Standardized Test Sites Scoring Ambiguities

In addition to the number of targets that are greater than 11× deep, a further complication occurs in the open field. Some ordnance and clutter are emplaced in clusters so that the targets have overlapping signatures. Of primary concern to any user of a geophysical sensor is its ability to detect munitions relative to its false-alarm rate under realistic conditions. However, both "detection" and "false-alarm rate" are ambiguous terms in any buried-munitions sensor test when no attempt to physically remove munitions from the ground is made, because it is not clear how the target relocation process and dig rules might affect the achieved performance.[1] But the practical difficulties of operating a test site where munitions are excavated and replaced after each test make such an option prohibitively costly.

If the munitions (and any emplaced clutter) are spaced far enough apart relative to the size of the scoring halo, there is little ambiguity in assigning alarms to buried munitions. However, a desirable feature of an open field test site is realism. Clusters of munitions and clutter are known to exist on real-world sites slated for remediation. The Standardized UXO Test Sites contain clusters of objects that range in size from two objects within roughly a meter of each other up to tens of objects covering tens of square meters. These clusters make counting detections difficult. When the physical signatures of the clutter and munitions overlap, they can effectively form one continuous signature that may be much larger than the signature from a single object. Small scoring halos will not typically cover the signature of the entire cluster. To make a detection (a "hit" in the standardized site analysis (SSA) and standardized scoring system) in this situation, the demonstrator performing the test must find the relative location of sources within the cluster. During a real response action, a contractor often marks the location of a large signature, assuming that it will be reacquired (potentially with a different sensor than used for the primary search) and dug by an excavation crew. Attempts to define rules for associating clusters of targets and declarations have proven to be arbitrary and have not resulted in meaningful evaluation of the true detection capabilities of a system.

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[1] See Thomas Altshuler et. al., "Demonstrator performance at the Unexploded Ordnance Advanced Technology Demonstraton at Jefferson proving Ground (Phase I) and Implications for UXO Clearance," IDA Paper P-3114 (Alexandria, Va.: Institute for Defense Analyses, October 1995) for a detailed review of the ambiguities.

In addition to the 11× rule-of-thumb depth filter, the SSA presents the Pd and rBAR of demonstrators at the Standardized Test Sites, after excluding six obvious clusters like the one in Figure 5-4a. However, defining an "obvious cluster" is itself a problem. Even after filtering out clusters with many objects, an examination of remaining misses demonstrates that even just two objects that are close to each other can manifest sufficient signature masking to make detection ambiguous. Figures 5-13 and 5-14 show the "shadow" effect of just two objects that are near each other.

Beyond the difficulty of defining detection near a cluster, there are unusual cases at each Standardized Test Site that should be considered separately. Examples include permanent obstacles that preclude physical access to buried targets for some systems and areas prone to flooding, where some demonstrators were prohibited from surveying. Some are designed challenges; others are random events. For example, at APG, there is a chain link fence in the middle of the open field. Some items are buried so close to this fence that many sensors did not pass over them while maneuvering to avoid the fence. This was particularly true for towed arrays. Another example is heavy rain flooding a portion of the open field area at APG in the summer of 2004. Several ordnance locations became inaccessible during this period.

The SSA removed "inaccessible to survey" ordnance from scoring in the same filter as the large clusters. The SSA does, however, score against targets that may have been missed due to small, local divergences in the survey path that systems would be expected to cover under normal field circumstances. Note that with analog surveys (mag and flag and EM and flag), a precise record of the area surveyed is not produced, as in the case of digital surveys. As a result, the "inaccessible to survey" allowance of the SSA is not applied to analog surveys. In a real response action using analog instruments, if a portion of the survey region was missed on the original survey, it would go undocumented. A precise GPS record of the sensor's entire survey track allows temporarily inaccessible areas (e.g., the flooded area at the APG open field) or accidentally missed areas (large track separation) to be accurately identified and resurveyed later. This QA/QC measure is not possible in surveys without georeferenced data.

Figure A-2 shows the detection by ordnance type and vendor. The table gives some of the reasons that targets were missed by specific vendors that surveyed the APG open field.

NRL EM61 Array

Ordnance	Reasons	Pd
"BDU28"	None	1.00
"20mmP"		0.80
"40mmP"	Shadow	0.80
"60mmM"	Shadow	0.95
"81mmM"	Halo and Shadow	0.90
"105mmP"	None	1.00
"155mmP"	Deep	0.95

NAEVA EM61 Array

Ordnance	Reasons	Pd
"BDU28"		0.90
"20mmP"		0.70
"40mmP"		0.90
"60mmM"		0.85
"81mmM"		0.90
"105mmP"		0.95
"155mmP"		0.90

NRL MATDS Mag Array

Ordnance	Reasons	Pd
"BDU28"	Shadow	0.85
"20mmP"		0.50
"40mmP"	Shadow	0.90
"60mmM"	Shadow	0.80
"81mmM"	Shadow	0.95
"105mmP"	None	1.00
"155mmP"	None	1.00

NRL GMTADS GEM3 Array

Ordnance	Reasons	Pd
"BDU28"	Shadow	0.90
"20mmP"		0.70
"40mmP"	Boundary and Shadow	0.80
"60mmM"	Shadow	0.85
"81mmM"	Shadow	0.95
"105mmP"	None	1.00
"155mmP"	Deep	0.90

TTFW EM61

Ordnance	Reasons	Pd
"BDU28"	None	1.00
"20mmP"		0.70
"40mmP"	Halo and Shadow	0.80
"60mmM"	Halo and Shadow	0.85
"81mmM"	Halo and Shadow	0.90
"105mmP"	Halo and Shadow	0.95
"155mmP"	Deep and Halo	0.95

Figure A-2. Detection by ordnance types at standardized test sites.

A.2 Detection Results by Ordnance Types at the APG Open Field

Figures A-3 through A-7 supplement the plots in Section 5.3.3. The plots show the depths of 100% detection and the depth of the deepest target detected at APG. The 100% detection depth is nearly always shallower than the 11× line, but the depth of deepest detection exceeds the 11× depth in most cases.

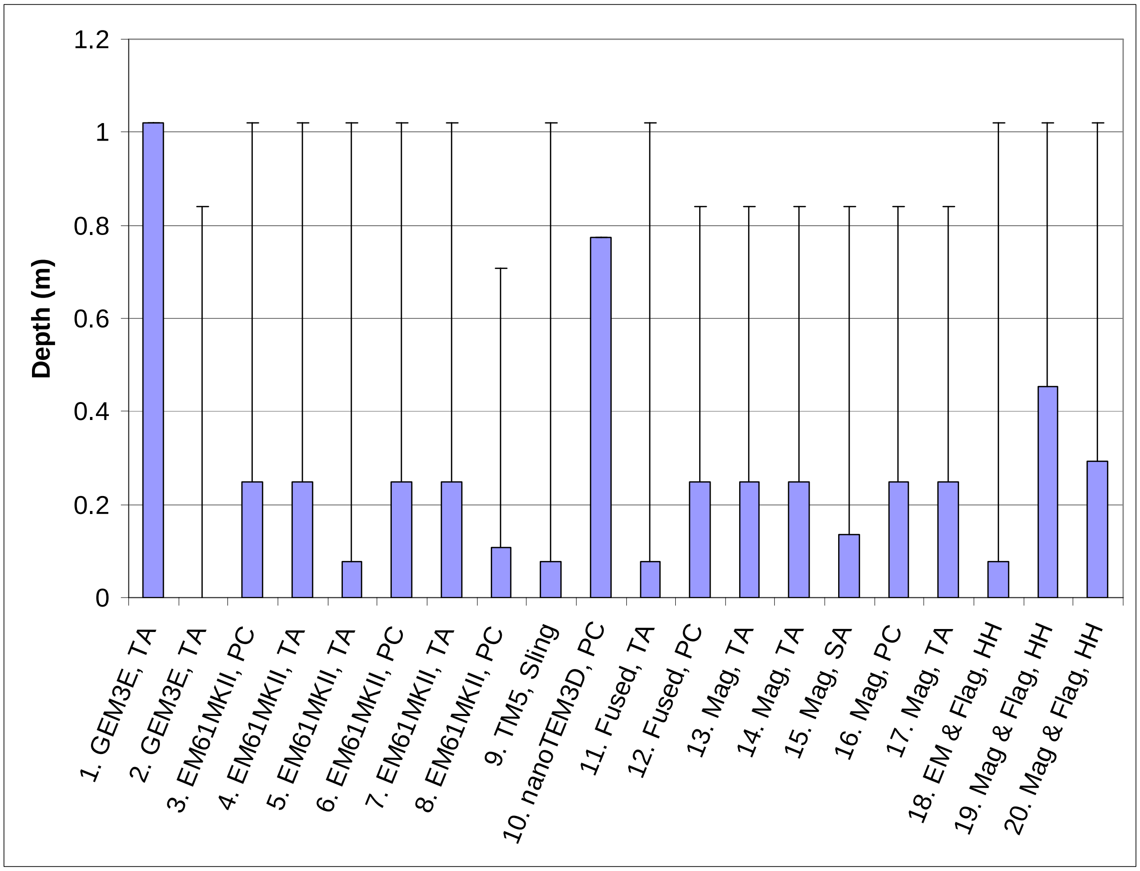

Figure A-3. Performance at APG versus 2.75-inch rockets. The bars indicate the depth to which 100% of the 2.75-inch rockets were detected by each demonstrator and the whiskers the deepest item detected.

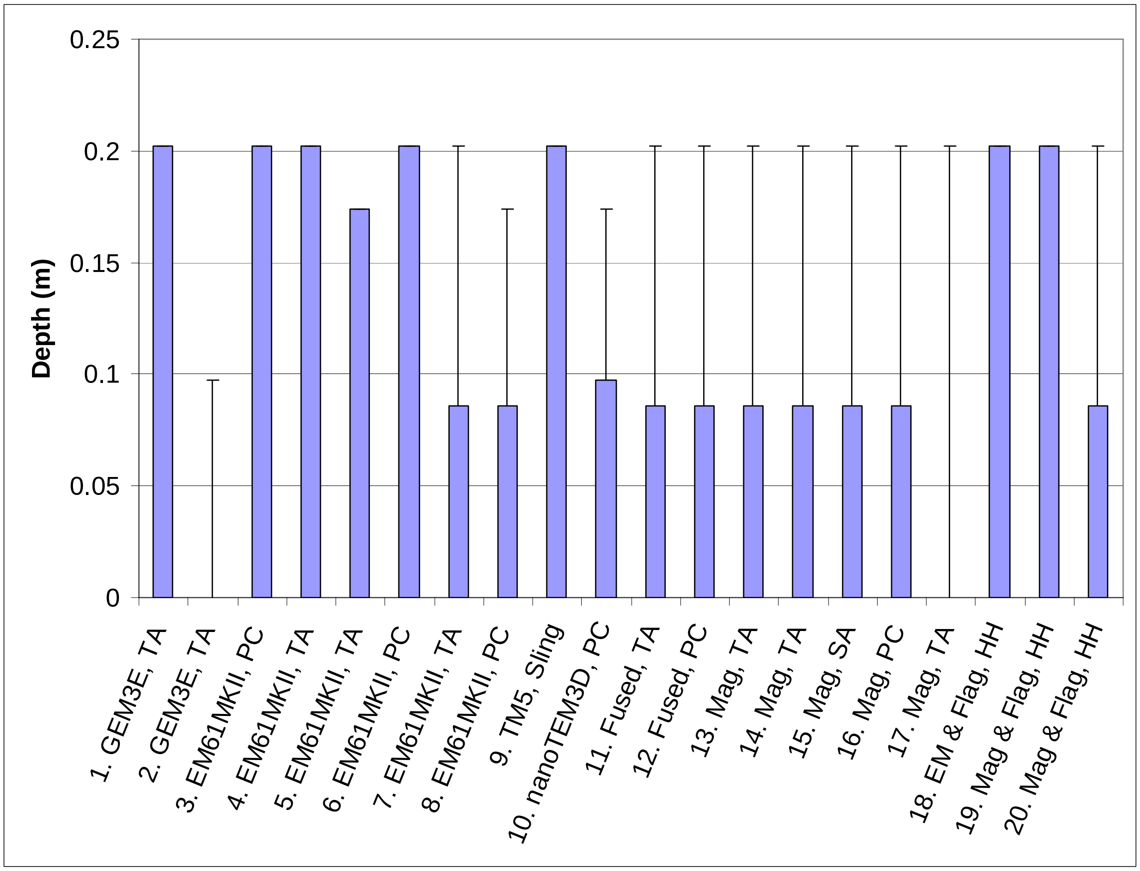

Figure A-4. Performance at APG versus BDU 28 items. The bars indicate the depth to which 100% of the BDU 28 items were detected by each demonstrator and the whiskers the deepest item detected.

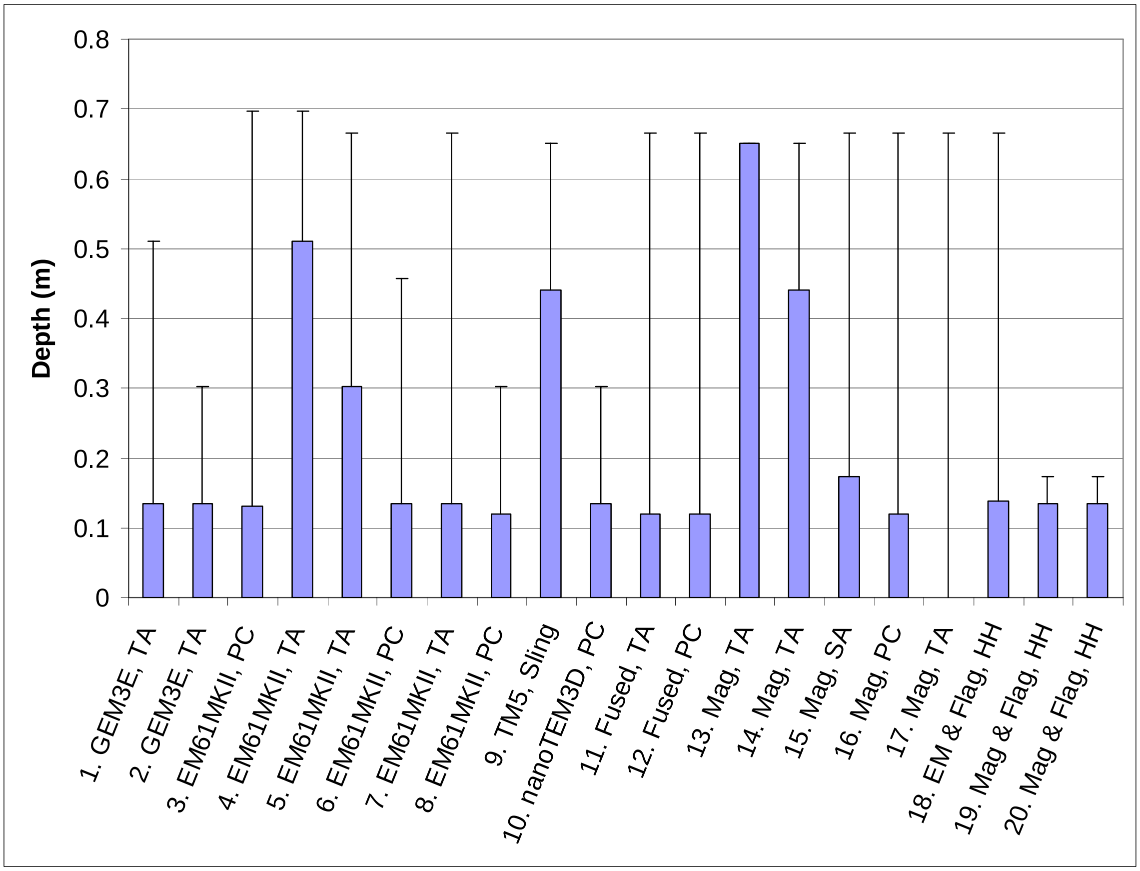

Figure A-5. Performance at APG versus 40 mm items. The bars indicate the depth to which 100% of the 40 mm were detected by each demonstrator and the whiskers the deepest item detected.

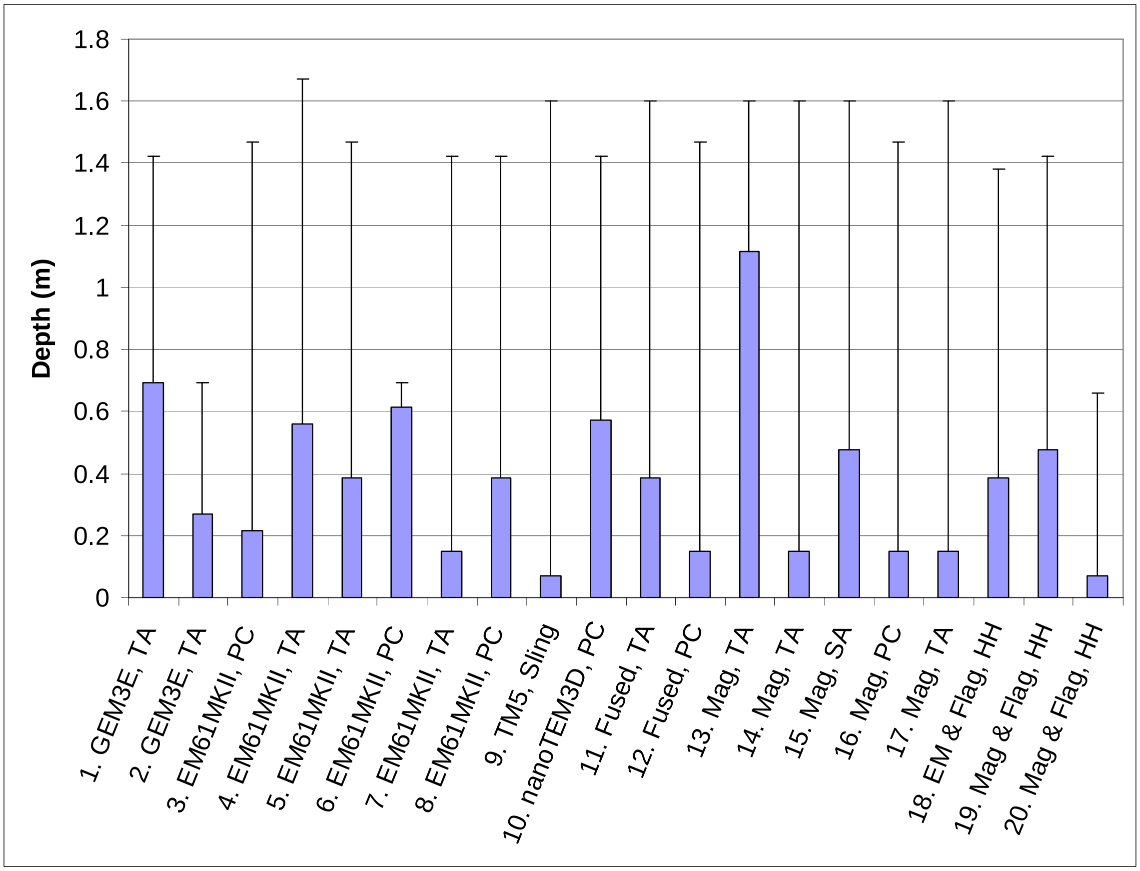

Figure A-6. Performance at APG versus 81 mm items. The bars indicate the depth to which 100% of the 81 mm were detected by each demonstrator and the whiskers the deepest item detected.

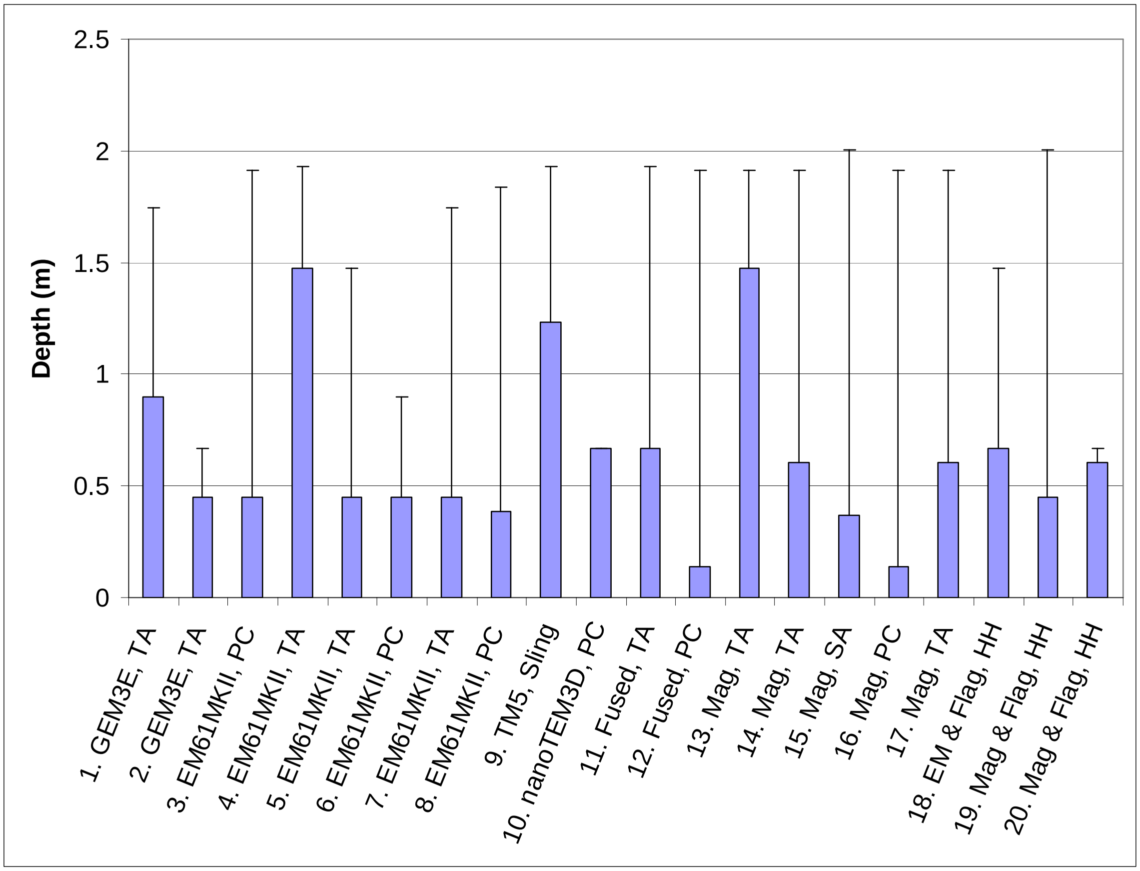

Figure A-7. Performance at APG versus 105 mm items. The bars indicate the depth to which 100% of the 105 mm were detected by each demonstrator and the whiskers the deepest item detected.

A.3 Detection Results by Ordnance Types at the YPG Open Field

The plots in figures A-8 through A-15 show the depths of 100% detection and the depth of the deepest target detected at YPG.

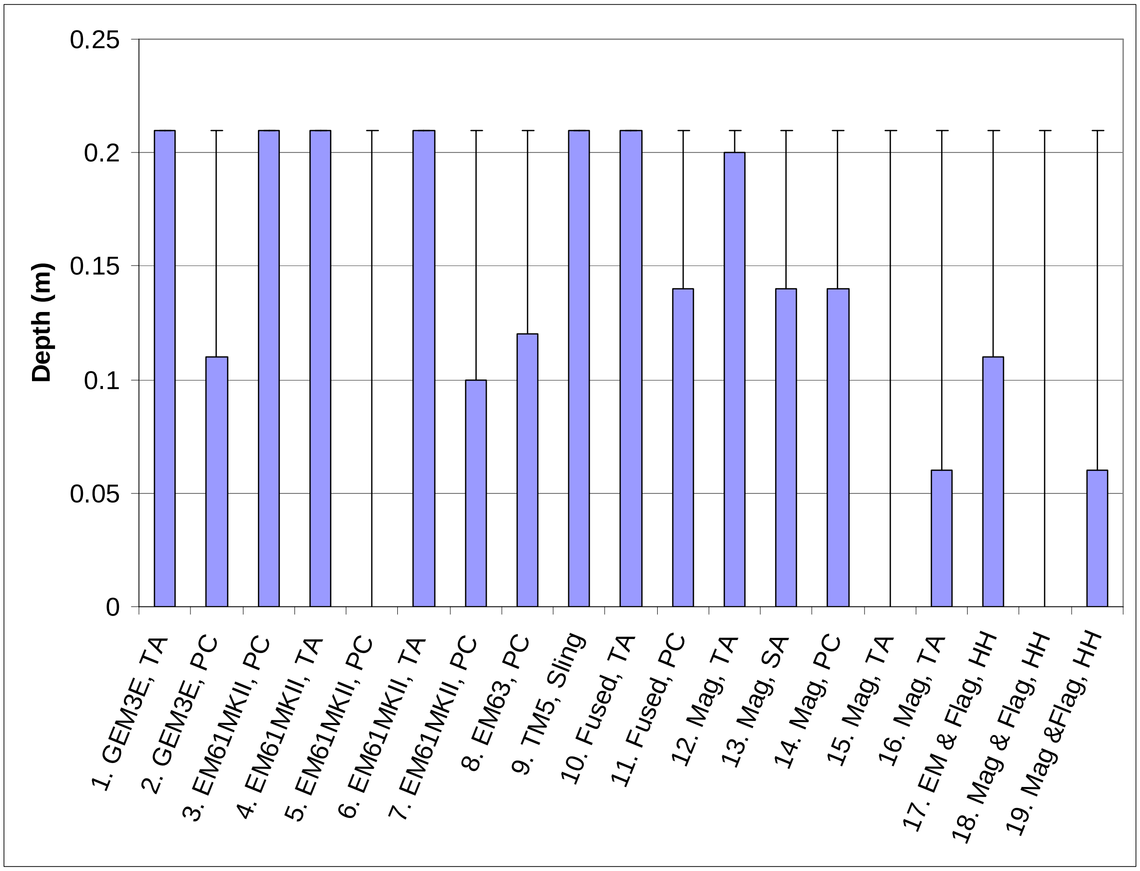

Figure A-8. Performance at YPG versus BDU-28 items. The bars indicate the depth to which 100% of the BDU 28 were detected by each demonstrator and the whiskers the deepest item detected.

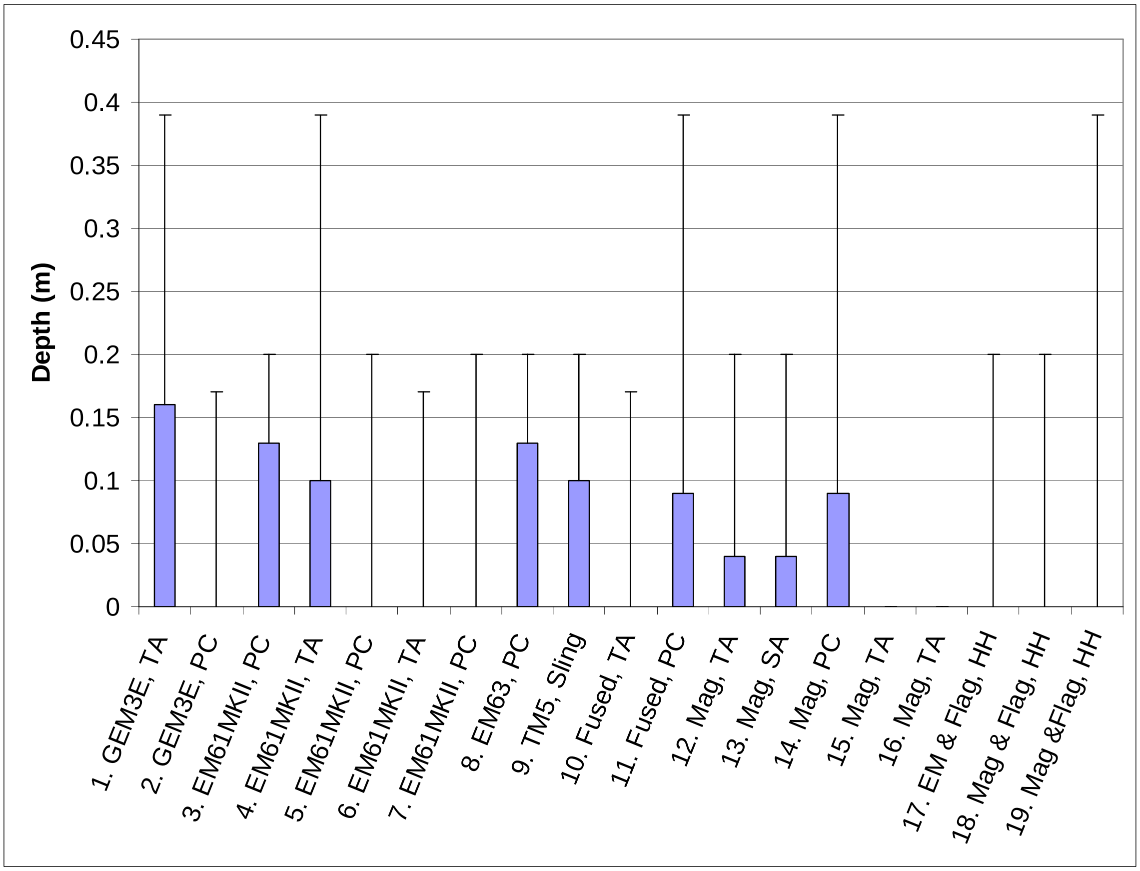

Figure A-9. Performance at YPG versus 20 mm items. The bars indicate the depth to which 100% of the 20 mm were detected by each demonstrator and the whiskers the deepest item detected.

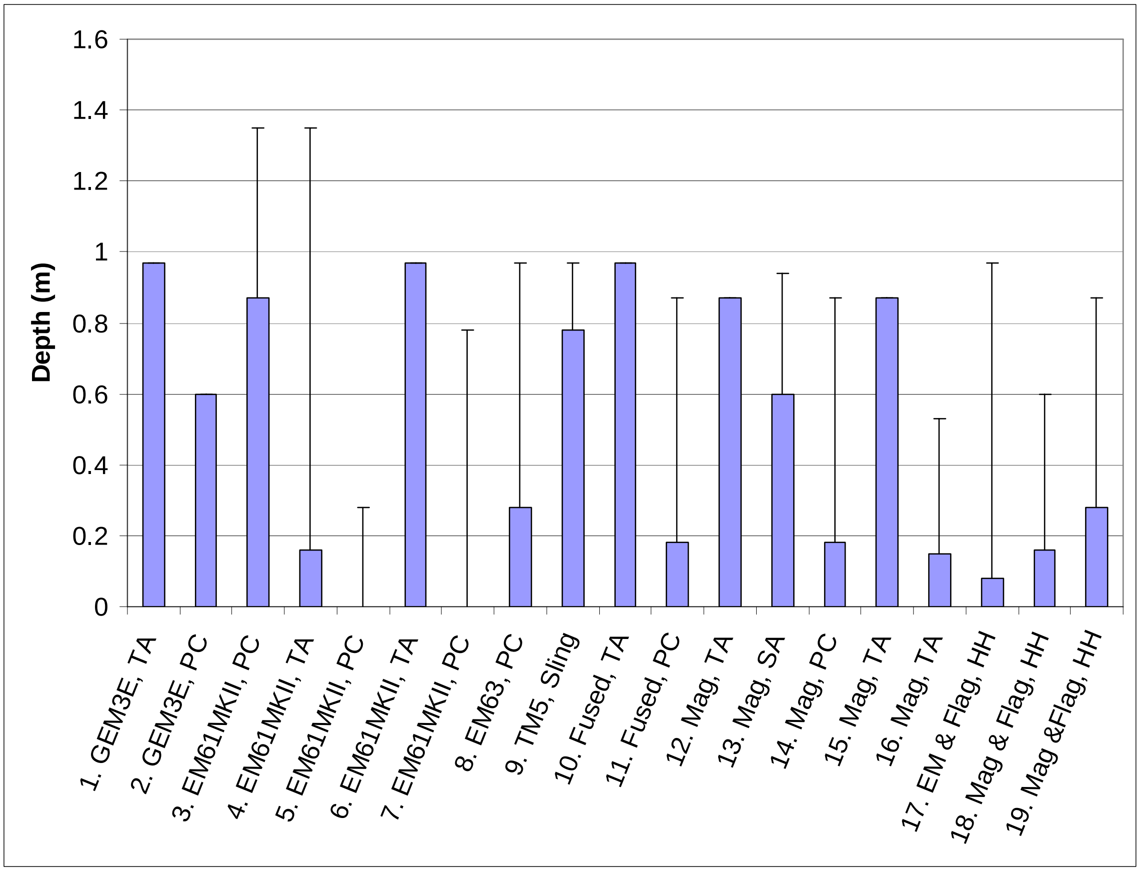

Figure A-10. Performance at YPG versus 2.75-inch rockets. The bars indicate the depth to which 100% of the 2.75-inch rockets were detected by each demonstrator and the whiskers the deepest item detected.

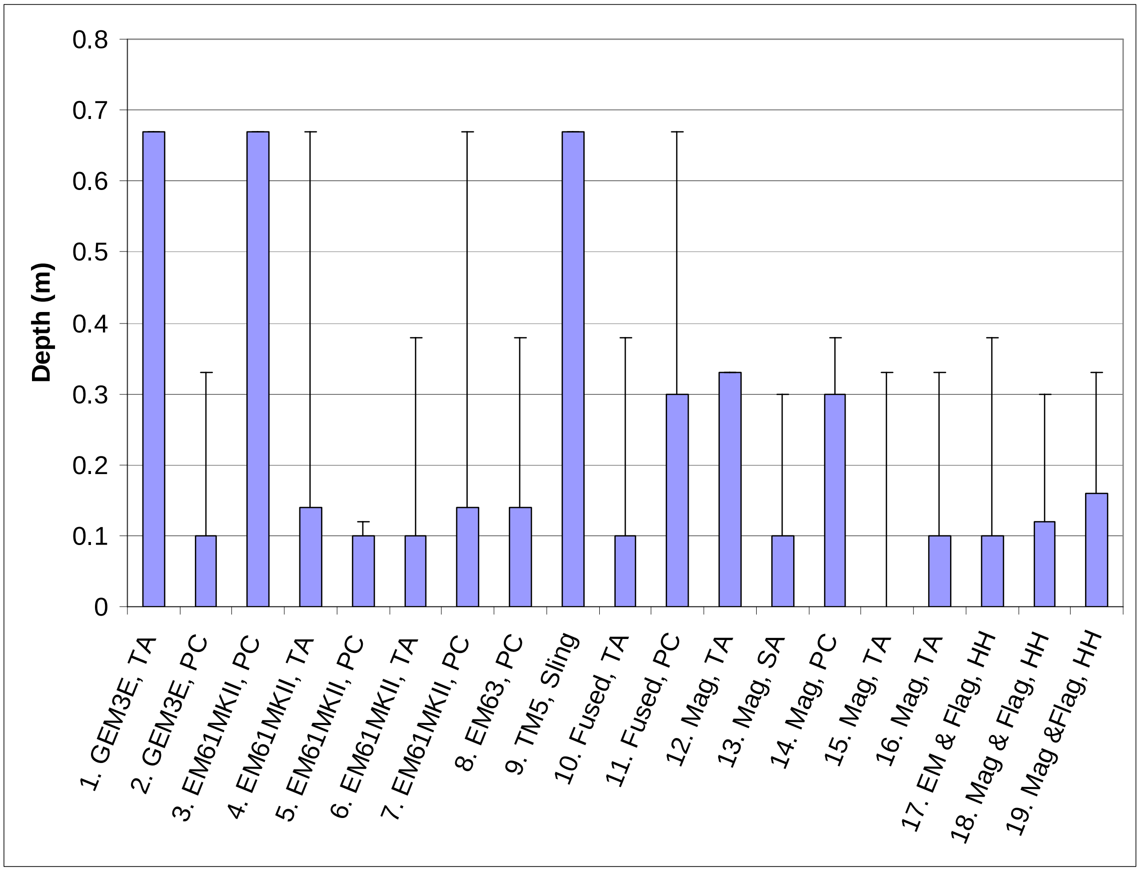

Figure A-11. Performance at YPG versus 40 mm items. The bars indicate the depth to which 100% of the 40 mm were detected by each demonstrator and the whiskers the deepest item detected.

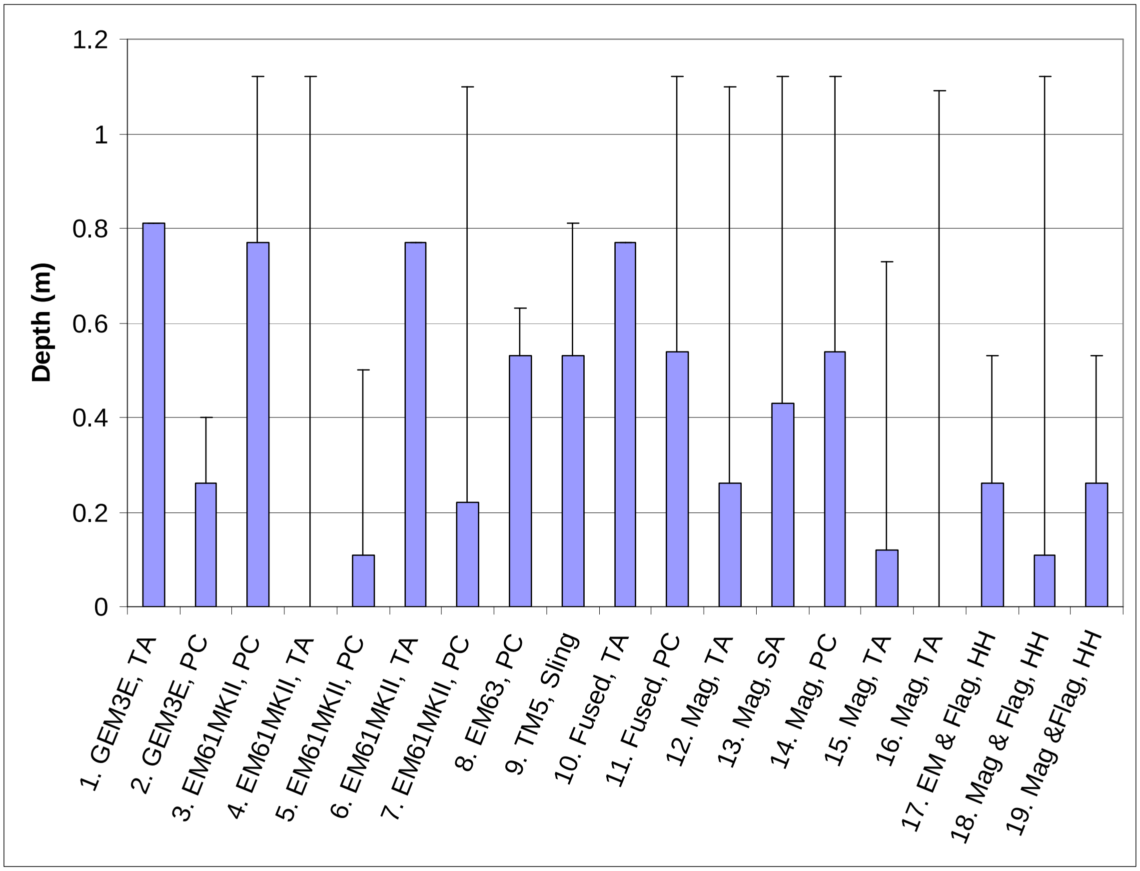

Figure A-12. Performance at YPG versus 60 mm items. The bars indicate the depth to which 100% of the 60 mm were detected by each demonstrator and the whiskers the deepest item detected.

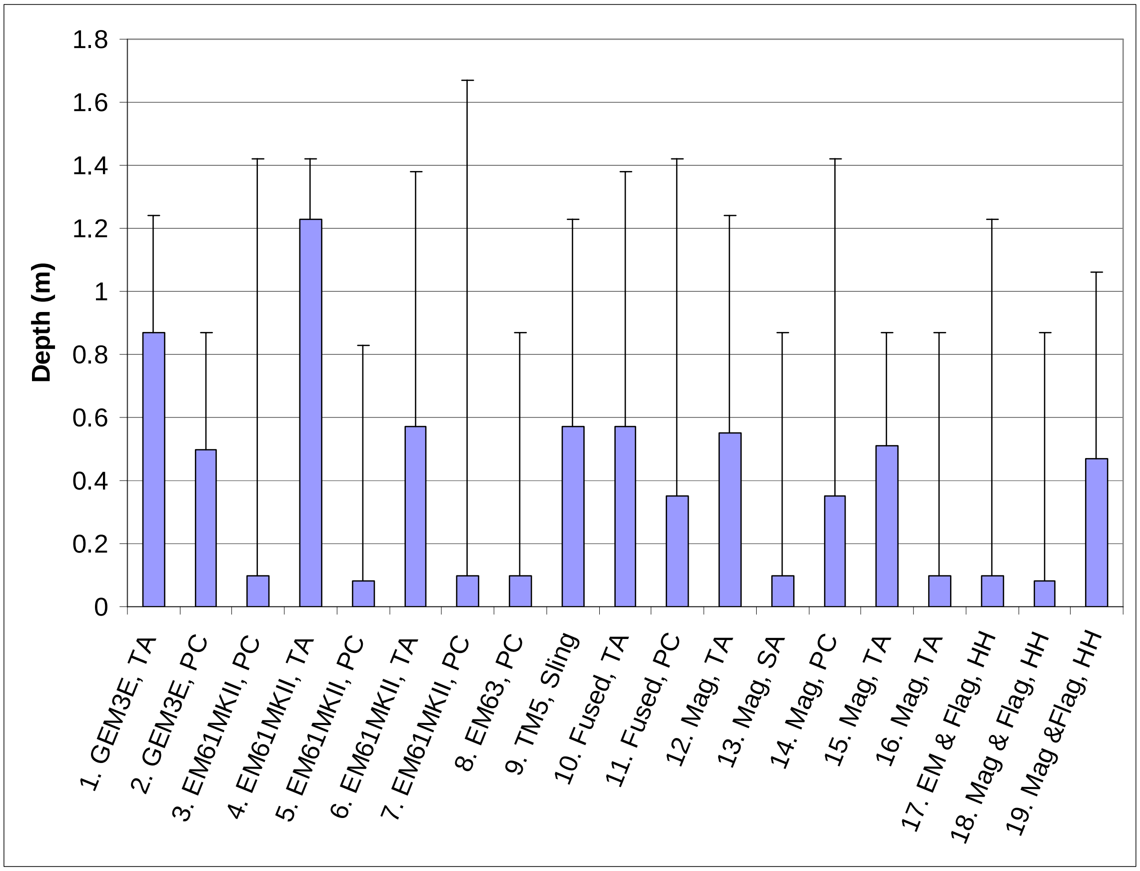

Figure A-13. Performance at YPG versus 81 mm items. The bars indicate the depth to which 100% of the 81 mm were detected by each demonstrator and the whiskers the deepest item detected.

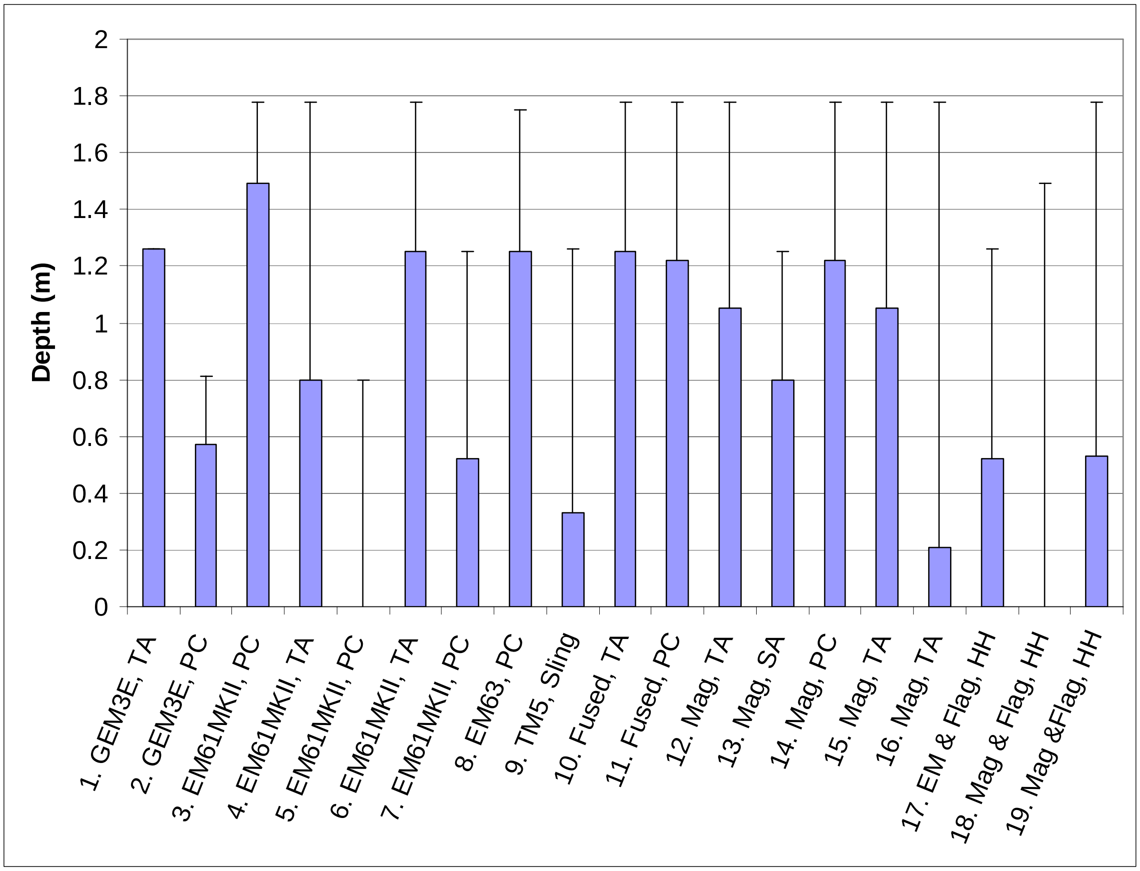

Figure A-14. Performance at YPG versus 105 mm items. The bars indicate the depth to which 100% of the 105 mm were detected by each demonstrator and the whiskers the deepest item detected.

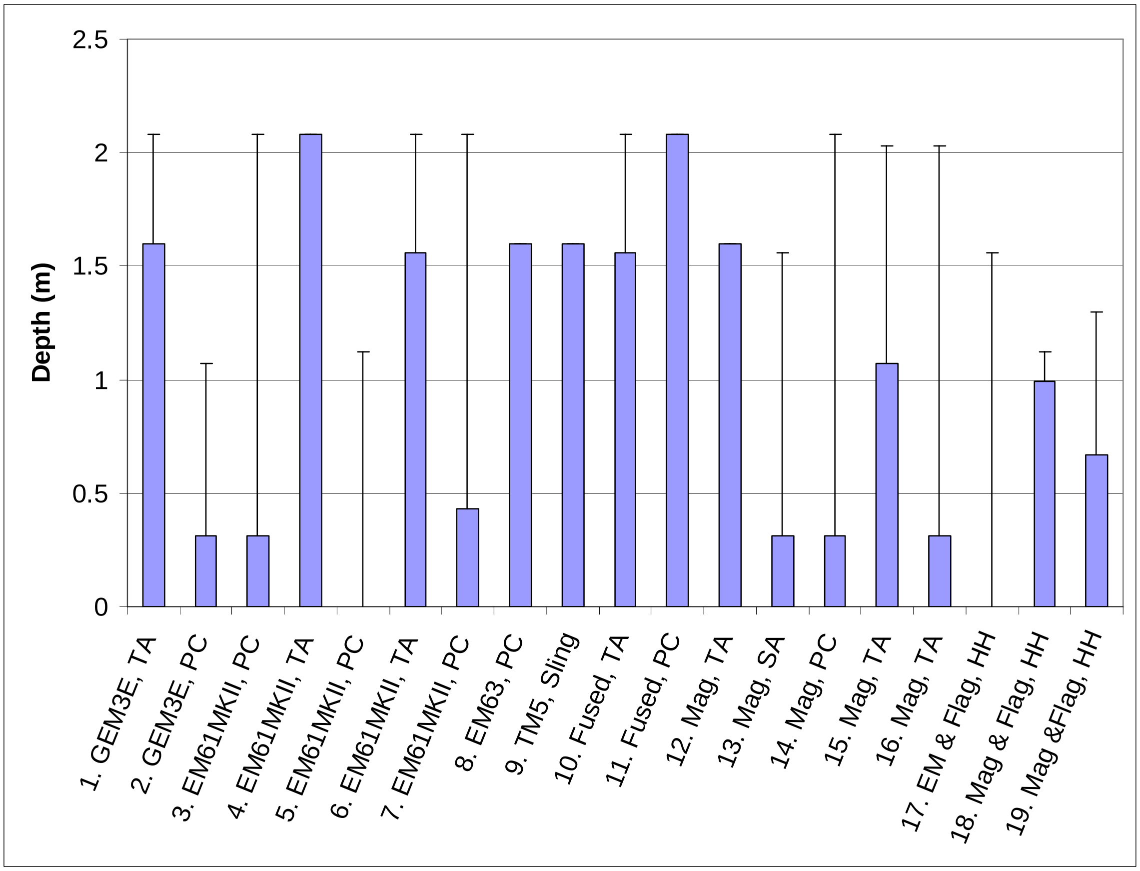

Figure A-15. Performance at YPG versus 155 mm items. The bars indicate the depth to which 100% of the 155 mm were detected by each demonstrator and the whiskers the deepest item detected.

Appendix B—Standardized Test Sites Performance Analysis: Detectability Plots

B.0 Detection Plots

Figures 5-7 through 5-12 show the probability of detection for ordnance types as a function of depth. The probabilities are aggregates of the best demonstrators for each sensor type. The ordnance are grouped in depth bins equal to 1/6 of the 11× diameter rule-of-thumb depth for each ordnance (i.e., a depth bin is 11/6 times the diameter of the ordnance). The plotted depths are at the beginning of each depth bin.

The aggregate *Pd* from each depth bin is reported for selected munitions. The uncertainties shown represent a 70% confidence level. They are calculated assuming a true detection probability, *P*, and true miss probability, 1 – *P*. Given the total number of targets encountered in a particular bin, the observed *Pd* (fraction detected) is a random sample from a binomial distribution whose most probable value is *P*. The uncertainty expresses the 70% confidence interval in which P is expected to lie when the observed *Pd* is indicated by the black dot.

The curve fit to the data is:

$$Pd(d) = \frac{1}{2} - \frac{1}{2}\tanh\left(\frac{a-d}{b}\right),$$

where d is depth, and a and b are parameters determined from a least squares fit to the observed probabilities in each bin.

The fit is not weighted by the uncertainties. Many factors dictate the precise shape of the curve, including the background noise distribution, the data-analysis method, and field techniques. The *tanh* function was chosen as a fitting function solely because it approximates the global features of the probability of detection curve. At low depths, the above equation is nearly one and, at great depths, it is nearly zero. Terms a and b describe how steeply the probability descends from one to zero and at what depth the probability passes below 50%. In cases where there were too few populated bins or the numerical fit did not converge, no fit is included in the graph.

Appendix C—Munitions Actions Studied

C.0 Munitions Actions Studied

Table C-1 shows the survey results from the 66 instrument evaluations at 44 munitions response sites studied. This information complements the GPO analysis for Chapter 4 and the state-of-the-practice analysis in Chapter 3. Not all GPOs for the detailed analysis are included in this table. The GPOs that are missing are Camp Elliot 2004, Fort Ord 2001, and Lowry 1998.

Table C-1 Detailed Tabulation of Survey Results

Site	Year	Action	GPO-Detailed Analysis	Munitions Mapping Technology	Munitions Sweep Technology	Munitions Reacquisition Technology	QA/QC Technology	Contractor	Reference
Adak NAF, AK OU B-1	2000	RI	X	EM61		Vallon Ferrous Locator Schonstedt		Foster Wheeler	Foster Wheeler Environmental Corporation and Environmental Chemical Corporation, 2001, "Final Remedial Investigation / Feasibility Study Report For OUB1 Sites, Former Naval Air Facility, Adak Island, Alaska", Prepared for Commanding Officer, Engineering Field Activity
Adak NAF, AK OU B-1	2001	RA	X	EM61		Vallon Ferrous Locator Schonstedt		Foster Wheeler	Foster Wheeler Environmental Corporation and Environmental Chemical Corporation, 2002, "Draft Final After Action Report - 2001 Field Season, Former Naval Air Facility, Adak Island, Alaska", Prepared for Commander, Engineering Field Activity
Adak NAF, AK OU B-1	2002	RA		EM61		Vallon Ferrous Locator Schonstedt		Foster Wheeler	Foster Wheeler Environmental Corporation, 2003, "Final After Action Report for 2002 Field Season for OU B-1 Sites, Former Naval Air Facility, Adak Island, Alaska", MAY 2003
Badlands Bombing Range, SD Sectors 1 - 9	1999-'00	EECA		G858 Airborne Array	Schonstedt	Schonstedt		Parsons	Parsons, 2003, "Final Engineering Evaluation and Cost Analysis Report for the Badlands Bombing Range, Volume I, Revision 1", Prepared for U.S. Army Engineering Support Center, Huntsville, Alabama and U.S. Army Corps Of Engineers, Omaha District, Nebraska,
Badlands Bombing Range, SD Sectors 10, 11	2003	EECA	X (1999 GPO)	G858 Airborne Array	Schonstedt G858	Schonstedt G858	G858	Parsons	Parsons, 2002, "Final Engineering Evaluation And Cost Analysis Work Plan for the Badlands Bombing Range, Phase IV", Prepared for U.S. Army Engineering Support Center, Huntsville, Alabama and U.S. Army Corps Of Engineers, Omaha District, Nebraska, April 2002 USACOE, 2003. "Badlands Bombing Range Newsletter, November 2003", U.S. Army Corps of Engineers, Omaha District
Camp Beale, CA	2002	EECA	X (2002 GPO)	EM61-Mk2				Earth Tech	Earth Tech, 2003, "Engineering Evaluation/Cost Analysis, Volume 1, Former Camp Beale, Yuba and Nevada Counties, California", July 2003
Camp Beale, CA	2004	SI		EM61-Mk2		Schonstedt EM61-Mk2		Earth Tech	Earth Tech, 2004, "Site Inspection (SI) Work Plan, Former Camp Beale, Yuba and Nevada Counties, California", September, 2004
Camp Bonneville, WA	2004	RA		Geonics EM61-TD	White Spectrum XLT metal Detector			Tetra Tech, Inc.	"Final Corrective Action Work Plan for Interim Cleanup Action Landfill 4/Demolition Area 1 Camp Bonneville Military Reservation, WA", TETRA TECH, INC., April 2004 Greg Johnson State of WA confirmed Camp Bonneville instruments
Camp Bowie, TX Moving Target Berm	2000	TCRA			Schonstedt 52Cx magnetometers		Schonstedt 52Cx magnetometers	EOD Technology, Inc.	"FINAL REPORT TIME CRITICAL OE REMOVAL ACTION MOVING TARGET BERM FORMER CAMP BOWIE, BROWNWOOD, TEXAS", dated 9/11/2001, EODT
Camp Butner, NC	2001-'02	EECA		EM61-Mk2	Schonstedt	Schonstedt		Parsons	Parsons, 2002, "Final Work Plan for Engineering Evaluation/Cost Analysis for the former Camp Butner Site", Prepared for: U.S. Army Engineering and Support Center, Huntsville, July 2002. Parsons, 2003, "Draft Final Engineering Evaluation/Cost Analysis Rep
Camp Butner, NC	2002-'03	TCRA		EM61 EM61 HH	Schonstedt GA-52Cx White's Eagle Spectrum (6000 Pro XLT)			Parsons	Parsons, 2003, "Final Time Critical Removal Action Report, Lakeview Subdivision, Former Camp Butner, Butner, North Carolina", Prepared for U.S. Army Corps of Engineers, Huntsville Center and U.S. Army Corps of Engineers, Wilmington District, August 2003
Camp Claiborne, LA	2001	RA	X	EM61-Mk2 G858		EM61-Mk2 G585 Schonstedt		EODT	EOD Technology, 2002, "Final Report for the Ordnance And Explosive (OE) Investigation & Removal Action Former Camp Claiborne, Rapides Parish, Louisiana", Prepared for: U.S. Army Engineering & Support Center, Huntsville, Alabama, November 2002
Camp Croft, SC	1999-'00	RA		EM61	Foerster Ferex 4.021 (MK26) Vallon Ferrous Locator Schonstedt GA-72Cd	EM61 Schonstedt GA-72Cd		UXB International	UXB International, 2001,"Final Removal Report, Ordnance Removal Action, Former Camp Croft, OOU-3 A, B, and C, OOU-6, and OOU-11 C and D, Spartanburg, South Carolina", April 2001

Site	Year	Action	GPO-Detailed Analysis	Munitions Mapping Technology	Munitions Sweep Technology	Munitions Reacquisition Technology	QA/QC Technology	Contractor	Reference
Camp Croft, SC OOU-6	2001-'02	RA		EM61 GEM3 MTADS-MPA (EM)	Schonstedt	Schonstedt EM61 GEM3	Schonstedt	Zapata Engineering; Blackhawk	Zapata Engineering, 2002, "Site Specific Final Report, Former Camp Croft Army Training Facility, OOU-6, Spartanburg County, Spartanburg, South Carolina", September 2002
Camp Croft, SC OOU 3, 11C, and 11D	2004	RA	X	EM61-Mk2	Schonstedt	EM61-Mk2 Schonstedt		NAEVA Geophysics, Zapata Engineering	Zapata Engineering, 2004, Ordnance And Explosives Removal Action, Former Camp Croft (Ordnance Operable Units 3, 11C, And 11D), Spartanburg, South Carolina, Final Work Plan", Prepared For: US Army Engineering And Support Center, Huntsville and US Army Cor
Camp Elliot, CA Equistrian Stage Area Site	2003	RA		EM61-Mk2		EM61-Mk2 Fisher Impulse Schonstedt GA52-Cx		EODT	SCI UXO/OE Services, 2004, "Final Site Specific Final Removal Action Report, Ordnance and Explosives Construction Support for Mission Trails Regional Park, Equestrian Staging Area Project, Former Camp Elliott-East Elliott, San Diego, California, Prepared for Los Angeles District, U.S. Army Corps of Engineers, 12 March 2004
Camp Ellis, IL	1999-'00	EECA		Geonics EM61-TD Geometrics G858 Cs mag	Schonstedt GA-52Cx	Geonics EM61-TD Geometrics G858 Cs mag Schonstedt GA-52Cx	Schonstedt GA-52Cx	Parsons	"FINAL EECA FORMER CAMP ELLIS MILITARY RESERVATION TABLE GROVE, ILLINOIS" PARSONS, January 12, 2006
Camp Gordon Johnson, FL	1999-'00	EECA		EM61	Schonstedt GA-52Cx	EM61 HH Schonstedt GA-52Cx		Parsons	Parsons Engineering Science, 2001, "Draft Engineering Evaluation And Cost Analysis (EE/CA) Report, Former Camp Gordon Johnston, Franklin County, Florida", prepared for U.S. Army Engineering and Support Center, Huntsville, July 2001
Camp Hero, NY	2001	EECA		EM61	Schonstedt GA-52Cx	EM61	N/A	Parsons	Parsons, Inc., 2002, "Draft Final Engineering Evaluation/Cost Analysis(EE/CA) Report, Former Camp Hero, Montauk, New York", prepared for U.S. Army Engineering and Support Center, Huntsville, February 2002.
Camp Ibis, CA	2002	EECA		EM61		EM61 Schonstedt Model GA-72CV		Parsons	Parsons, 2002, "Final Engineering Evaluation / Cost Analysis Work Plan, Former Camp Ibis, San Bernardino County, California", Prepared for U. S. Army Corps of Engineers, Huntsville Center, February 2002 Larry Sievers USACE confirmed the instruments used at Camp Ibis
Camp Robinson, AR	2001	EECA		G858		Schonstedt G858		Parsons	Parsons, 2003, "Final Engineering Evaluation/Cost Analysis for Former Camp Joseph T. Robinson, North Little Rock, Arkansas", Prepared for U.S. Army Corps of Engineers, Little Rock District and U.S. Army Engineering and Support Center, Huntsville. Alabama,
Camp Swift, TX	2002	EECA	X (2000 GPO)	G858		Schonstedt G858	Schonstedt G858	Parsons	Parsons, 2003, "Draft Final Engineering Evaluation/Cost Analysis (EE/CA), Former Camp Swift, Prepared for U.S. Army Corps of Engineers, Fort Worth District, Fort Worth, Texas, September 2003 Parsons, 2001, "Work Plan for Engineering Evaluation and Cost Analysis, Camp Swift, Texas", Prepared for: U.S. Army Engineering and Support Center, Huntsville, February 2001.
Camp Swift, TX School Site	2003	TCRA			Schonstedt GA-52Cx		G858	EODT	EOD Technologies, Inc., 2003, "Final Work Plan for the Time Critical OE Removal Action at The New School Site, Former Camp Swift, Bastrop, Texas", Prepared For U.S. Army Engineering & Support Center, Huntsville, Huntsville, AL, April 2003
Camp Wheeler, GA	2004	EECA		Foerster Ferex 4.032 fluxgate magnetometers		Schonstedt magnetometer		EODT	"DRAFT FINAL ENGINEERING EVALUATION AND COST ANALYSIS (EE/CA) REPORT for the FORMER CAMP WHEELER MACON, GEORGIA, EODT" June 2005 EOD Technology, 2004, "Final Geophysical Letter Report for the Ordnance and Explosives (OE) Engineering Evaluation and Cost Analysis (EE/CA), Former Camp Wheeler, Macon, Georgia", Prepared for: U.S. Army Engineering and Support Center, Huntsville, Alabama
Conway Bombing Range, SC	1999-'00	EECA		EM61		EM61 Schonstedt		Parsons; USA Environmental	Parsons, 2003, "Final Engineering Evaluation And Cost Analysis Report for the Former Conway Bombing and Gunnery Range, Conway, South Carolina", Prepared for U.S. Army Engineering Support Center, Huntsville, Alabama, September 2003
Conway Bombing Range, SC Goodson Property of Area B (Range III – Impact Zone)	2000	TCRA		MTADS-Mag G858	Schonstedt GA-52Cx	Schonstedt GA-52Cx G858	Schonstedt GA-52Cx G858	Parsons; Blackhawk Geometrics	Parsons, 2003, "Final Time Critical Removal Action Report, Conway Bombing and Gunnery Range, Conway, South Carolina", Prepared for U.S. Army Engineering Support Center, Huntsville, Alabama, February 2003

Site	Year	Action	GPO-Detailed Analysis	Munitions Mapping Technology	Munitions Sweep Technology	Munitions Reacquisition Technology	QA/QC Technology	Contractor	Reference
F.E. Warren AFB, WY	2004	RI		EM61-Mk2 Handheld Fisher Induction Metal Detector	Handheld Schonstedt GA-52Cx	Handheld Schonstedt GA-52Cx		URS Group Inc.	Remedial Investigation Work Plan for the Closed Base Ranges Range - Reconnaissance Report", URS Group, Inc. June 2004. URS Talk at JSEM 2006
Five Points (Dallas NAS), TX Outlying Field	2005	RA		EM61-MK2		EM61-Mk2 Schonstedt			*American Technologies, 2004, "Final Work Plan Ordnance And Explosives (OE) Removal Action (RA) at the Five Point OLF for Dallas NAS, Arlington, Texas", Prepared for: US Army Engineering and Support Center, Huntsville, September 2004*
Fort Campbell, KY Range 28	2003	RA	X	EM61-MK2 GX3/GX4	Schondstedt				EOD Technology, 2003, "Final Geophysical Letter Report for the OE Clearance, Range 28, Fort Campbell, Kentucky", Prepared for: U.S. Army Engineering and Support Center, Huntsville, Alabama, October 2003
Fort Hood, TX Digital Multipurpose Range Complex	2003	RA	X	EM61-MK2 GX3/GX4					EOD Technology, 2004, "Draft Geophysical Letter Report for the UXO Support During Construction Activities, Digital Multipurpose Range Complex (DMPRC), Fort Hood, Texas", Prepared for: U.S. Army Engineering and Support Center, Huntsville, Alabama, January
Fort McClellan, AL Water Tank Construction Site	2004	RA	X	EM61-MK2		Whites Vallon	Whites Vallon		Tetra Tech FW, 2004, "Geophysical Prove-Out Letter Report, Fort McClellan, Alabama", Prepared for: U.S. Army Engineering and Support Center, Huntsville, Alabama, March 2004
Fort Ord, CA Del Rey Oaks Area	2000	RA		EM61 EM61 -HH G858	Schonstedt GA-52Cx	EM61 EM61-HH G858 Schondstedt GA-52Cx	EM61 EM61-HH G858 Schondstedt GA-52Cx	USA Environmental	USA Environmental, 2001, "Final After Action Report, Geophysical Sampling, Investigation, and Removal, Former Fort Ord, California, Site Del Rey Oaks Group, Volume 1 of 15", Prepared for U.S. Army Corps of Engineers, Sacramento District, California, April 24, 2001
Fort Ord, CA	2002	SI		MTADS-Mag		Schonstedt		USA Environmental	USA Environmental, 2003, "Final Project Report, Meandering Path Geophysical Mapping, Former Fort Ord, California", Prepared for U. S. Army Engineering Support Center, Huntsville, Alabama, October 2003.
Fort Ord, CA MRS-SEA.1–4 (seaside)	2002-'03	TCRA			Schonstedt GA-52Cx			PARSONS	"FINAL TECHNICAL INFORMATION PAPER MRS-SEA.1–4 TIME-CRITICAL REMOVAL ACTION AND PHASE 1 GEOPHYSICAL OPERATIONS" 11 February 2006, PARSONS
Fort Ord, CA MRS-MOCO2	2003	RA		EM61-MK2 G858 magnetometer	Schonstedt GA-52Cx		Schonstedt GA-52Cx	Parsons	"FORMER FORT ORD, MONTEREY, CALIFORNIA MILITARY MUNITIONS RESPONSE PROGRAM DRAFT NON-TIME-CRITICAL REMOVAL ACTION MRS-MOCO.2 (PHASES 1 AND 2) AFTER-ACTION REPORT" March 2006, PARSONS
Fort Ord, CA MRS-MOCO2	2005	RA		EM61-MK2	Schonstedt GA-52Cx	EM61-MK2	Schonstedt GA-52Cx	Parsons	"FORMER FORT ORD, MONTEREY, CALIFORNIA MILITARY MUNITIONS RESPONSE PROGRAM DRAFT NON-TIME-CRITICAL REMOVAL ACTION MRS-MOCO.2 (PHASES 1 AND 2) AFTER-ACTION REPORT" March 2006, PARSONS
Fort Ritchie, MD	1999-'02	RA	X (1999 GPO) X (2002 GPO Addendum)	EM61	Schonstedt GA-72Cd	Schonstedt GA-72Cd	Schonstedt GA-72Cd	Shaw Environmental	Shaw Environmental, 2003, "Fort Ritchie Army Garrison Non-Time-Critical OE Removal Action, Ordnance and Explosives Removal Action Report, Final Document", Prepared for U.S. Army Corps of Engineers, Baltimore District, Maryland, April 2003
Fort Sam Houston, TX	2000	EECA		G858		G858		Sanford Cohen and Associates	Sanford Cohen and Associates, 2000, "Site Specific Final Report Fort Sam Houston Meandering Path Geophysical Survey, Fort Sam Houston, San Antonio, Texas", Prepared for US Army Engineering and Support Center, Huntsville, Alabama, December 2000
Helena Valley, MT Limestone Hills Training Area	2004	SI		G-tek TM-4 Mag Array (4 sensor, handheld)			G-tek TM-4e PEMI (equivalent to G-tek TM5-EMU)	G-tek was contracted by Tetra Tech	"MAGNETOMETER SURVEY TO DETECT AND MAP UNEXPLODED ORDNANCE Limestone Hills, Townsend, MT EOD OPERATION YEAR 3" 2004, G-Tek

Site	Year	Action	GPO-Detailed Analysis	Munitions Mapping Technology	Munitions Sweep Technology	Munitions Reacquisition Technology	QA/QC Technology	Contractor	Reference
Jackson Park, WA	2005	RI		EM61- MK2					Personal contact with Harry Craig (EPA Region 10) Phase 1 completed RI, phase II ongoing
Kirtland AFB, NM PBRs N-1,2,3,&4	2005	EECA		GX3/GX4 (EM-61) Array		Whites Metal Detector		EODT	"Draft Engineering Evaluation and Cost Analysis Report for the Former Kirtland Precision Bombing Ranges Albuquerque, NM", EODT, May 2005
Lake Bryant BGR, FL	2002	EECA		EM61- MK2				Zapata Engineering	Zapata Engineering, 2003, "Final Geophysical Prove-Out Report, Ordnance and Explosives (OE) Engineering Evaluation and Cost Analysis, Former Lake Bryant Bombing Range, Ocala, Florida", Prepared for: U.S. Army Engineering and Support Center, Huntsville and
Lowry BGR, CO Beacon Point	2002-'03	RA		EM61 (time domain) Vehicle Towed Array (EM61X5) EM61 Man-Portable (MP) Unit		White Spectrum XLT metal detector Vallon VMX2		Foster Wheeler	"DELTA SECTOR FINAL COMPLETION REPORT BEACON POINT DEVELOPMENT ORDNANCE CLEARANCE FORMER LOWRY BOMBING AND GUNNERY RANGE AURORA, COLORADO" FOSTER WHEELER ENVIRONMENTAL CORPORATION, April 25, 2003
Lowry BGR, CO High Plains	2002-'03	RA		EM61 (time domain) Vehicle Towed Array (EM61X5) EM61 Man-Portable (MP) Unit		White Spectrum XLT metal detector Vallon VMX2		Foster Wheeler	"ALPHA SECTOR FINAL COMPLETION REPORT HIGH PLAINS ORDNANCE CLEARANCE FORMER LOWRY BOMBING AND GUNNERY RANGE AURORA, COLORADO" FOSTER WHEELER ENVIRONMENTAL CORPORATION, MAY 2, 2003
Lowry BGR, CO Southshore Site	2003	RA		MTADS-EM		Schonstedt GA-52Cx		Blackhawk UXO Services	"UXO INVESTIGATION TO REDUCE UXO HAZARD POTENTIAL COMPLETION REPORT SOUTHSHORE DEVELOPMENT SITE FORMER OWRY BOMBING AND GUNNERY RANGE AURORA, COLORADO" Prepared By Blackhawk UXO Services, September 9, 2003 Blackhawk UXO Services, 2003, "Geophysical Prove Out, Southshore Development Site, Former Lowry Bombing And Gunnery Range, Aurora, Colorado, Prepared For: Laing Village, LLC, July 10, 2003
Lowry BGR, CO FUDS	2005	RA			Schonstedt 52c Shadow X-5 (handheld FEM)		Schonstedt 52c Shadow X-5 (handheld FEM)	Shaw E&I	Final Master Work Plan UXO Investigation and Clearance Activities FLBGR Arapahoe County, CO" Revision 5, Shaw Environmental, Inc., January 19, 2005
Lowry BGR, CO BT5 GFPR	2005	RA		EM61-MK2	Schonstedt	EM61-MK2 Schonstedt	EM61-Mk2	G-tek	"Work Plan, Part I Revision 3" CH2MHill, September 2005
Lowry Training Annex, CO Navy DRI	2002	RI		MTADS-EM		Schonstedt		CH2MHill	(still looking for report)
Lowry Training Annex, CO EOD Range	2004	RA			Schonstedt 52c Shadow X-5 (handheld FEM)		Schonstedt 52c Shadow X-5 (handheld FEM)	Shaw E&I	(similar Work Plan as FUDS RA/2005)
Lowry Training Annex, CO FLTA EOD area	2005	RI		EM61-MK2		Schonstedt 52c Shadow X-5 (handheld FEM)		Shaw E&I	"DRAFT Geophysical Mapping and Anomaly Investigation Plan Former Lowry Training Annex (FLTA)" Colorado, March 11th, 2005
Makawao Gunnery Site, HI	2003	EECA		Geonics EM61-MK2		Fisher handheld 1266XB EM detector	Fisher handheld 1266XB EM detector	ZAPATAENGINEERING	"ORDNANCE AND EXPLOSIVE ENGINEERING EVALUATION/COST ANALYSIS DRAFT FINAL REPORT MAKAWAO GUNNERY SITE", ZAPATAENGINEERING, P.A. July 2003
McCoy AFB, FL Area 5	1999-'00	RA		EM61-TD		EM61-TD Schonstedt GA-52Cx	Schonstedt GA-52Cx	Parsons	"SITE SPECIFIC FINAL REPORT MCCOY AIR FORCE BASE ORLANDO, FLORIDA", August 2001, Parsons

Site	Year	Action	GPO-Detailed Analysis	Munitions Mapping Technology	Munitions Sweep Technology	Munitions Reacquisition Technology	QA/QC Technology	Contractor	Reference
MMR-Camp Edwards, MA	1999-'01	Other		EM61 Scintrex Smartmag KIMS (EM61X4 Towed Array) Airborne Array		Schonstedt		NAEVA, Blackhawk Geometrics	U.S. Army Corps of Engineers, New England District, 2003, “Munitions Survey Project Phase I, Final Report, Massachusetts Military Reservation, Camp Edwards, Massachusetts”, Prepared for National Guard Bureau, Arlington, Virginia, May 2003
MMR-Camp Edwards, MA	2002	EECA		EM61		EM61 Schonstedt GA-52Cx	EM61 Schonstedt GA-52Cx		American Technologies, Incorporated, 2002, “Final Work Plan for Ordnance and Explosive (OE) Removal Action, Volume I, Camp Edwards Former "H" Range (Mortar Range), Sandwich, Massachusetts”, April 2002 American Technologies, Incorporated, 2003, “Final Ordnance And Explosives (OE) Engineering Evaluation And Cost Analysis (EE/CA) Report, Camp Edwards Former H Range, Sandwich, Massachusetts, Volume II”, April 2003
Pohakuloa Training Area, HI 2000 acres located in the Northeast region of Pohakuloa Training Area (PTA)	2004	SI		EM61-MK2	Minelab Explorer II			American Technologies, Inc.	"FINAL SITE SPECIFIC FINAL REPORT MEC Range Reconnaissance Survey at The Proposed FY06 Battle Area Complex Site Pohakuloa Training Area, Big Island, Hawaii", AMERICAN TECHNOLOGIES, INC. December 13, 2004
Pole Mountain, WY Pole Mountain Target and Maneuver Area	2000	EECA		Foerster Mark 26 total magnetic field vertical gradiometer system		Foerster Mark 26		Earth Tech	"EECA Former Pole Mountain Target and Maneuver Area, Albany County WY"' Earth Tech, Decmeber 2000
Pole Mountain , WY Target and Maneuver Area	2005	EECA		EM61-MK2 Time Domain Electromagnetic System	Minelab Explorer II	EM61-MK2 Time Domain Electromagnetic System Minelab Explorer II	magnetometer (model not clearly specified in report)		"DRAFT FINAL SUPPLEMENTAL INVESTIGATION WORK PLAN MUNITIONS AND EXPLOSIVES OF CONCERN RESPONSE FORMER POLE MOUNTAIN TARGET AND MANEUVER AREA ALBANY COUNTY, WYOMING", American Technologies Incorporated, July 25, 2005
Rocky Mountain Arsenal, CO Site ESA-4a	2002	RI		EM61 MK1 & MK2		Handheld Schonstedt Whites EM metal detector Fisher EM detector	EM61 MK1 & MK2	Tetra Tech	Ken Vogler (CDPHE) provided limited documentation from "Rocky Moun tain Arsenal Munitions Testing Site ESA-4A Qualtiy Assurance Geophysical Survey Plan", Tetra Tech, Revision 1, Dated Jan 18, 2005. Interview with Mark Doller (UXO Lead Rocky Mountain Arsen
Savanna Army Depot, IL	2004	EECA	X	EM61-MK2					Science Applications International Corporation and American Technologies, 2004, “Final Geophysical Prove-Out Report at Savanna Army Depot Activity - Open Burning Ground, Savanna, Illinois”, Prepared for: U.S. Army Engineering and Support Center, Huntsvill
Spencer Artillery Range, TN	2004	EECA	X	EM61-MK2					EOD Technology, 2004, “Geophysical Letter Report, Ordnance and Explosives (OE) Engineering Evaluation and Cost Analysis (EE/CA, Former Spencer Artillery Range, Spencer, Tennessee, Prepared for: U.S. Army Engineering and Support Center, Huntsville, Alabama
Storm King, NY	2001	EECA		EM61 GEM3	Fisher 1266-X	Schonstedt		Parsons	Parsons, 2002, “Draft Final Engineering Evaluation / Cost Analysis, Storm King Site, Orange County, New York”, Prepared for U.S. Army Corps of Engineers, New York District and Huntsville Center, July 2002
Tobyhanna, PA	2004	TCRA	X		Schonstedt		Schonstedt	Weston	Weston, 2004, “Final Work Plan, Expanded Scope Time Critical Removal Action (TCRA) for Emergency Vehicle Access Roads, Pennsylvania State Game Lands #127, Tobyhanna, Pennsylvania”, Prepared for U.S. Army Corps of Engineers, Baltimore District, April 2004
Trabuco Bombing Range, CA Trabuco Creek Bikeway	2004	TCRA	X (2004 GPO)	EM61-MK2		EM61-MK2 Schonstedt White's All-Metal Detector	EM61-MK2	SCI UXO OE Services	SCI UXO/OE Services, 2005, “Final Site Specific Removal Action Report, Time Critical Removal Action (TCRA), Trabuco Creek Bikeway, Former Trabuco Bombing Range, Rancho Santa Margarita, California”, Prepared for: Los Angeles District, U.S. Army Corps of Engineers, February 2005
Vieques NTR, PR	2000	SI		towed array of five Schonstedt 52Cx fluxgate	White Spectrum XLT metal Detector			Chemrad	"Final Preliminary OE Site Assessment Report for the Green Beach Area US Naval Ammunition Support Attachment, Vieques Island, Puerto Rico", CH2M Hill, July 2001

Site	Year	Action	GPO-Detailed Analysis	Munitions Mapping Technology	Munitions Sweep Technology	Munitions Reacquisition Technology	QA/QC Technology	Contractor	Reference
Waikoloa Manuever Area, HI	2003	EECA	X	G-tek TM5-EMU EM61-MK2		G-tek TM5-EMU EM61-MK2			USA Environmental, 2003, “Draft Geophysical Prove-Out Letter Report for the OE Engineering Evaluation And Cost Analysis (EE/CA) Waikoloa Maneuver Area - Phase III EE/CA, Kamuela, Island of Hawaii, Hawaii”, Prepared for: U.S. Army Engineering and Support C
York Naval Ordnance Plant, PA AOC's - B, C, D, & E	2004	TCRA			Schonstedt GA-72Cd Foerster MK26		Schonstedt GA-72Cd Foerster MK26	Plexus Scientitific Corporation	Plexus Scientific Corpration, 2004, "Draft Final Time Critical Removal Action (TCRA) Work Plan, Former York Naval Ordnance Plant, York, Pennsylvannia", Prepared for U.S. Army Corps of Engineers, Baltimore District, Maryland, June 2004

C.1 GPO Design Characteristics

The ordnance types and the physical area used for the GPO influence how well a system performs. Table C-2 shows the design characteristics of the various GPOs studied.

Table C-3 shows the detection instrument tested versus the target ordnance seeded at each GPO site.

In addition to detection, the background alarm rate was reviewed for each GPO site with available data. The background alarm rate is defined as the number of nonordnance targets picked divided by the area surveyed. Table C-4 shows the background alarm rate for this analysis.

Table C-2 GPO Site Characteristics

Site	State	Study	Year	Test Site Name/ID	Design	Width (m)	Length (m)	Area (acres)	Land Cover/Terrain	Total Number of MEC Types[2]	Total Number of Seed Items[2,3]	Number of MEC Types Seeded Below 11x Depth	Number of Seed Items Below 11x Depth	Percent of Seed Items Below 11x Depth
Adak NAF	AK	VDS[1]	2000 2001	VDS Test Loop	Track	1	1219	0.30	1) Steep Terrain - High Veg 2) Steep Terrain - Low Veg 3) Flat Terrain - High Veg 4) Flat Terrain - Low Veg 5) Flat to Steep Terrain - Rocky Ground Cover	8	182	2	18	10%
Badlands Bombing Range	SD	GPO	1999	Proveout Grid	Grid	30	40	0.30	Open	8	17	7	13	76%
Badlands Bombing Range - Impact Area	SD	GPO	2001	BBR IA Test Grid	Grid	200	200	9.88	Open	3	27	0	0	0%
Camp Beale	CA	GPO	2002	Spenceville Wildlife Area	Grid	91	91	2.07	Gently rolling terrain; open	9	61	7	10	16%
Camp Beale	CA	GPO	2002	Sutter Water District	Grid	91	91	2.07	Gently rolling terrain; open	9	62	7	10	16%
Camp Beale	CA	GPO	2002	Gold Country Ranch - Digital Test	Grid	91	91	2.07	Gently rolling terrain; open	10	63	8	9	14%
Camp Beale	CA	GPO	2002	Gold Country Ranch - Analog Test	Grid	91	91	2.07	Gently rolling terrain; open	10	36	8	11	31%
Camp Claiborne	LA	GPO	2001	Grid 1863	Grid	30	30	0.23	Wooded	8	24	2	3	13%
Camp Croft	SC	GPO	2004	GPO Test Grid	Grid	35	35	0.30	Half Open / Half Heavy Brush & Trees	5	26	1	2	8%
Camp Elliott	CA	GPO	2004	Marine Corps Air Station (MCAS) - Miramar GPO Plot	Grid	15	24	0.09	Open	12	40	0	0	0%
Camp Swift	TX	GPO	2000	GPO Test Grid	Grid	6	46	0.07	Open	4	20	2	2	10%
Fort Campbell	KY	GPO	2003	Range 28, GPO Grid #1	Grid	30	30	0.23	Open	13	22	0	0	0%
Fort Hood	TX	GPO	2004	Digital Multi-Purpose Range Complex GPO Grid	Grid	8	100	0.20	Open	7	24	1	1	4%
Fort McClellan	AL	GPO	2004	Test Grid #1 (Bains Gap Road)	Grid	20	41	0.20	Open	10	49	1	2	4%
Fort Ord	CA	ODDS	2002	Field Test Site #1	Grid	(4) 30 x 30 grids (less exclusion areas)		0.88	Fairly steep hillside; contained heavy brush removed by a manual and mechanical brush cutting techniques	10	67	2	2	3%
Fort Ord	CA	ODDS	2002	Field Test Site #2	Grid	(4) 30 x 30 grids		0.92	Fairly level; contained heavy brush removed by a manual and mechanical brush cutting techniques	10	118	2	3	3%
Fort Ord	CA	ODDS	2002	Field Test Site #4	Grid	(4) 30 x 30 grids (less exclusion areas)		0.65	Low area; grasses and a moderate to heavy density of trees	7	134	2	13	10%
Fort Ord	CA	ODDS	2002	Field Test Site #6	Grid	(1) 30 x 30 grid		0.23	Moderate slope; contained thick vegetation removed by manual brush cutting	7	17	0	0	0%
Fort Ritchie	MD	GPO 1 GPO 2	1999 2002	Section 3 - Grid 14	Grid	15	15	0.06	Open	4	16	0	0	0%
Lowry Bombing and Gunnery Range	CO	GPO	1998	USAESH Proveout Site	Grid	61	61	0.92	Open	15	40	7	16	40%
Savanna Army Depot	IL	GPO	2004	Open Burning Ground GPO Grid	Grid	15	60	0.22	Wooded	9	25	1	1	4%
Spencer Artillery Area	TN	GPO	2004	GPO Test Grid	Grid	30	30	0.23	Open Partialiy Wooded?	13	28	2	2	7%
Tobyhanna	PA	GPO	2004	Test Area #1	Grid	15	30	0.11	Open	3	9	1	1	11%
Tobyhanna	PA	GPO	2004	Test Area #2	Grid	15	15	0.06	Wooded	4	8	0	0	0%
Trabuco Bombing Range	CA	GPO	2004	Trabuco Creek Bikeway	Track	3	60	0.04	Open	4	12	1	1	8%
Waikoloa Maneuver Area	HI	GPO	2003	Waikola Known Grid #1	Grid	30	30	0.23	Open	8	31	0	0	0%
Waikoloa Maneuver Area	HI	GPO	2003	Waimea Known Grid #2	Grid	30	30	0.23	Open	9	32	0	0	0%
									Minimum	3	8	0	0	0%
									Maximum	15	182	8	18	76%
									Average	8	44	2	4	10%
									Total	74[4]	1190	64	120	10%

[1] - VDS - Validation of Detection Systems Test
[2] - Includes MEC, simulants, and MEC parts of known diameter
[3] - Fort Ord Field Test Sites 1, 2, and 4 - MEC items were not seeded, but consisted of actual range anomalies blindly re-surveyed by all instrument sytems and finally dug.
[4] - Total number of unique MEC types. Many sites use same MEC types.

Table C-3. Detection Instruments Tested Compared to Target Ordnance Seeded

Installation	GPO	Instrument Types	Tested	Selected, Recommended, or Validated	Seeded Targets
Adak NAF	2000 2001	EM	EM61	EM61	Projectile, 20 mm; Projectile, 37 mm; Grenade, Hand; Mortar, 60 mm; Projectile, 3-in/50; Mortar, 81 mm; Projectile, 105 mm; Projectile, 5-in/54 Caliber
Badlands Bombing Range	1999	EM Mag	EM61 G858	G858	Simulant, 20 mm Projectile; Projectile, 37 mm; Simulant, 37 mm Projectile; Simulant, 2-inch (Pipe); Simulant, 60 mm Projectile; Simulant, 2.75-inch Mortar; Simulant, 100-lb Practice Bomb; Simulant, 250-lb Bomb
Badlands Bombing Range - Impact Area	2001	EM Mag	MTADS-EM MTADS-Mag Airborne Mag Array	MTADS-EM MTADS-Mag Airborne Mag Array	Projectile, 105 mm; Projectile, 155 mm; Projectile, 8-inch
Camp Beale	2002	EM Mag	(For DGM) MTADS-EM MTADS-MPA(EM) MTADS-Mag EM61-MK2 G858 Fast Nano GDP-32 (For Safety and Reacquisition) Schonstedt 52Cx White Eagle Spectrum MD White Surfmaster PRO MD Foerster Ferex EM61-HH	(For DGM) MTADS-EM MTADS-MPA(EM) EM61-MK2 (For Safety and Reacquisition) Schonstedt 52Cx Foerster Ferex	Projectile, 37 mm; Grenade, Hand; Projectile, 57 mm; Mortar, 60 mm; Rocket, 2.36-inch; Projectile, 75 mm; Mortar, 81 mm; Projectile, 105 mm; Projectile, 155 mm; Bomb, 100-lb

Installation	GPO	Instrument Types	Tested	Selected, Recommended, or Validated	Seeded Targets
Camp Claiborne	2001	EM Mag	EM61 G858	EM61	Projectile, 20 mm; Projectile, 37 mm; Bomb, 3-lb; Projectile, 57 mm; Rocket, 2.36-inch; Rocket, 2.75-inch; Bomb, 25-lb; Projectile, 105 mm
Camp Croft	2004	EM Mag	EM61 G858	EM61	Rocket, Motor, 2.36-inch; Grenade, Hand; , Rifle; Simulant, Rifle Grenade; Simulant, 2.36-inch Rocket
Camp Elliot	2004	EM Mag	EM61 G858	EM61	Rocket, Motor, 2.36-inch; Projectile, 37 mm; Bomb, 3-lb; Grenade, Hand; Mortar, 60 mm; Rocket, 2.36-inch; Rocket, 2.75-inch; Projectile, 75 mm; Mortar, 81 mm; Projectile, 90 mm; Projectile, 105 mm; Projectile, 155 mm
Camp Swift	2001	EM Mag	EM61 G858	G858	Simulant, Rifle Grenade; Simulant, 2.36-inch Rocket; Simulant, 75 mm Projectile; Simulant, 105 mm Projectile
Fort Campbell	2003	EM for digital Mag for handheld	EM61-MK2 GX3 EM61 Array Schonstedt White's MD	EM61-MK2 GX3 EM61 Array Schonstedt	Projectile, 20 mm; Projectile, 30 mm; Rocket, Motor, 2.36-inch; Rocket, 35 mm; Projectile, 37 mm; Simulant, M39 Submunition; Submunition, M75; Bomblet, BLU-26 (1-lb) ; Rocket, 2.75-inch; Projectile, 75 mm; Mortar, 81 mm; Bomblet, BLU-61 (2.7-lb); Projectile, 105 mm
Fort Hood	2004	EM	EM61-MK2 GX4 EM61 Array	EM61-MK2 (difficult vegetated or terrain areas), GX4 EM61 Array (open areas)	Projectile, 20 mm; Cartridge Case, 30 mm; Projectile, 40 mm; Mortar, 60 mm; Rocket, 2.75-inch; Mortar, 81 mm; Projectile, 155 mm

Installation	GPO	Instrument Types	Tested	Selected, Recommended, or Validated	Seeded Targets
Fort McClellan	2004	EM	EM61-MK2	EM61-MK2	Rocket, Motor, 2.36-inch; Projectile, 37 mm; Signal, Illum; Grenade, Hand; Mortar, 60 mm; Rocket, 2.36-inch; Projectile, 75 mm; Mortar, 3-inch Stokes; Mortar, 81 mm; Projectile, 105 mm
Fort Ord	2001	EM Mag	Schonstedts (3 models) G858 EM61 EM61 HH MTADS-TDEM MTADS-CVM GEM-3	See ODDS Study report for flow chart – most were recommended for one or more specific conditions	Flare, Parachute; Flare, Surface; Fuze, Projectile; Grenade, Hand; Grenade, Rifle; Grenade, Rifle (Tail Boom); Mortar, 4.2-inch; Mortar, 60 mm; Mortar, 60 mm (Tail Boom); Mortar, 81 mm; Mortar, 81 mm (Tail Boom); Projectile, 20 mm; Projectile, 37 mm; Projectile, 40 mm; Projectile, 57 mm; Projectile, 75 mm; Rocket, 2.36-inch; Rocket, 3.5-inch; Rocket, Motor, 2.36-inch; Rocket, Motor, 3.5-inch; Signal, Illum; Simulator, Explosive Boobytrap
Fort Ritchie	1999	EM Mag	<u>(Digital)</u> EM61 EM61-HH Scintrex SmartMag <u>(Analog)</u> Schonstedt 52Cx Lobo MD White's MD	EM61 (open areas) Schonstedt 52Cx (wooded or difficult terrain areas)	Projectile, 37 mm; Rocket, 2.36-inch; Mortar, 3-inch Stokes; Projectile, 105 mm
Fort Ritchie	2002	EM	EM61-MK2 EM61	EM61-MK2	Projectile, 37 mm; Rocket, 2.36-inch; Mortar, 3-inch Stokes; Projectile, 105 mm

Installation	GPO	Instrument Types	Tested	Selected, Recommended, or Validated	Seeded Targets
Lowry Bombing and Gunnery Range (Buckley Field)	1998	EM Mag	MTADS-EM MTADS-Mag	MTADS-EM MTADS-Mag	Projectile, 20 mm; Simulant, 1-inch Iron Sphere; , 1-inch Steel Sphere; Simulant, 1.5-inch Steel Sphere; Bomb, 4-lb; Simulant, 2-inch (Pipe); Bomb, 3-lb; Rocket, 2.75-inch; Bomblet, 10-lb; Simulant, 3-inch Steel Sphere; Rocket, 3.25-inch Target; Bomb, 20-lb; Bomb, Igniter; Bomb, 100-lb ; Bomb, 250-lb; Bomb, 500-lb
Savanna Army Depot	2004	EM Mag	EM61-MK2 G858	EM61-MK2	Projectile, 20 mm; Projectile, 37 mm; Fuze, Rocket; Grenade, Hand; Projectile, 60 mm; Projectile, 75 mm; Mortar, 81 mm; Rocket, 3.5-inch; Projectile, 155 mm
Spencer Artillery Range	2004	EM Mag	EM61-MK2 G858 Ferex 4.032	EM61-MK2	Simulant, .50 cal; Projectile, 20 mm; Projectile, 37 mm; Grenade, Hand; Mortar, 60 mm; Rocket, 2.36-inch; Projectile, 75 mm; Mortar, 81 mm; Simulant, 3.25-inch Rocket; Projectile, 105 mm; Projectile, 155 mm; Simulant, 8-inch Projectile (Pipe); Simulant, 240 mm Projectile
Tobyhanna Artillery Range	2004	EM Mag	EM61-MK2 G858 Schonstedt[1]	EM61-MK2 (open areas) G858 (wooded areas) Schonstedt[1]	Projectile, 37 mm; Simulant, 37 mm Projectile; Projectile, 75 mm; Projectile, 155 mm
Trabuco Bombing Range	2004	EM	EM61-MK2	EM61-MK2	Simulant, 3.5-lb Practice Bomb; Bomb, 3-lb; Simulant, 3-lb MK23 Practice Bomb (Iron); Simulant, 3-lb MK5 Practice Bomb (Zinc Alloy)

Installation	GPO	Instrument Types	Tested	Selected, Recommended, or Validated	Seeded Targets
Waikoloa Maneuver Area	2003	EM	EM61-MK2 G-tek TM5-EMU	G-tek TM5-EMU	Projectile, 37 mm; Grenade, Hand; Grenade, Rifle; Mortar, 60 mm; Rocket, 2.36-inch; Projectile, 75 mm; Mortar, 81 mm; Projectile, 105 mm; Mortar, 4.2-inch; Projectile, 155 mm

1. Tobyhanna—The Schonstedt was not formally tested, but was recommended for mag and flag based on the success they had in reacquiring targets during the GPO.

Table C-4 GPO Results – Background Alarm Rate Summary

Site	Test_Site	Year	Operator	Instrument	Mode	Size of Test Area (acres)	Seed Count	Picked Target Count	Hit Count	Non-Seed Target Count	Detection Rate (All Items)	BAR (non-seed targets/acre)	rBAR
Adak NAF	VDS_LOOP	2000	GEO1_UXO4	EM-61	Digital	0.30	157	175	151	24	96%	80	1.0
Adak NAF	VDS_LOOP	2001	GEO2NAEVA-UXO4	EM-61	Digital	0.30	179	203	176	27	98%	90	1.1
Adak NAF	VDS_LOOP	2000	GEO4-UXO3	EM-61	Digital	0.30	157	182	154	28	98%	93	1.2
Adak NAF	VDS_LOOP	2000	GEO2_UXO2	EM-61	Digital	0.30	157	207	154	53	98%	176	2.2
Adak NAF	VDS_LOOP	2001	GEO1FW-UXO1	EM-61	Digital	0.30	179	266	169	97	94%	322	4.0
Badlands Bombing Range - Impact Area	BBR-IA Seed Area	2001	Naval Research Lab	MTADS_CVMag	Digital	9.88	27	116	26	90	96%	9	1.0
Camp Beale	GCR-DG	2002	ZONGE	EM-61 MK2	Digital	2.07	69	119	39	80	57%	39	1.0
Camp Beale	GCR-DG	2002	ZONGE	Zonge GDP-32	Digital	2.07	69	187	34	153	49%	74	1.9
Camp Beale	GCR-DG	2002	ZONGE	G-858	Digital	2.07	69	189	35	154	51%	75	1.9
Camp Beale	GCR-DG	2002	BLACKHAWK GEOSERVICES	MTADS_CVMag	Digital	2.07	69	197	34	163	49%	79	2.0
Camp Beale	GCR-DG	2002	BLACKHAWK GEOSERVICES	MTADS_EM	Digital	2.07	69	361	58	303	84%	147	3.8
Camp Beale	GCR-DG	2002	BLACKHAWK GEOSERVICES	MTADS_MPA	Digital	2.07	69	468	62	406	90%	197	5.1
Camp Beale	SWA	2002	ZONGE	G-858	Digital	2.07	67	70	36	34	54%	16	1.0
Camp Beale	SWA	2002	ZONGE	EM-61 MK2	Digital	2.07	67	88	46	42	69%	20	1.2
Camp Beale	SWA	2002	ZONGE	Zonge GDP-32	Digital	2.07	67	71	29	42	43%	20	1.2
Camp Beale	SWA	2002	BLACKHAWK GEOSERVICES	MTADS_EM	Digital	2.07	67	163	58	105	87%	51	3.1
Camp Beale	SWA	2002	BLACKHAWK GEOSERVICES	MTADS_CVMag	Digital	2.07	67	186	53	133	79%	64	3.9
Camp Beale	SWA	2002	BLACKHAWK GEOSERVICES	MTADS_MPA	Digital	2.07	67	195	56	139	84%	67	4.1
Camp Beale	SWD	2002	ZONGE	G-858	Digital	2.07	68	66	32	34	47%	16	1.0
Camp Beale	SWD	2002	ZONGE	EM-61 MK2	Digital	2.07	68	79	39	40	57%	19	1.2
Camp Beale	SWD	2002	ZONGE	Zonge GDP-32	Digital	2.07	68	60	10	50	15%	24	1.5
Camp Beale	SWD	2002	BLACKHAWK GEOSERVICES	MTADS_CVMag	Digital	2.07	68	229	56	173	82%	84	5.1
Camp Beale	SWD	2002	BLACKHAWK GEOSERVICES	MTADS_EM	Digital	2.07	68	272	58	214	85%	104	6.3

Site	Test_Site	Year	Operator	Instrument	Mode	Size of Test Area (acres)	Seed Count	Picked Target Count	Hit Count	Non-Seed Target Count	Detection Rate (All Items)	BAR (non-seed targets/acre)	rBAR
Camp Beale	SWD	2002	BLACKHAWK GEOSERVICES	MTADS_MPA	Digital	2.07	68	267	51	216	75%	105	6.4
Camp Claiborne	GRID1863	2001	EODT	G-858	Digital	0.23	25	76	21	55	84%	240	1.0
Camp Claiborne	GRID1863	2001	EODT	EM-61_1x0.5	Digital	0.23	25	91	25	66	100%	287	1.2
Camp Croft	CCR1	2004	NAEVA	G-858	Digital	0.30	26	48	4	44	15%	145	1.0
Camp Croft	CCR1	2004	NAEVA	EM-61 MK2	Digital	0.30	26	91	22	69	85%	228	1.6
Camp Swift	CS_GRID6X72	2000	PARSONS	EM-61_1x0.5	Digital	0.07	20	25	16	9	80%	131	1.0
Camp Swift	CS_GRID6X72	2000	PARSONS	G-858	Digital	0.07	20	29	20	9	100%	131	1.0
Fort Campbell	R28-GR1	2003	EODT	EM-61 MK2 GX3/GX4	Digital	0.23	22	37	20	17	91%	74	1.0
Fort Campbell	R28-GR1	2003	EODT	EM-61 MK2	Digital	0.23	22	40	20	20	91%	87	1.2
Fort Campbell	R28-GR1	2003	EODT	Whites (Model?)	Analog	0.23	22	80	13	67	59%	292	3.9
Fort Campbell	R28-GR1	2003	EODT	Schonstedt GA-52Cx	Analog	0.23	22	296	20	276	91%	1202	16.2
Fort Hood	DMPRG-G1	2004	EODT	EM-61 MK2 GX3/GX4	Digital	0.20	24	20	16	4	67%	20	1.0
Fort Hood	DMPRG-G1	2004	EODT	EM-61 MK2	Digital	0.20	24	44	20	24	83%	121	6.0
Fort Ord	ODDS-FTS-1	2000	Parsons	EM-61	Digital	0.88	69	255	52	203	75%	230	1.0
Fort Ord	ODDS-FTS-1	2000	Parsons	EM-61 HH	Digital	0.88	69	309	53	256	77%	290	1.3
Fort Ord	ODDS-FTS-1	2000	Parsons	G-858	Digital	0.88	69	361	44	317	64%	359	1.6
Fort Ord	ODDS-FTS-1	2000	Parsons	GEM-3	Digital	0.88	69	741	64	677	93%	766	3.3
Fort Ord	ODDS-FTS-1	2000	Parsons	Schonstedt GA-52C	Analog	0.88	69	1464	65	1399	94%	1583	6.9
Fort Ord	ODDS-FTS-1	2000	Parsons	Schonstedt GA-72Cv	Analog	0.88	69	1946	65	1881	94%	2129	9.3
Fort Ord	ODDS-FTS-1	2000	Parsons	Schonstedt GA-52Cx	Analog	0.88	69	5857	69	5788	100%	6550	28.5
Fort Ord	ODDS-FTS-2	2000	Parsons	G-858	Digital	0.92	155	531	113	418	73%	455	1.0
Fort Ord	ODDS-FTS-2	2000	Blackhawk GeoServices	MTADS_CVMag	Digital	0.92	155	609	80	529	52%	576	1.3
Fort Ord	ODDS-FTS-2	2000	Parsons	EM-61	Digital	0.92	155	725	142	583	92%	635	1.4
Fort Ord	ODDS-FTS-2	2000	Parsons	EM-61 HH	Digital	0.92	155	739	129	610	83%	664	1.5
Fort Ord	ODDS-FTS-2	2000	Blackhawk GeoServices	MTADS_EM	Digital	0.92	155	769	126	643	81%	700	1.5
Fort Ord	ODDS-FTS-2	2000	Parsons	GEM-3	Digital	0.92	155	871	139	732	90%	797	1.8
Fort Ord	ODDS-FTS-2	2000	Parsons	Schonstedt GA-52C	Analog	0.92	155	2009	148	1861	95%	2027	4.5
Fort Ord	ODDS-FTS-2	2000	Parsons	Schonstedt GA-72Cv	Analog	0.92	155	2927	149	2778	96%	3025	6.6
Fort Ord	ODDS-FTS-2	2000	Parsons	Schonstedt GA-52Cx	Analog	0.92	155	7010	154	6856	99%	7466	16.4

Site	Test_Site	Year	Operator	Instrument	Mode	Size of Test Area (acres)	Seed Count	Picked Target Count	Hit Count	Non-Seed Target Count	Detection Rate (All Items)	BAR (non-seed targets/acre)	rBAR
Fort Ord	ODDS-FTS-4	2000	Parsons	G-858	Digital	0.65	136	255	69	186	51%	287	1.0
Fort Ord	ODDS-FTS-4	2000	Parsons	EM-61	Digital	0.65	136	284	74	210	54%	324	1.1
Fort Ord	ODDS-FTS-4	2000	Parsons	EM-61 HH	Digital	0.65	136	353	72	281	53%	433	1.5
Fort Ord	ODDS-FTS-4	2000	Parsons	GEM-3	Digital	0.65	136	457	96	361	71%	557	1.9
Fort Ord	ODDS-FTS-4	2000	Parsons	Schonstedt GA-52C	Analog	0.65	136	1251	133	1118	98%	1724	6.0
Fort Ord	ODDS-FTS-4	2000	Parsons	Schonstedt GA-72Cv	Analog	0.65	136	1859	135	1724	99%	2658	9.3
Fort Ord	ODDS-FTS-4	2000	Parsons	Schonstedt GA-52Cx	Analog	0.65	136	3372	136	3236	100%	4990	17.4
Fort Ord	ODDS-FTS-6	2000	Parsons	EM-61	Digital	0.23	26	76	14	62	54%	270	1.0
Fort Ord	ODDS-FTS-6	2000	Blackhawk GeoServices	MTADS_CVMag	Digital	0.23	26	111	7	104	27%	453	1.7
Fort Ord	ODDS-FTS-6	2000	Parsons	G-858	Digital	0.23	26	122	9	113	35%	492	1.8
Fort Ord	ODDS-FTS-6	2000	Parsons	EM-61 HH	Digital	0.23	26	146	19	127	73%	553	2.0
Fort Ord	ODDS-FTS-6	2000	Blackhawk GeoServices	MTADS_EM	Digital	0.23	26	204	17	187	65%	815	3.0
Fort Ord	ODDS-FTS-6	2000	Parsons	Schonstedt GA-52C	Analog	0.23	26	299	20	279	77%	1215	4.5
Fort Ord	ODDS-FTS-6	2000	Parsons	GEM-3	Digital	0.23	26	523	21	502	81%	2187	8.1
Fort Ord	ODDS-FTS-6	2000	Parsons	Schonstedt GA-72Cv	Analog	0.23	26	589	24	565	92%	2461	9.1
Fort Ord	ODDS-FTS-6	2000	Parsons	Schonstedt GA-52Cx	Analog	0.23	26	1268	26	1242	100%	5410	20.0
Fort Ritchie	SEC3-GRID14	1999	NAEVA	EM-61 HH	Digital	0.06	17	25	14	11	82%	192	1.0
Fort Ritchie	SEC3-GRID14	1999	NAEVA	Smartmag	Digital	0.06	17	46	16	30	94%	523	2.7
Savanna Army Depot	OBG-GR1	2004	ATI	EM-61 MK2 (L&F)	Digital	0.22	34	48	34	14	100%	63	1.0
Savanna Army Depot	OBG-GR1	2004	ATI	EM-61 MK2 (USRADS)	Digital	0.22	34	51	33	18	97%	81	1.3
Savanna Army Depot	OBG-GR1	2004	ATI	G-858 (L&F)	Digital	0.22	34	41	19	22	56%	99	1.6
Savanna Army Depot	OBG-GR1	2004	ATI	G-858 (USRADS)	Digital	0.22	34	47	23	24	68%	108	1.7
Trabuco Bombing Range	TCB	2004	NAEVA	EM-61 MK2	Digital	0.04	17	38	17	21	100%	472	1.0
Waikoloa	WK-K1	2003	ATI	TM-5 EMU	Digital	0.23	31	48	31	17	100%	74	1.0
Waikoloa	WK-K1	2003	ATI	EM-61 MK2	Digital	0.23	31	71	30	41	97%	179	2.4
Waikoloa	WK-K1	2003	USA	EM-61 MK2	Digital	0.23	31	135	28	107	90%	466	6.3
Waikoloa	WM-K2	2003	ATI	TM-5 EMU	Digital	0.23	34	40	33	7	97%	30	1.0
Waikoloa	WM-K2	2003	ATI	EM-61 MK2	Digital	0.23	34	45	23	22	68%	96	3.1
Waikoloa	WM-K2	2003	USA	EM-61 MK2	Digital	0.23	34	86	27	59	79%	257	8.4