ESTCP
Cost and Performance Report

(MM-0633)

Demonstration of an Enhanced Vertical Magnetic Gradient System for UXO

December 2008

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 DEC 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED

4. TITLE AND SUBTITLE **Demonstration of an Enhanced Vertical Magnetic Gradient System for UXO**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP) U.S. Department of Defense**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited.

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**51**	

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

COST & PERFORMANCE REPORT
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ACRONYMS AND ABBREVIATIONS

Ac	acre
AGL	above ground level
AS	analytic signal
ASCII	American Standard Code for Information Interchange
BDZ	Badger Drop Zone
BRAC	Base Realignment and Closure Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CTT	closed, transferred, and transferring
DGPS	Differential Global Positioning System
DoD	Department of Defense
EMI	electromagnetic induction
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FBO	fixed-base operator
FKPBR	Former Kirtland Precision Bombing Range
FOM	Figure of Merit
FP	false positive
FUDS	formerly used defense sites
GPO	geophysical prove-out
GPS	Global Positioning System
HM-3	A three-sensor, first generation total field helicopter system
IMU	Inertial Measurement Unit
IDA	Institute for Defense Analyses
IR	Improvement Ratio
KPBR	Kirtland Precision Bombing Range
MCB	Marine Corps Base
m/s	meters per second
MTADS	multisensor towed-array detection system
NAD 83	North American Datum 1983
nT/m	nano Tesla per meter

ACRONYMS AND ABBREVIATIONS (continued)

OE	Ordnance and Explosives
ORAGS	Oak Ridge Airborne Geophysical System
ORNL	Oak Ridge National Laboratory
P_d	probability of detection
P_{fp}	probability of false positive
QA	quality assurance
QC	quality control
ROC	receiver operating characteristic
rpm	revolutions per minute
s.d.	standard deviation
SEMS	SERDP/ESTCP Management System
SHR	separation/height ratio
SNR	signal-to-noise ratio
SORT	Simulated Oil Refinery Target
STC	Supplemental Type Certificate
TF	total field
USAESCH	U.S. Army Engineering and Support Center, Huntsville
UTM	Universal Transverse Mercator
UXO	unexploded ordnance
VG	vertical gradient
VSEMS	Vehicular Simultaneous Electromagnetic Induction and Magnetometer System
WAA	wide area assessment

ACKNOWLEDGEMENTS

We wish to express our sincere appreciation to Dr. Jeffrey Marqusee and Dr. Anne Andrews of the Environmental Security Technology Certification Program (ESTCP) Office for providing both support and funding for this project.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

It is estimated that unexploded ordnance (UXO) may contaminate 15 million acres or more within the United States alone. A need for improved technologies for mapping and detecting UXO has led to development of a sequence of airborne reconnaissance systems using electromagnetic (Beard et al., 2004; Doll et al., 2005; Holladay et al., 2006) and magnetic (Gamey et al., 2004) sensors. The benefits of vertical gradient (VG) configurations in magnetometer systems are common knowledge, and these configurations are routinely used in ground-based UXO investigations. Overall, airborne systems provide a tool for wide area assessment (WAA) to support evaluation and reconnaissance over large Department of Defense (DoD) sites where only a portion of the site is contaminated with ordnance.

In 2002, Battelle staff (then at Oak Ridge National Laboratory [ORNL]) evaluated a prototype airborne vertical magnetic gradient system for mapping and detecting UXO (ORNL, 2005). At least two categories of magnetic noise influence the effectiveness of airborne systems for UXO mapping and detection—rotor noise and maneuver noise. Both have been shown to be effectively reduced by pairing magnetometers in a vertical magnetic gradient configuration (Gamey et al., 2004). Based on the success of the 2002 tests, Battelle committed corporate funds to design and construct two new systems, both employing the VG concept. Both systems were intended as an improvement over earlier systems, which showed only moderate performance in the detection of mid-size ordnance, 81mm and smaller.

Airborne total field systems demonstrated detection rates of less than 50% for these ordnance types in earlier performance assessments (Tuley and Dieguez, 2005).

The vertical magnetic gradient systems of VG-16 and VG-22, differ in the number of magnetometers as well as the separation between magnetometer pods (where a pod houses two magnetometers) and in their swath width. The VG-16 system employs 16 cesium-vapor airborne-quality magnetometers, and has 1.7-m horizontal separation between magnetometer pods rendering a 12-m swath width. In contrast, VG-22 employs 22 cesium-vapor airborne-quality magnetometers in a similar vertical magnetic gradient configuration with 1.0-m horizontal separation between seven magnetometer pods in the foreboom structure rendering a 6-m swath width.

Both systems were developed with WAA in mind, with the expectation that VG-16 would provide an improved tool for airborne WAA surveys contaminated with large munitions. The VG-22 system was intended for WAA use at sites where smaller ordnance types could be detected more reliably. In practice, the suitability of a system for WAA or for detection of individual items has been determined on the basis of blind-seeded tests and post-survey validation of anomalies. Lower probability of detection (P_d) may be acceptable for systems used for WAA applications, but the detection systems must still demonstrate the ability to detect some portion of the ordnance types that are of interest at a site. No universal detection thresholds have been established for either type of application, but site-specific detection requirements have been implemented at some sites.

The primary focus of this project was a survey at the Kirtland Precision Bombing Range (KPBR) in New Mexico. The site was established by the Environmental Security Technology Certification Program (ESTCP) for development and evaluation of WAA technologies. VG-16 and VG-22 were deployed at two areas of the KPBR. A 500-acre site located between the runways at Double Eagle Airport (within the KPBR) was selected as a blind test grid. Approximately 100 seed items were emplaced by ESTCP contractors. Detection of those items was assessed by Institute for Defense Analyses (IDA) staff based on dig lists provided by Battelle for both systems. Data were also acquired by both systems in an area north of the Double Eagle airport (referred to as the "North Area"). For VG-16, surveys within the North Area were conducted within two 500-acre plots, and for VG-22, data were acquired within two 250-acre plots located within the 500-acre VG-16 plots.

1.2 OBJECTIVE OF THE DEMONSTRATION

There were two distinct objectives for this demonstration: 1) assessing the effectiveness of two vertical magnetic gradient systems for mapping and detecting small ordnance items and assessing the effectiveness of the VG configurations for WAA applications. The demonstration site for this project was used for previous WAA demonstrations and therefore provided a basis for achieving this second objective.

1.3 REGULATORY DRIVERS

No specific regulatory drivers influenced this technology demonstration. UXO-related activity is generally conducted under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) authority. Regardless of a lack of specific regulatory drivers, many DoD sites and installations are aggressively pursuing innovative technologies to address a variety of issues associated with ordnance and ordnance-related artifacts (e.g., burial sites) that resulted from weapons testing and/or training activities. These issues include footprint reduction and site characterization, areas of particular focus for this technology demonstration. In many cases, the prevailing concerns at these sites can lead to airborne surveying and other remediation activities, despite the absence of relevant regulatory drivers and mandates.

1.4 DEMONSTRATION RESULTS

The VG-22 system achieved an overall detection (P_d) of 86%, and VG-16 achieved an overall detection of 55% for all ordnance types emplaced in the blind-seed grid, emplaced and assessed by ESTCP with support from IDA. When broken down by ordnance type, these results exceed the anticipated performance of both systems for all ordnance types except 60 mm and represent a significant improvement over the performance of airborne systems in previous blind-seeded assessments. The 60 mm emplaced at FKPBR lacked tail fins and nose cones, resulting in lower mass than other ordnance types. Review of the "missed" anomalies indicated that nearly all anomalies were detected but were not selected because we chose a detection threshold that was too high. We would have achieved an overall P_d of 98% with VG-22 had we chosen a detection threshold of 2.0 nano Tesla per meter (nT/m) instead of the 2.5 nT/m that we used. If only the medium-to-large ordnance types are considered (81 mm and larger) the detection rates increase to 100% for VG-22 and 90% for VG-16, using the original 2.5 nT/m threshold.

The success of the VG-22 system in this WAA and the high quality of maps derived from VG-22 data have led us to consider whether the system might be suitable for applications that would normally be restricted to ground-based systems, where detection of individual items is required. The Former Kirtland Precision Bombing Range (FKPBR) demonstration included only a few small ordnance items (e.g. 40 mm-60 mm) as it was assumed that the performance of airborne systems would be poor for such items. A more thorough assessment of VG-22 performance with small ordnance items is recommended in order to determine its suitability for broader applications. Until such an assessment is conducted, the applicability of the VG-22 system for broader use will remain an open question.

Validation results from the North Area at FKPBR, where M-38 practice bombs are the predominant ordnance type, were largely inconclusive because there were few if any UXO-like objects recovered from 260 excavations. Pseudo-receiver operating characteristic (ROC) curves for the North Area have P_d represented by the fraction of point-like targets and probability of false positive (P_{fp}) represented by the fraction of non-point-like targets.

1.5 STAKEHOLDER/END-USER ISSUES

Issues related to this demonstration project center on the appropriate use of the technology. Clearly, the improved airborne system is unable to detect all UXO items of potential interest. This may not be critical for WAA surveys, where detection of a portion of the target ordnance items or detection of concentrations of small ordnance items is acceptable. Airborne geophysical systems continue to be constrained by the presence of tall vegetation and rough terrain that increases the distance between the system and the UXO items of interest, thereby limiting detection ability. This has been shown to be less problematic for VG systems than for total field systems. It remains apparent that application of the technology to small survey areas will not be cost-effective due to the large cost associated with mobilization/demobilization and considerable helicopter costs. Users should consider both the intended UXO targets and survey area (size, terrain, and vegetation) before considering the use of airborne systems for UXO detection, mapping, and/or WAA.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The VG-16 system was designed to maximize sensitivity in wide-area assessment surveys, where data are to be acquired at approximately 3-m altitude or higher. By comparison, the VG-22 system was designed to address the concerns raised in the IDA report with regard to airborne magnetometer systems, where it is critical to detect and assess ordnance 81 mm and smaller. The VG-16 and VG-22 systems differ in the number of magnetometers, the separation between magnetometer pods (where a pod houses two magnetometers), and their swath width. A rack-mount configuration is used to house the electronics for both systems. Sensor positioning is provided by post-processed Global Positioning System (GPS)/Inertial Measurement Unit (IMU) data with 100 Hz update rate and 2 cm/0.01° accuracy.

The VG-16 system (Figure 1) employs 16 cesium-vapor airborne-quality magnetometers and has 1.7-m horizontal separation between magnetometer pods rendering a 12-m swath width. In contrast, VG-22 (Figure 2) employs 22 cesium-vapor airborne-quality magnetometers in a similar VG configuration with 1.0-m horizontal separation between seven magnetometer pods in the foreboom structure, rendering a 6-m swath width. The swath width ultimately determines the number of survey passes, and thus the flight time required to survey a site of specified size. VG-22 also was designed to be flown with sensors closer to the earth's surface. At sites where the minimum flight altitude is 3 m or higher, where large ordnance is of primary concern, or where the purpose of the survey is to identify concentrations of ordnance (as opposed to detection of individual ordnance items, i.e. a lower P_d is acceptable), VG-16 would be a more technically appropriate and cost-effective system choice that would outperform total field systems. On the other hand, when detection of smaller individual ordnance is the primary survey objective or it is more critical to attain the highest possible P_d, the VG-22 system is a more appropriate choice.

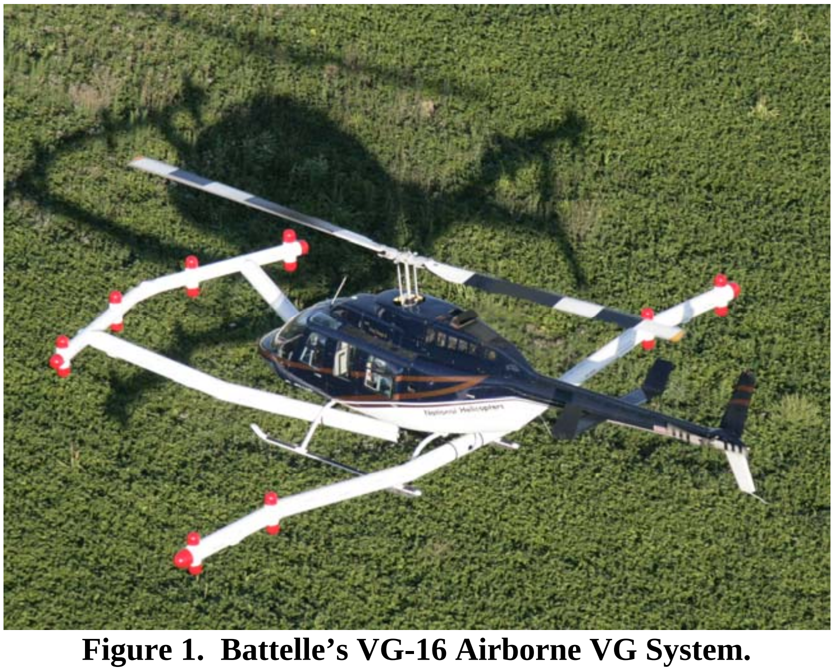

Figure 1. Battelle's VG-16 Airborne VG System.

Figure 2. VG-22 Airborne VG System.

2.2 PROCESS DESCRIPTION

An operational summary is presented here with further detail provided in Sections 3 and 4. Mobilization is accomplished by ground transportation of the airborne components, electronic subsystems, and personnel. The helicopter and aircrew are mobilized by air to the base of operations. The base of operations is usually a local or regional airport with suitable security and fuel. The geophysical base stations for GPS and magnetics are established at known civil survey monuments. A processing center is set up at or near the aircraft base of operations.

Installation is conducted by the aircraft mechanic, according to Federal Aviation Administration (FAA) requirements and the Supplemental Type Certificate (STC) permit, with support of the geophysical ground crew. This involves dismounting the tow hook arrangement and installing brackets at these and other hard points in the airframe. The booms, sensors, and recording systems are subsequently attached to the bracket mounts and mounted inside the aircraft.

Survey blocks are chosen and boundary coordinates determined. These are entered into the onboard navigation system. Consideration is given to ambient magnetic fields, topography, vegetation, and survey efficiency. After installation, instruments are tested for functionality before and during an initial check flight. Calibration flights are then conducted to determine digital time lags and compensation coefficients required to correct the readings for the magnetic presence of the helicopter.

After calibration, site surveying commences. The pilot and geophysical system operator are present in the aircraft during survey operations. The operator is responsible for updating and managing the navigation software as well as real-time quality control (QC) of the incoming geophysical data. Surveying continues on a line-by-line basis until the entire block is covered. Depending on the size of the survey area, multiple flights may be required.

At the end of each flight, data are downloaded to a personal computer for QC evaluation. This includes verification of data integrity and quality from all sensor sources. Data from the ground base station instruments for differential GPS and magnetic diurnal corrections are integrated with the airborne data. The dataset is analyzed for completeness of areal coverage (no large gaps or unsurveyed areas) and for consistency of survey altitude throughout the survey block. Lines or areas of unacceptable or missing data are noted and resurveyed as appropriate.

Upon completion of the survey, the data are processed to correct for the effects of digital time lag, selective availability in GPS, magnetic sensor dropouts, compensation for aerodynamic motion, magnetic diurnal, array balancing, regional magnetic field, helicopter rotor noise, and positioning of individual magnetometers. Magnetic anomalies are analyzed to derive dig lists and interpretive visual products (e.g., maps), depending on the application.

General and site-specific health and safety plans are generated for each survey project. These plans include provisions for general ground safety, extend them using DoD models for UXO site safety, further extend them to encompass airborne operations, and then add wholly new considerations for airborne operations in a UXO theatre. The appropriate management at Battelle, the helicopter operator, and the project sponsor approve these health and safety plans.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

In addition to the surveys at the Battelle Airborne UXO Test Grid in Ohio and the FKPBR in New Mexico (this report), the VG-16 system was deployed in Wisconsin and Florida during fiscal year 2007. At Fort McCoy, Wisconsin, it was used for a wide-area assessment survey of the 600-acre Badger Drop Zone (BDZ), while at the Rodman Training Range (Pinecastle Range Complex), Florida, it was used for a 2,800-acre survey at higher altitudes. The VG-22 system was deployed at the Marine Corps Base (MCB) Camp Lejeune, North Carolina, over a 910-acre survey for UXO in a salt marsh environment.

The VG technology was previously demonstrated for ESTCP as a prototype system with data acquired at the Aberdeen Test Center, Maryland; Pueblo of Laguna, New Mexico; and the Badlands Bombing Range, South Dakota. Results of these tests were submitted to ESTCP in 2005 (ORNL, 2005).

At Fort McCoy in western Wisconsin, the 570-acre BDZ was surveyed with the VG-16 system in October 2006 for WAA applications. The resulting analytic signal map was used to generate an anomaly density map. The information collected from this survey will be used to assess the level of UXO contamination and identify selected areas for future removal operations, thus ensuring long-term sustainability of the BDZ as a training facility and maneuver area.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Airborne surveys for UXO are capable of providing data for characterizing potential UXO contamination at a site at considerably lower cost per acre than ground-based systems. Furthermore, the data may be acquired in a shorter period of time. Airborne systems are particularly effective at sites having low-growth vegetation and minimal topographic relief. They can also be used where heavy brush or mud makes it difficult to conduct ground-based surveys. Sensitivity of airborne systems is less than that of ground surveys (e.g., towed array surveys using the Vehicular Simultaneous Electromagnetic Induction and Magnetometer System [VSEMS]), which can operate with sensors at less than 0.5 m above ground level (AGL).

In recent years, the utility of airborne surveys for WAA applications has become widely recognized. For large areas, the time and cost of ground-based surveys can become prohibitive, even if only a small portion of the site is to be surveyed. Airborne geophysical surveys have been shown to be a useful tool for many of these sites. Previous tests have shown that airborne magnetometer systems are limited in their detection of small- to mid-sized ordnance items, nominally 81mm and smaller (Tuley and Dieguez, 2005). This could cause airborne systems to be unsuitable at sites where such ordnance types are predominant or abundant. For instance, airborne systems are unable to detect 20-mm rounds, and should never be used for WAA at a site where these are a critical ordnance type. What level of detection must be proven for a system and ordnance type in order for the system to be appropriate for WAA applications at a site? The answer to this question must be rooted in rigorous statistical analysis and risk profiles developed in cooperation with regulators and stakeholders for each site.

Both airborne and ground magnetometer systems are susceptible to interference from magnetic rocks and magnetic soils. Rugged topography or tall vegetation limits the utility of helicopter systems, necessitating survey heights too high to resolve individual UXO items. The performance of the VG configurations demonstrated in this project is expected to be superior to that of total field systems and should allow effective operation where topography or vegetation requires a few meters of increase in the functional altitude of operation.

Airborne systems also have an advantage in areas where ground access is limited or difficult due to surface conditions (dense foliage, swamps, marshes) or inherent danger (exposure to UXO or other contaminants). Areas with a sensitive ecological environment may also benefit from the less intrusive airborne technologies.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

All quantitative objectives are based on comparison of the VG response relative to previous total field systems. Direct comparison is not always possible, but some parameters can be assessed more directly. In particular, the reduction of rotor and maneuver noise can be examined.

Table 1. Performance Objectives of Vertical Magnetic Gradient System.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Qualitative	Ease of Use	Pilot approval	Yes
	Terrain/vegetation restrictions	Acceptable for targets of interest	Yes
	Aerodynamic stability	Safety, certification, no restrictions	Yes
	Detection capabilities	Better delineation of clustered targets	Unresolved. Pairs of targets were generally too far apart to register as clusters. Results match detection of single targets.
Quantitative	Signal-noise (compared to total [magnetic] field [TF])	>4x signal-to-noise ratio (SNR) improvement in rotor noise over TF system	Yes
	Probability of detection	Seeded test items were assigned expected detection metrics, as summarized in Table 2. % of seed items detected used to measure P_d.	Mostly. IDA analysis determined that expected levels were achieved, except for 40 mm (VG-16) and 60 mm (both systems)
	False alarm rate	<10% false positive (FP) /(UXO + FP count) (VG-16)* <10% FP /(UXO + FP count) (VG-22)* Based on dig results in the two validation areas, as assessed by the Institute for Defense Analyses (IDA).	Unresolved. Only one UXO-like object was uncovered during the validation of the North Area.
	Location accuracy	<0.5 m mean, <0.4 m s.d. northing and easting (after inversion) for VG-16 <0.4 m mean and <0.3 s.d. northing and easting (after inversion) for VG-22	Yes
	Survey rate	100 hectare/day for VG-16; 50 hectare/day for VG-22	Yes
	Percent site coverage	100% of the accessible area	Yes

* We define FP (false positives) as non-ferrous sources.

3.2 SELECTION OF TEST AND SURVEY SITE

The ESTCP Program Office requested that a demonstration be conducted at the FKPBR (Figure 3) in New Mexico, where previous WAA surveys were conducted.

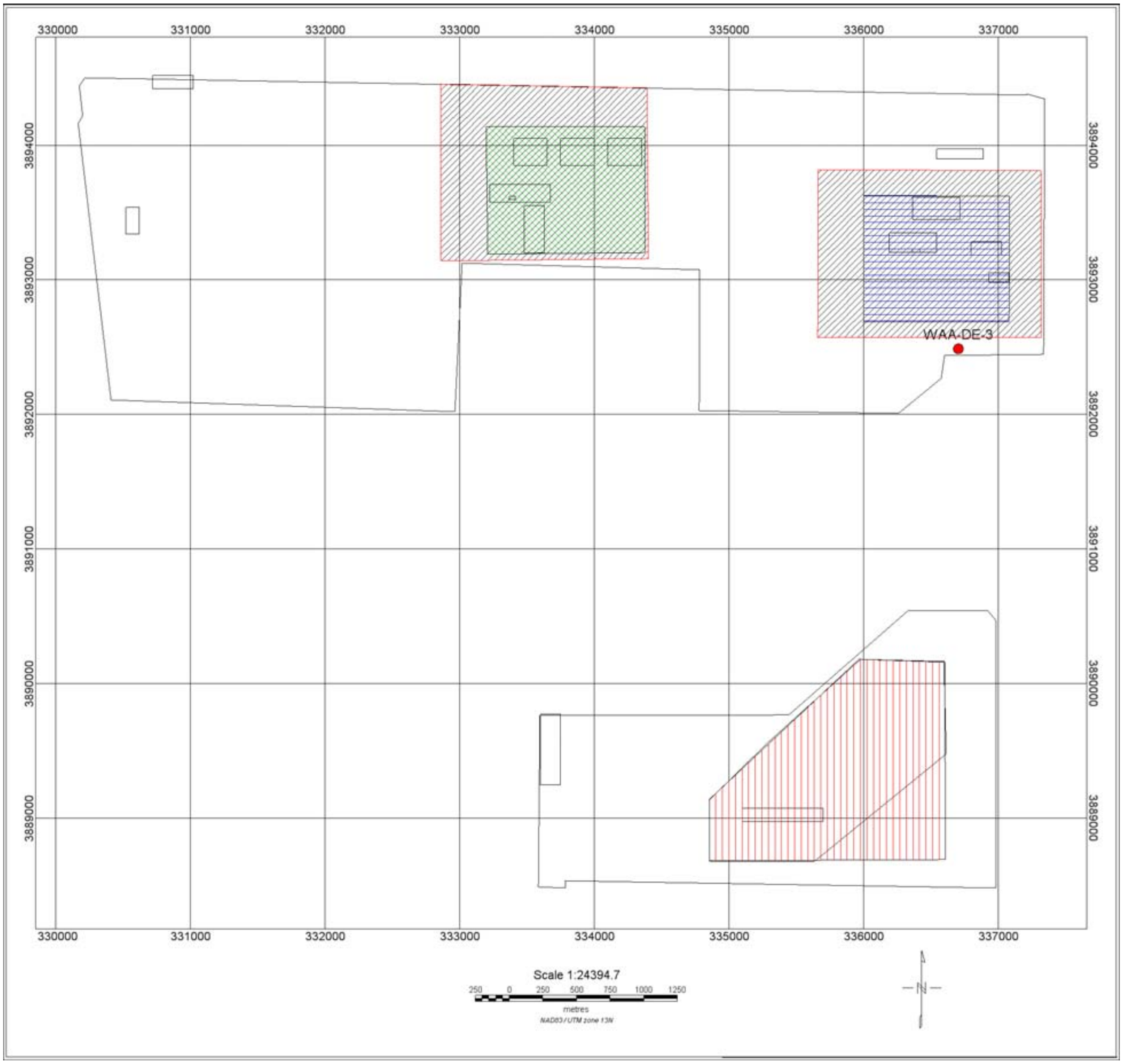

Figure 3. Map of the FKPBR WAA Sites, Showing the North and South Areas Adjacent to Double Eagle Airport from Previous ESTCP WAA Projects.
(Area 1 [the grey area] consists of 1,000 acres; Area 2 [the green and blue areas] totals 500 acres, and Area 3 (shaded red) consists of 500 acres. The grey and red blocks were flown with VG-16. The eastern part of Area 1 was flown twice with VG-16, once at 1.5 m nominal altitude and once at 5 m nominal altitude. Only the green, blue, and red blocks were flown with VG-22. Locations of previous ground surveys [provided by M. May, IDA] are included as smaller rectangles. Perimeter polygon for the north and south areas provided by H. Nelson, Naval Research Laboratory.)

3.3 TEST SITE HISTORY AND CHARACTERISTICS

The FKPBR is a 38,000-acre area that was used in World War II as a training area for Kirtland Air Force Base. The ESTCP WAA pilot study area consists of 5,000 acres adjacent to Double Eagle Airport, near Albuquerque, New Mexico. Within this study area are at least three bombing targets and a Simulated Oil Refinery Target (SORT). Known or suspected ordnance types at the site are M-38 practice bombs and 250-lb high explosive bombs. The runways of Double Eagle Airport encompass the South Area, and several power lines, fences, and outbuildings are located adjacent to or within the survey areas. Most prominent are a building along the SE side of the South Area and a powerline that crosses the southern portion of the eastern North Area.

3.4 PHYSICAL SETUP AND OPERATION

Mobilization involved packing and transporting all system components by trailer to the appropriate site and installing them on a Bell 206L Long Ranger helicopter. Calibration and compensation flights were conducted and results evaluated. The cesium magnetometers, GPS systems (positioning and attitude), fluxgate magnetometers, data recording console, laser altimeter, and acoustic altimeters were tested to ensure proper operation and performance. The VG systems are designed for daylight operations only. Lines are flown in a generally east-west or north-south pattern depending on local logistics and weather conditions with a nominal 12-m flight line spacing for VG-16 and 6 m for VG-22 for the high density survey coverage. Binary data from the magnetometers are recorded on the console at a rate of 1,200 Hz (samples per second). A typical survey speed for the system was 20 meters per second (m/s).

The period of operations at Kirtland extended from April 16 through May 10, 2007. The crew travelled to New Mexico between April 16 and April 18. Weather delayed the helicopter arrival until April 20. Installation was completed on April 21, but high winds caused data acquisition to be delayed until April 22. Data acquisition with the VG-22 system extended through April 29. This constitutes an overall average daily acquisition rate of 125 acres/day inclusive of weather days, site availability limitations, and other constraints. The VG-22 system was replaced with the VG-16 system on April 29. Acquisition with the VG-16 system was conducted between April 30 and May 8, with de-installation and demobilization beginning on May 9. The daily acquisition rate for the VG-22 system was about half that of the VG-16 system due to its narrower swath width.

3.5 ANALYTICAL PROCEDURES

3.5.1 Operating Parameters for the Technology

The Battelle VG systems are designed for daylight operations only. Lines are flown in a generally east-west or north-south pattern depending on local logistics and weather conditions with a nominal 12-m flight line spacing for the high density survey coverage. Binary data from the magnetometers were recorded on the console at a rate of 1,200 Hz (samples per second). A typical survey speed for the system was 20 m/s. Average survey height ranged from 1 to 3 m for both systems over all areas at FKPBR (apart from the 500-acre area flown at 5 m to assess altitude effects). In areas where background magnetic susceptibility and variation was small, vegetation height low, and topographic change gradual, the system can be expected to detect ordnance such as M38 practice bombs, 105-mm and 155-mm artillery shells, and smaller ordnance as well as fragments and non-ordnance items. These thresholds can be expected to increase as any of the aforementioned variables increase.

3.5.2 Experimental Design

The design parameters to be used for this technology demonstration (see Section 4, Performance Assessment) focused on prior-generation airborne results as the baseline performance condition. Progressive improvements can be seen in the development of the technology.

Analysis of early HM-3 (a three-sensor, first generation total field helicopter system) data by the IDA (Andrews et al., 2001) yielded the following results: 78% to 83% ordnance, 17% to 24% false positives. Positional accuracy of the data improved from approximately 2 m in Hammerhead tests to about 1 m with the Oak Ridge Airborne Geophysical System (ORAGS)-Arrowhead eight-sensor system. The subsequent results of an airborne system comparison conducted by ESTCP at Pueblo of Isleta, New Mexico (Tuley and Dieguez, 2005), provided additional metrics on the performance of the ORAGS-Arrowhead System and a multisensor towed-array detection system (MTADS) (Table 2).

3.5.2.1 <u>Data Processing Procedures</u>

The 1,200-Hz raw data were de-sampled in the signal processing stage to a 120-Hz recording rate. All other raw data were recorded at a 120-Hz sample rate. Data were converted to an American Standard Code for Information Interchange (ASCII) format and imported into Geosoft formatted databases for processing. With the exception of the differential GPS postprocessing, all data processing was conducted using the Geosoft software suite with specialized modules adapted for our hardware configuration and data format. The QC, positioning, and magnetic data processing procedures are described below.

3.5.2.2 <u>Quality Control</u>

All data were examined in the field to ensure sufficient data quality for final processing. The adequacy of the compensation data, heading corrections, time lags, orientation calibration, overall performance and noise levels, and data format compatibility were confirmed during data processing. During survey operations, flight lines were plotted to verify full coverage of the area. Missing lines or areas where data were not captured were reacquired. Data were also examined for high noise levels, data dropouts, significant diurnal activity, or other unacceptable conditions. Lines flown, but deemed to be unacceptable for quality reasons, were reflown.

3.5.2.3 <u>Positioning</u>

During flight, the pilot was guided by an onboard navigation system that used real-time satellite-based Differential Global Positioning system (DGPS) positions. This provided sufficient accuracy for data collection (approximately 1 m), but was inadequate for final data positioning. To increase the accuracy of the final data positioning, a base station GPS was established at known geodetic base survey markers at or near each survey location. Raw data in the aircraft and on the ground were collected. Aircraft orientation was measured by an integrated IMU with an update rate of 100 Hz and a 0.01° accuracy. Differential corrections were post-processed to provide increased accuracy in the final data positioning. Final latitude and longitude data were projected onto orthogonal grids using the North American Datum 1983 (NAD 83) Universal Transverse Mercator (UTM) Zone 13N. Vertical positioning was monitored by laser altimeter with an accuracy of 2 cm. No filtering was required of these data, although occasional dropouts were removed.

3.5.2.4 Magnetic Data Processing Procedure

The magnetic data were subjected to several stages of geophysical processing. These stages included correction for time lags, removal of sensor dropouts, compensation for dynamic helicopter effects, removal of diurnal variation, correction for sensor heading error, array balancing, and removal of helicopter rotor noise. Calculation of the magnetic analytic signal was derived from the corrected residual magnetic total field data.

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

VG maps of the blind-seeded south area at FKPBR are shown in Figures 4 and 5. The validation results for this area, calculated by IDA, are presented in Tables 2 and 3. The detection rates for all ordnance types and for both systems exceeded the expected performance, with the exception of 60 mm (both systems) and 40 mm (VG-16). Validation of anomalies was limited to the seeded items, so we were unable to assess false positive occurrences. Only the seeded items were considered targets of interest. It is quite possible that unknown ordnance items are contained within the grid. Due to the size of the blind-seeded area, data were acquired only at the lowest safe altitude. The mean sensor altitude for the VG-16 system was 2.12 m and for the VG-22 system 1.36 m.

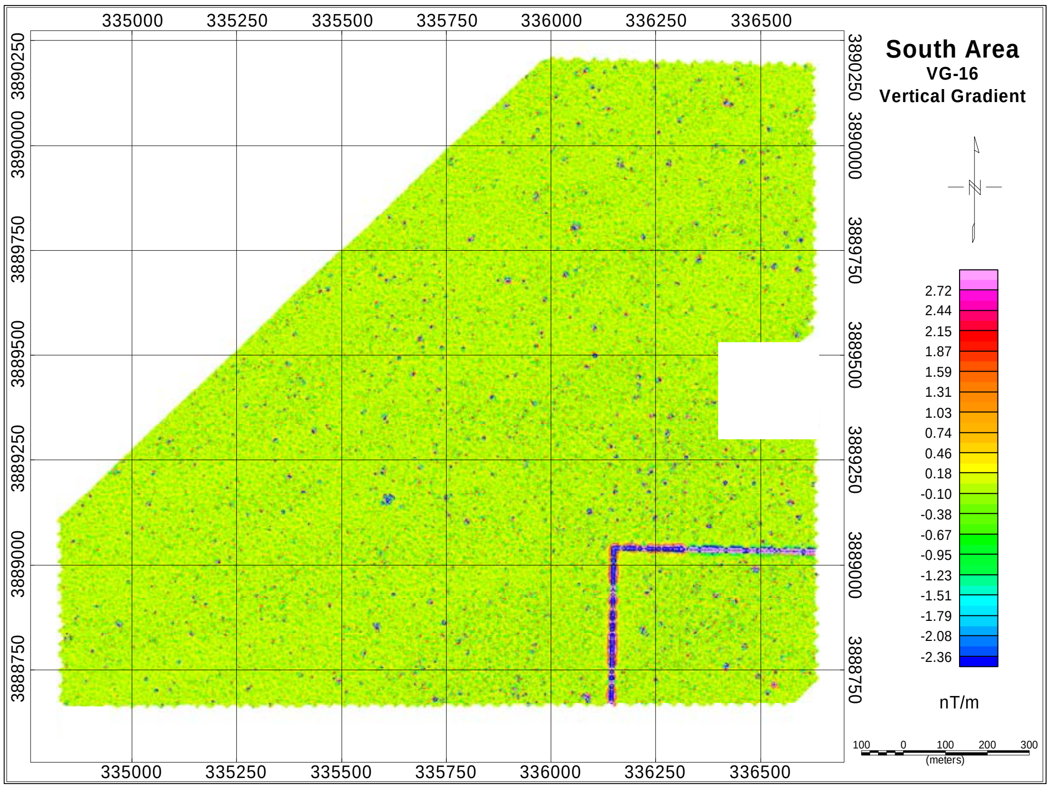

Figure 4. VG-16 VG Map of the South Area at FKPBR.

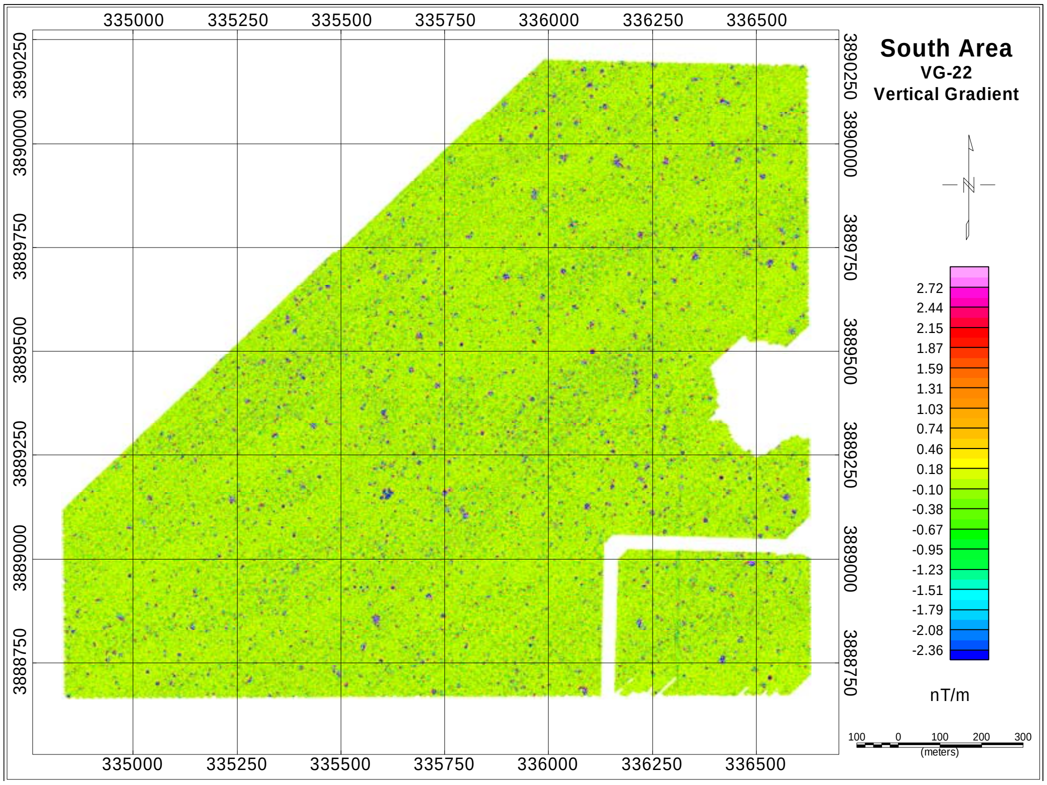

Figure 5. VG-22 VG Map of the South Area at FKPBR.

Table 2. Observed and Anticipated Detection Rates for VG-16 and VG-22 at FKPBR Seeded Grid Versus Detection Rates from Isleta (as reported by Tuley et al., 2005).

Ordnance Type	Isleta Results (Tuley and Dieguez, 2005)	Total Seeded, FKPBR	VG-16 Expected	VG-16 Observed (5,560 picks or 11 picks/acre)*	VG-22 Expected	VG-22 Observed (6,391 picks or 12 picks/acre)*
40 mm	NA	4	5%	0%	10%	100%
57 mm	NA	5	25%	40%	30%	80%
60 mm	25%	18	50%	11%	60%	56%
81 mm	47%	18	60%	72%	70%	100%
105 mm proj	73%	7	85%	86%	90%	100%
105 mm HEAT	NA	13	85%	100%	90%	100%
155 mm	NA	23	90%	100%	95%	100%

*Anomalies were picked automatically from the analytic signal peaks using a 2.5nT/m threshold against a background noise level of 1.0 nT/m (mode of the gridded data). The threshold choice was somewhat arbitrary due to the small number of reference items available for the calibration grid. Based on VG test results from the Battelle UXO test site, we anticipated that some small items would be missed at this threshold.

The location accuracy of the two systems is detailed in Table 3. Anomalies were inverted to fit a single magnetic dipole model. The final target locations were taken from the inversion results. Where the inversion failed to resolve a target, the original analytic signal peak location was used. Analysis of both systems used a maximum 1.5-m search radius, although none of the positive detections were found at this maximum range. The higher standard deviation in VG-16 target location errors was expected due to the wider sensor spacing (1.7 m in VG-16 versus 1.0 m in VG-22) and coarser grid interval. The reason for the 15-cm systematic shift in VG-16 East position is unknown, because both systems used identical base station and positioning equipment.

Table 3. Positioning Errors for Seeded Targets, Blind-Seed (South) Area, FKPBR.

Positioning Errors	VG-16	VG-22
Mean Offset	15cm	2cm
Mean East Offset	+15cm	-0.4cm
Mean North Offset	-2cm	-2cm
Mean Radial Offset	39cm	23cm
Std Dev East Offset	33cm	21cm
Std Dev North Offset	29cm	22cm
Std Dev Radial Offset	44cm	30cm

The positioning errors are expressed by the following parameters:

Mean East Offset: $\Delta X_{mean} = \sum(X_{obs} - X_{actual})/N$

Mean North Offset: $\Delta Y_{mean} = \sum(Y_{obs} - Y_{actual})/N$

Mean Offset: $\sqrt{((\Delta X_{mean})^2 + (\Delta Y_{mean})^2)}$

Mean Radial Offset: $\sum\sqrt{((X_{obs} - X_{actual})^2 + (Y_{obs} - Y_{actual})^2)}\ /N$

Standard Deviation East Offset: $\sqrt{(\sum(\Delta X_i - \Delta X_{mean})^2/N)}$

Standard Deviation North Offset: $\sqrt{(\sum(\Delta Y_i - \Delta Y_{mean})^2/N)}$

The first three means express systematic errors in the position of the data relative to the base station. They show that the systematic error in positioning is much larger for VG-16 than VG-22, and that most of this is associated with easting. The Mean Radial Offset represents the average total error in positioning for the test items and includes the systematic error in positioning relative to the GPS base station.

As indicated earlier, validation was conducted within the northwest area. Battelle provided prioritized dig lists for these two areas, based on the selection process described for the South Area. After IDA reviewed the dig lists, Battelle was provided results from 25% of the study area in order to develop a revised prioritization of the dig list. This was intended as a means for assessing the effectiveness of using feedback from early dig results to guide subsequent anomaly prioritization.

The two validation sites were chosen because of the availability of existing ground-based SERDP/ESTCP Management System (SEMS) data and because they were positioned on the edge of a target, with Area 1 being closer to the center of the target than Area 2. Anomalies within these areas were generally isolated with few overlapping anomalies (Figures 6 and 7). The dig results included considerable frag (2 ounces to 2 pounds), but consisted primarily of clutter and geologic sources. Only one UXO-like object was uncovered during validation, so a conventional assessment could not be completed from the dig reports (Michael May, IDA, personal communication, December 13, 2007). As an alternative, it was determined to conduct an analysis of the validation data by separating "point-like targets" (including clutter and "hot rocks", but not "hot dirt", geology, or "no-finds" and non-point targets. These were used to formulate "pseudo-ROC curves." VG detected 78% of point-like targets that were detected with the ground-based system and 81% of non-point targets. VG-16 detected 55% of point-like targets and 81% of non-point targets. There is no consistent preference for analytic signal versus inversion ranking for anomaly prioritization, and no significant benefit to feedback can be recognized.

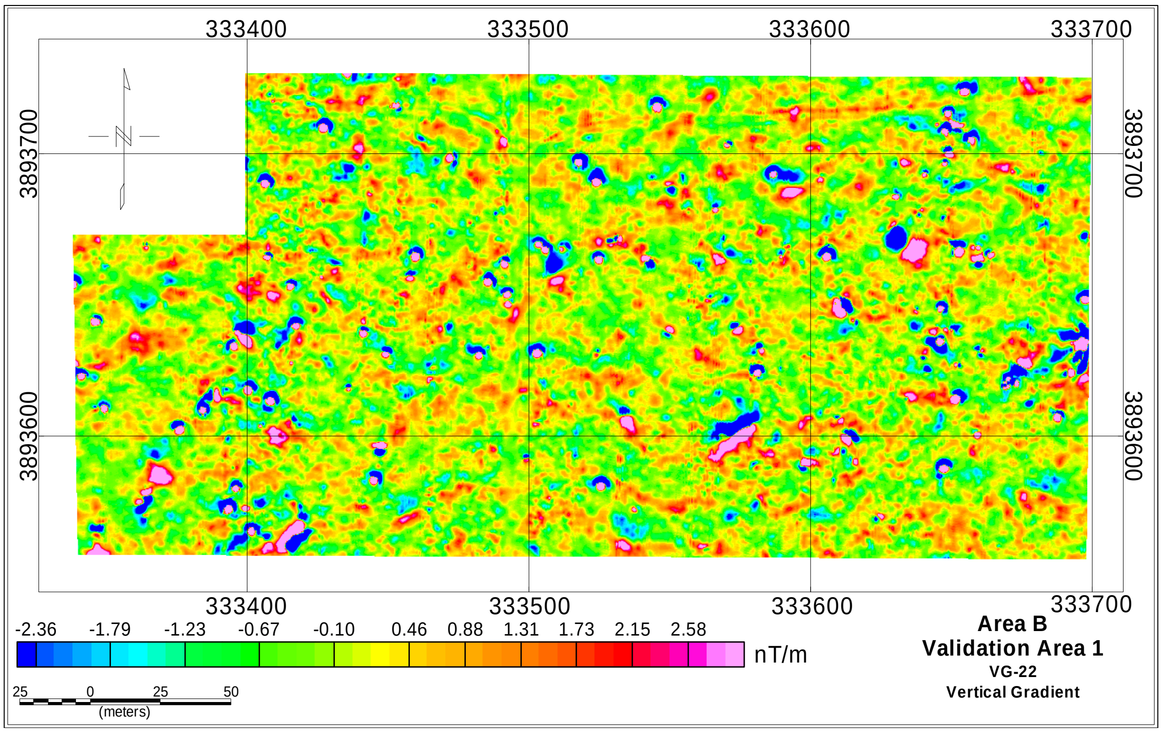

Figure 6. VG-22 VG Map for Validation Area 1, North Area B, at FKPBR.

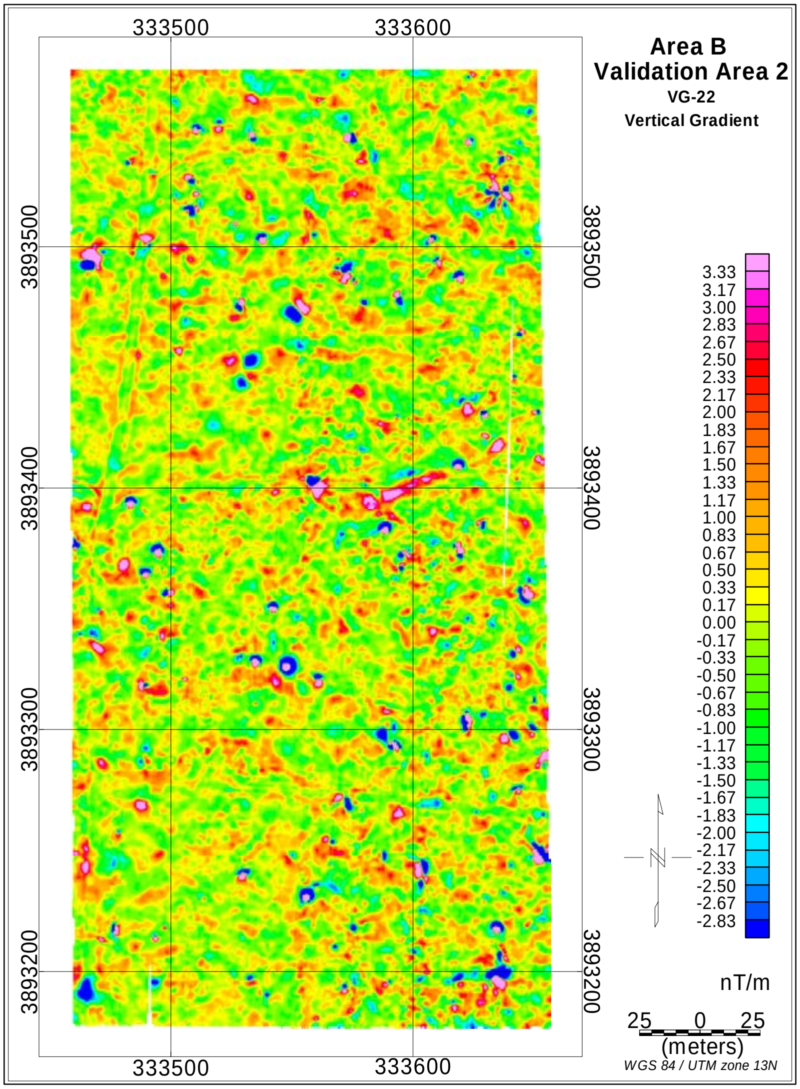

Figure 7. VG-22 VG Map for Validation Area 2, Area B at FKPBR.

4.2 PERFORMANCE CRITERIA

Effectiveness of the demonstration is determined from comparisons of the processed/analyzed results from the demonstration survey and the established ground-truth. Some qualitative parameters may be judged against results of previous airborne and ground-based surveys at FKPBR and elsewhere. Evaluation of seeded items provides a basis for assessing detection of small ordnance items. These comparisons include both the quantitative and qualitative items described in this section, which are documented fully in project reports available from ESTCP. Demonstration success is defined as the successful acquisition of airborne geophysical data (without any aviation incident or airborne system failure) and meeting the baseline requirements for system performance as established previously in Section 3.1. Methods utilized by Battelle on both current and past airborne acquisitions to ensure airborne survey success include daily quality assurance (QA)/QC checks on all system parameters (e.g., GPS, magnetometer operation, data recording, system compensation measurements, etc.) in the acquired data sets, a series of compensation flights at the beginning of each survey, continual inspection of all system hardware and software ensuring optimal performance during the data acquisition phase, and review of data upon completion of each processing phase.

Several factors associated with data acquisition cannot be strictly controlled, such as aircraft altitude and attitude. Altitude is recorded and entered into the data analysis and comparisons with previous results. The aircraft attitude measuring system provides a documented database that cannot be directly compared with previous surveys when this system was not available. The consistent and scientific evaluation of performance is accomplished by using identical or parallel (where parameters are dataset-dependent) processing methods with identical software to produce a final map and following consistent procedures in interpretation when comparing new and existing datasets from the respective test sites.

Data processing involves several steps, including GPS postprocessing, compensation, spike removal, time lag correction, heading correction, filtering, gradient calculations, and gridding. Each step can be performed in the same manner on the total field data to provide a basis for comparing the performance of the VG to total field systems. The processing procedures have been selected and developed from experience with similar data over several years for optimal sensitivity to UXO.

Data collection occurred at the specified flight altitudes over the various test areas. Table 4 identifies the expected performance criteria for this project, complete with expected/desired values (quantitative) and/or definitions and descriptions (qualitative).

Table 4. Performance Criteria and Results for the Battelle Airborne Gradiometer Systems.

Expected Performance Metric (Pre-demo)	Performance Confirmation Method	Actual Performance (Post-demo)
Primary Criteria (Performance Objectives) – Quantitative		
Ordnance detection on blind seed grid	Comparison to blind seed data. Number of successful detections/number of seed items.	Yes, see Table 2.
Ordnance detection (VG-16 and VG-22) >90% detection of M38 on North Area	Comparison to excavation data. Number of successful detections/number of excavated ordnance and explosives (OE) and OE related scrap items.	Unresolved. Only one UXO-like object was uncovered during the validation of the North Area.
False positives (VG-16 and VG-22) <10% in North Area (2)	Comparison to excavation or seed data. Number of unsuccessful detections/total number of detections.	Unresolved. Only one UXO-like object was uncovered during the validation of the North Area.
Anomaly positional accuracy <0.5 m mean, <0.4 m s.d. northing and easting(after inversion, VG-16) <0.4 m mean and <0.3 s.d. northing and easting (after inversion, VG-22)	Comparison to seed item locations.	Yes. See Table 3. VG-16: 0.44 m mean, s.d. 0.44 m VG-22: 0.02 mean; s.d. 0.30 m
Rotor noise performance improved over TF system (SNR improved by 4x)	SNR calculated from VG and TF over common targets.	Yes, achieved 4.3x noise reduction.
Low-frequency noise improvement over TF system (Figure of Merit [FOM] and Improvement Ratio [IR] improved by 4x)	FOM & IR calculated from VG and TF during compensation flight.	Yes, achieved 6.6x noise reduction.

Table 4. Performance Criteria and Results for the Battelle Airborne Gradiometer Systems (continued).

Expected Performance Metric (Pre-demo)	Performance Confirmation Method	Actual Performance (Post-demo)
Primary Criteria (Performance Objectives) – Qualitative		
Delineation of clustered targets	Comparison of results for seeded pairs of closely spaced targets with results of Gamey et al., 2007.	Unresolved. Pairs of targets were generally too far apart to register as clusters. Results match detection of single targets.
Altitude effects on sensitivity	Comparison of low level data with data acquired at 5 m altitude, Area B.	Only general relationships could be determined, as no validation was conducted in Area B.

Criteria	Expected Performance	Performance Confirmation Method	Actual Performance (Post-demo)
Secondary Criteria (Performance Objectives) – Qualitative			
Reliability	No system or component failures	Observations and documentation	No system components failed during the surveys.
Ease of use	Pilot "comfort" when flying with the system installed	Observations and documentation	Pilot finds performance is comfortable under normal weather conditions.
Safety	Conformance with all FAA requirements and requirements documented in the Mission Plan	Observations and documentation	Systems met all FAA flightworthiness requirements.
	Aerodynamic stability	Performance as assessed by pilot and aeronautical engineer, comparison with predecessor systems	Both systems are very stable; VG-22 is a little more difficult to fly than VG-16.
	Certification	FAA/STC certification awarded	FAA STC certificate awarded for both configurations.
Maintenance	System mount points, hardware, and component inspection	Observations and documentation	Minimal wear and tear.

(1) We define the term "ordnance detection" to mean the percentage of ordnance items that produced magnetic anomalies discernible above the noise floor and within a defined search radius. The term does not imply that the anomalies were or were not correctly classified.
(2) By the term "false positive," we refer to nonferrous sources. Thus all ferrous items (ordnance and non-ordnance) are considered true positives, and reported anomalies associated with rocks or nonferrous manmade items are considered false positives.
(3) By the term "anomaly positional accuracy," we mean the distance between the documented UXO or clutter item location and the location predicted by the geophysical anomaly or its inversion.

The VG systems outperformed the total field systems used in the 2002 ESTCP study at Pueblo of Isleta, New Mexico, as assessed by Tuley and Dieguez (2005), to the extent that background conditions at these two proximal sites can be considered equivalent. False alarm rates (P_{fp}) are strongly influenced by site conditions and could not be predicted.

4.3 DATA ASSESSMENT

VG-16 demonstrated a detection rate of 90% for items 81 mm and larger, and a 55% P_d overall. VG-22 demonstrated a detection rate of 100% for the medium and large items and an 86% detection overall. The 60-mm mortars displayed a surprisingly weak response with respect to their diameter, resulting in a low detection probability. This is probably due to the fact that, without their fins and nose cones, they are actually smaller than the 57-mm and 40-mm projectiles.

Anomalies from the eight missed 60 mm and one missed 57 mm were reviewed in an effort to determine the reason they were missed. Altitude was consistent over the entire grid and did not vary significantly for the missed targets, so this explanation was dismissed. These demonstrate that nearly all the missed targets were associated with an isolated anomaly, but upon further review, it was determined that these peaks fell below the picking threshold of 2.5 nT/m. The P_d for VG-22 at the South Area could therefore be improved by lowering the detection threshold to 2.0 nT/m. This would require an increase in the number of picks from 6,391 to 10,528, or from 12 picks/acre to 20 picks/acre. This results in detection of the missed 57 mm and six of eight missed 60 mm, for a revised overall P_d of 98%. We cannot assess P_{fp} for the blind test grid because the origin of the remaining anomalies is unknown and many could be associated with intact or fragmented ordnance.

4.3.1 Pairs of Seeded Targets

In addition to the individual items discussed above, ESTCP also seeded pairs of 60 mm targets at horizontal separations between 1 m and 4 m. As part of a study on the magnetic response of clustered targets (Gamey, 2007), it has been shown that when the ratio of the target separation to the sensor height (separation/height ratio, or SHR) exceeds 1.5, the targets should be treated as discrete anomalies. When the SHR is less than 0.5 then targets combine their amplitudes almost linearly into a single peak. Between these two limits targets cannot be distinguished as individual items, nor do their signatures combine to significantly increase the peak response amplitude. Within this middle range of partially overlapped signatures, the density of the collected data and the direction of target separation become extremely important for resolving peaks. For VG measurements, the signatures are narrower (higher spatial frequency) than total field anomalies and so these ratios must be adjusted by approximately 0.8 times. It should be recognized that these ratios are approximations only, as they do not include effects from relative target positions (NS versus EW) or data density.

The average sensor height (midpoint of gradient pair above the ground) for VG-22 over these targets was 1.3 m with the targets having an average burial depth of 12 cm. For two targets to combine signatures into a single unambiguous response, they must therefore be no more than 0.6 m apart. For targets to be clearly defined as separate anomalies, they must be more than 1.7 m apart. Targets spaced between these two limits are partially overlapped.

Max sep for fully overlapped anom	Min sep for clearly distinct anom
Sep/Height = 0.5x0.8 = 0.4	*Sep/Height* = 1.5x0.8 = 1.2
Height = 1.3 *m* + 0.1 *m*	*Height* = 1.3 *m*
Sep = 0.6 *m*	*Sep* = 1.7 *m*

Seeded target pairs were arranged with two pairs at 1 m separation, three pairs at 2 m, three pairs at 3 m, and two pairs at 4 m. None of these pairs are so close that they should produce a single dipole response with double the peak amplitude. The pairs that are 1 m apart should present a single, possibly distorted signature with amplitude similar to a single 60 mm. The pairs that are 2 m, 3 m, and 4 m apart should be treated as discrete items.

VG-16 detected a single peak over only two of the 10 pairs of 60 mm targets. This is comparable to the overall detection capability of the system for these targets. VG-22 detected all 10 pairs with different levels of resolution. Two of the target pairs were spaced 1 m apart and each was detected by a single peak in VG-22. The average radial offset between the anomaly peak and the actual individual target locations was 74 cm. This reflects the inherent ambiguity in trying to locate multiple targets from a single peak. There were eight target pairs spaced 2 m, 3 m, and 4 m apart (Figure 7) for a total of sixteen individual items. Nine of these sixteen (56%) were detected by a single anomaly peak with an average radial offset distance of 36 cm. This is directly comparable to the detection probability (56%) and radial offset distance (36 cm) achieved for the individual 60 mm seeded items in the rest of the grid.

4.3.2 Comparison of Data from 5 m Altitude with 1.5 m Altitude Results

VG and analytic signal (AS) maps of Area B (North Validation Area) for nominal 5 m altitude may be compared with their low-altitude counterparts to assess the utility of VG systems where site conditions do not allow operation at 1.5 m altitude. Unfortunately, the validation sites were in Area A, so we were unable to ground-truth the detection of UXO with VG-16 at 1 m to its performance at 5 m. However, some insight may be gained by comparing the dig lists. There were 2,001 anomalies picked for 5 m altitude at a threshold of 0.14 nT/m. The low-altitude dig list had 10,022 picks. On the 5 m list, 1,234 picks correspond to picks on the low-altitude list, and 767 picks on the 5 m list had no corresponding low-altitude picks, where they are assumed to match when within 2 m of one another.

About 50% of anomalies having amplitudes greater than about 25 nT/m are also detected at 5 m. Although some of the low-altitude anomalies are detected at 5 m, the proportion is much smaller for those with amplitudes less than 25 nT/m.

4.3.3 System Noise

4.3.3.1 Aircraft Compensation

The presence of the helicopter in close proximity to the sensors causes considerable deviation in the readings, which requires compensation. The orientation of the aircraft with respect to the sensors and the motion of the aircraft through the earth's magnetic field are contributing factors. A calibration flight is flown to record the information necessary to remove these effects. The maneuver consists of flying a box-shaped flight path at high altitude to gain information in each of the cardinal directions. During this procedure, the pitch, roll, and yaw of the aircraft are varied. This provides a complete picture of the effects of the aircraft at all headings in all orientations. The entire maneuver was conducted twice for comparison. The information was used to calculate coefficients for a 19-term polynomial for each sensor. The fluxgate data were used as the baseline reference channel for orientation. The polynomial is applied post flight to the raw data, and the results are referred to as the compensated data.

The use of VG reduces the raw compensation noise through common-mode rejection. The effectiveness of this can be seen in Figure 8. The raw VG noise in this sample is 6.6x lower than the total field data from the component sensors. This reduces the amount of airframe noise that the compensation routine must eliminate.

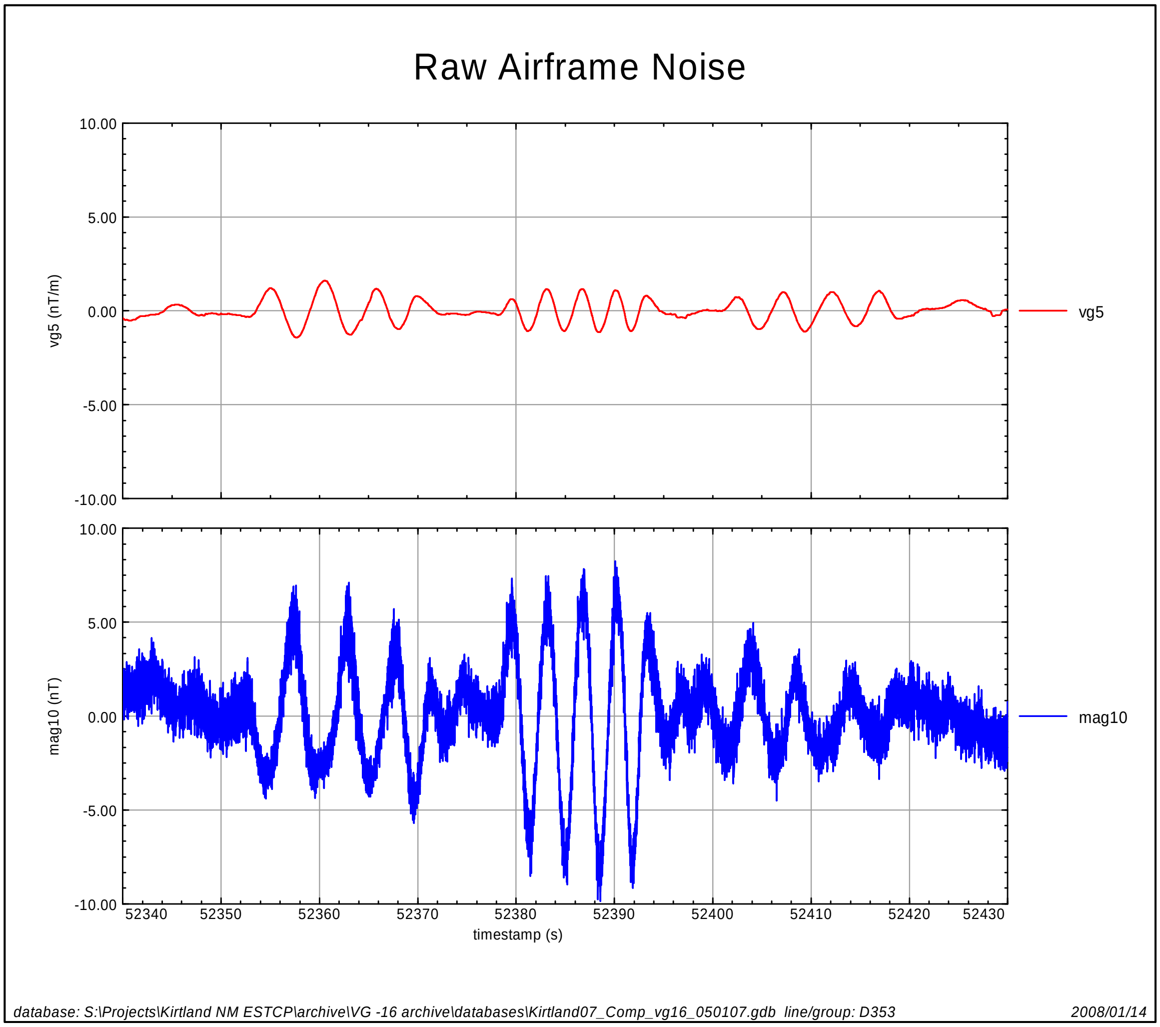

Figure 8. Raw Airframe Noise Prior to Compensation over a 90-sec Data Sample.
(The VG demonstrates a 6.6x reduction in noise. The high frequency noise observable in the total field profile is rotor noise, which is also reduced in the gradient.)

4.3.3.2 Rotor Noise

The aircraft rotor spins at a rate of about 400 revolutions per minute (rpm). This introduces noise to the magnetic readings at a frequency of approximately 6.6 Hz. Harmonics at multiples of this base are also observable but have much smaller amplitudes. This frequency is usually higher than the spatial frequency created by near-surface metallic objects and is removed with a frequency filter. The use of VG virtually eliminates this noise source, as can be seen in Figure 9. The raw rotor noise in this sample is 4.3x lower in the VG than the associated total field.

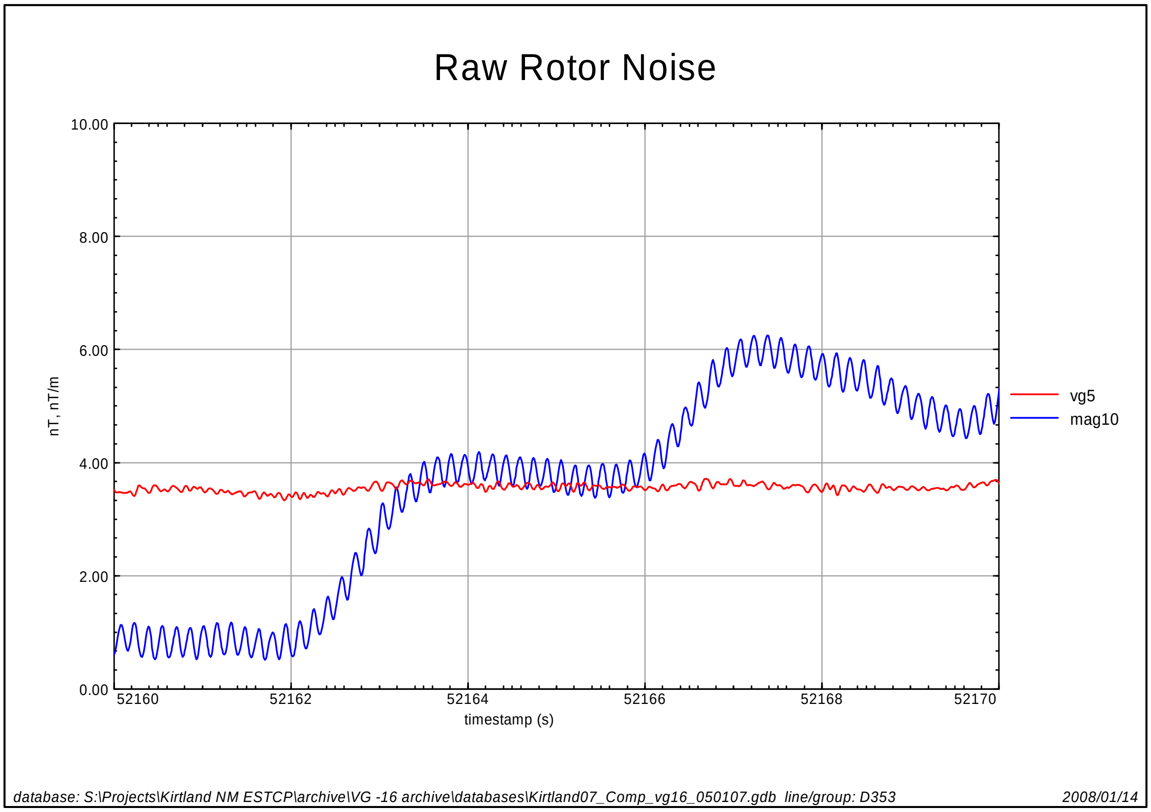

Figure 9. Raw Rotor Noise Over a 10-sec Data Sample Comparing Total Field and VG.
(The VG demonstrates a 4.3x reduction in noise.)

4.3.4 Personnel/Training Requirements

A variety of skilled personnel are required to conduct this type of geophysical survey. The pilot must be trained in low level or "ground effect" flying. The geophysical console operator must be skilled in making real-time decisions regarding data quality in order to identify poor quality data and call for immediate reflights. He must also be intimately familiar with the system in order to diagnose and perform any minor repairs to cabling, electronics, etc. in the field. The processing geophysicist must be familiar with airborne survey operation and data processing, as well as analysis of UXO targets. All crew must be familiar with safe operations in and around aircraft.

4.3.5 Health and Safety Requirements

We have conducted low-altitude airborne surveys for nearly 10 years without incident. General and site-specific health and safety plans are generated for each survey project. These plans include provisions for general ground safety, extend them using DoD models for UXO site safety, further extend them to encompass airborne operations, and then add wholly new considerations for airborne operations in a UXO theatre. The appropriate management at Battelle, the helicopter operator, and the project sponsor approve these health and safety plans.

With regard to the technology, the only regulatory agency involved in the implementation of this technology is the FAA. Because the boom mounting structure is bolted directly to the hard-points of the aircraft, this installation becomes a modification to the airframe that requires FAA approval. These approvals were obtained in the form of an STC. This certificate was obtained by the aeronautics engineer at the time of manufacture and permits the installation of this equipment in any standard Bell B206L Long Ranger aircraft.

4.3.6 Ease of Operation

The Battelle systems and their ORNL predecessors were designed in concert with input from our helicopter provider and aeronautical engineer for safe operation with minimal stress on both materials and pilot. The VG-16 system operates without any ballast because of its design, which optimizes weight distribution. VG-22 requires approximately 50 lb of ballast in the cargo bay to offset the additional mass of sensors in the foreboom structure. This is less ballast than required by many other systems. Pilots report that VG-16 is as comfortable to fly as the predecessor ORAGS-Arrowhead system. They find that VG-22 requires slightly more attention, due to extra mass in a foreboom. Pilots have full authority to defer operations when they consider flight conditions to be unsuitable. The systems have been flown at altitudes exceeding 5,000 feet, at temperatures in excess of 100°F, and in winds of up to 20 knots.

4.3.7 Limitations

The Battelle VG systems are designed for daylight operations only. Major factors in implementing or deploying the airborne system are topography and vegetation. Steep topographic variations make it difficult to achieve uniform altitude across many survey areas. Most topographic features will be coherent between lines, which makes them easy to identify and prevents confusing them with ordnance signatures. The impact on data quality is that the average altitude will increase making it more difficult to detect smaller objects.

Vegetation has a similar effect on data quality in that it necessitates an increase in survey altitude. Isolated pockets of vegetation or single trees can be handled in two ways. The first is to fly over them and create a small pocket of lower resolution data. The second is to fly around them and create a minor gap in data coverage. Continuous stretches of vegetation or forest should be avoided.

Geologic influence is another factor impacting the technology implementation. The difficulty of detecting ordnance in highly magnetic environments is well documented and impacts the airborne system as it would a ground system.

4.4 TECHNICAL COMPARISON

The VG systems described in this report have demonstrated performance that is improved over predecessor airborne systems for UXO applications. This is summarized in Tables 2 and 3. VG-22 detected 100% of seeded 81 mm and 105 mm seeded items, while the predecessor systems did no better than 47% and 73% respectively for the same items. It also performed very well with smaller seeded items, although the numbers of these was too small to fully assess system capability. The performance of VG-16 was better than predecessor systems, as anticipated given the nature of the system design, which places mean sensor position at greater altitude for a given altitude of the helicopter. The performance substantiates the differences in design criteria for the two systems.

System coverage for VG-16 is equivalent to that of the ORAGS-Arrowhead system, while VG-22 requires approximately twice the amount of flight time to cover an equivalent area. Overall value for end-users, therefore, is dependent on the purpose of the survey, ordnance of concern at the site, and attributes of the site (e.g., vegetation, terrain), as described previously.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

Cost information associated with the demonstration of the vertical magnetic gradient airborne technology was closely tracked and documented before, during, and after the demonstration to provide a basis for determination of the operational costs associated with this technology. It is important to note that the costs for airborne demonstrations and surveys are very much dependent on the character, size, and conditions at each site, ordnance objectives of the survey (e.g., flight altitude), type of survey conducted (e.g., high-density or transects), and technology employed for the survey (e.g., total field magnetic, vertical magnetic gradient, time domain electromagnetic induction [EMI]) so that a universal formula cannot be fully developed. For this demonstration, 2,000 acres of VG-16 data and 1,000 acres of VG-22 data were acquired within blocks totaling 1,500 acres (see Figure 3). Table 5 contains the cost elements that were tracked and documented for this demonstration. These costs include both operational and equipment costs associated with system application; mobilization and demobilization of equipment and personnel; salary and travel costs for project staff; subcontract costs associated with helicopter services, support personnel, and leased equipment; and costs associated with the processing, analysis, comparison, and interpretation of airborne results generated by this demonstration.

Table 5. Cost Elements for VG Survey Demonstration at FKPBR.

Cost Category	Subcategory	Details	Quantity	Cost[1]
Pre-survey (Start-up)	Site characterization	Site inspection	0 days	$0
		Mission plan preparation and logistics	18 days	$31,434
		Calibration site preparation	2 days	$8,555
	Mobilization	Equipment/personnel transport (includes travel)	3 days	$9,641
		Helicopter/personnel transport[1] (includes travel)	4 days	$24,331
		Unpacking and system installation	1 day	$7,073
		System testing and calibration	1 day	$2,796
Pre-Survey Subtotal				**$83,830**
Capital equipment	System use rate ($700/day)		25 days	$17,500
Capital subtotal				**$17,500**
Operating costs	Data acquisition	Helicopter time, including pilot and engineer labor	18 days (74 hours airtime)	$100,664
	Operator labor		18 days	$8,100
	Field data processing	Geophysicist	25 days	$39,442
	Field support/management	Geophysicist	14 days	$24,256
	Maintenance	Geosoft software maintenance[1]	1 each	$0
	Hotel, air fares, and per diem	Survey team	18 days	$7,267
	Fuel truck	Remote refueling[1]	NA	NA
	Airport landing fees and fixed-base operator (FBO) fees		18 days	$1,170
	Project management		4 days	$6,930
Operating Cost Subtotal				**$187,829**

Table 5. Cost Elements for Vertical Magnetic Gradient Survey Demonstration at FKPBR (continued).

Cost Category	Subcategory	Details	Quantity	Cost[1]
Post-survey	Demobilization	Disassembly from helicopter, packing, and loading for transport	1 day	$6391
		Equipment/personnel transport[1] (includes travel)	3 days	$9821
		Helicopter/personnel transport[1] (includes travel)	3 days	$18,364
	Additional data processing, analysis, interpretation (at Oak Ridge offices), and reporting			$119,703
Post-Survey Subtotal				**$154,279**
Total Costs				**$443,438**

[1]Includes all overhead and organization burden, fees, and associated taxes

5.2 COST ANALYSIS

5.2.1 Cost Drivers

The major cost drivers for an airborne survey are the cost of helicopter services and the data processing and analysis associated with the acquired data. In terms of tasks, these constitute most field-related costs (i.e. mobilization, data acquisition, and demobilization costs), which represent the single largest cost item for an airborne survey project.

Data processing and analysis functions constitute most of the remaining costs associated with the field-related costs for a survey. Peripheral costs associated with this demonstration-validation project, such as ground truth and excavations, are not part of the cost analysis.

The sensitivity of the overall cost to these drivers can be modeled under several different scenarios. Helicopter time on site is a factor of several variables. The first is the number and dimensions of the survey blocks. The greatest amount of nonsurvey time is spent in turns at the end of each line in preparation and alignment for the next line; therefore, fewer and longer survey lines are more efficient than numerous shorter ones. In practice, a maximum line length of 5 km is recommended.

As discussed above, other major cost drivers are mobilization, data processing, and demobilization. These costs are a function of project size and transportation distance, respectively. Processing costs and data delivery times typically decrease with experience at multiple sites. Mobilization costs are unlikely to decrease with time. The use of a local (to the survey project site) helicopter and pilot may offer decreased mobilization costs, but risks significantly increase acquisition costs if the aircraft engineer/mechanic responsible for system installation is unfamiliar with the equipment/installation process, or if the pilot is uncomfortable with the level of precision flying and height above the ground surface that is required.

5.2.2 Cost Comparisons

5.2.2.1 VG-16 Cost Comparison

This section compares costs of three different survey technologies. These include man-portable, the ground-based MTADS system, and the VG-16 vertical magnetic gradient airborne system. Operational costs for the VG-16 system are equivalent to those of the ORAGS-Arrowhead and comparable airborne total magnetic field systems.

Based on several sources of information regarding the deployment of ground-based towed array systems on a UXO contaminated site, five scenarios are presented for the purpose of comparing airborne surveys to ground-based surveys. These sources of information are generally informal and include discussions both with industry and U.S. Army Engineering and Support Center, Huntsville (USAESCH) staff experienced in the application of ground-based towed array surveying equipment and projects.

Following Harbaugh et al. (2007), we assume that the two ground-based technologies might survey only 2% of the total area of concern, while the airborne systems would survey between 2% and 100%. This level of ground surveying has been used in ESTCP's WAA Pilot Program. We also include higher proportions of ground surveying for comparison purposes. Harbaugh et al have proposed fixed costs of $75,000 (mobilization, demobilization, reporting) and acreage costs of $500/acre for use of MTADS at two sites. Similarly, they submit fixed costs of $45,000 plus acreage rates of $1,540/acre for man portable electromagnetic surveys at these sites. We assume that the cost of a ground-based magnetometer survey would be roughly equal to that of a ground-based electromagnetic survey.

Comparisons between airborne, vehicle, and man-portable magnetometer surveys are summarized in Table 6. These scenarios address sites of 1,000 to 50,000 acres of geographic extent, with varying rates of coverage from 100% to 2%. Airborne costs range from $71 to $181 per acre for a 100% coverage survey using the VG-16 WAA system. These costs include a nominal $50,000 mobilization cost from our bases of operation in Tennessee and Ontario, Canada. Airborne costs are corroborated by recent work for non-ESTCP sponsors, e.g., the surveys at Kirtland Air Force Base, Fort McCoy, Camp Lejeune, Pinecastle Range Complex, and Fort Ord.

Table 6. Costs for Airborne, Ground Vehicle, and Man-Portable Survey Platforms for Varying WAA Survey Densities.

(Shaded cells are minimum cost. Man-portable are most cost-effective for 0-30 acres (ac) actual coverage, vehicular systems from 30-150 ac and airborne over 150 ac. All costs are in thousands of dollars and include fixed mobilization costs.)

$air (VG-16)

ac	100%	50%	25%	10%	2%
1000	$ 231	$ 186	$ 150	$ 146	$ 143
2000	$ 292	$ 215	$ 163	$ 148	$ 144
5000	$ 495	$ 308	$ 226	$ 170	$ 153
20000	$ 1,510	$ 789	$ 462	$ 293	$ 198
50000	$ 3,600	$ 1,790	$ 997	$ 524	$ 269

$vehicle

ac	100%	50%	25%	10%	2%
1000	$ 575	$ 325	$ 200	$ 125	$ 85
2000	$ 1,075	$ 575	$ 325	$ 175	$ 95
5000	$ 2,575	$ 1,325	$ 700	$ 325	$ 125
20000	$ 10,075	$ 5,075	$ 2,575	$ 1,075	$ 275
50000	$ 25,075	$ 12,575	$ 6,325	$ 2,575	$ 575

$man

ac	100%	50%	25%	10%	2%
1000	$ 1,585	$ 815	$ 430	$ 199	$ 76
2000	$ 3,125	$ 1,585	$ 815	$ 353	$ 107
5000	$ 7,745	$ 3,895	$ 1,970	$ 815	$ 199
20000	$ 30,845	$ 15,445	$ 7,745	$ 3,125	$ 661
50000	$ 77,045	$ 38,545	$ 19,295	$ 7,745	$ 1,585

covered ac

ac	100%	50%	25%	10%	2%
1000	1000	500	250	100	20
2000	2000	1000	500	200	40
5000	5000	2500	1250	500	100
20000	20000	10000	5000	2000	400
50000	50000	25000	12500	5000	1000

Man-portable systems generally have significantly higher acquisition costs than airborne systems (ranging from $500 to $3,000 per acre, depending on site conditions), are extremely time-consuming, and may present risks to personnel, equipment, and the environment. Neither the airborne nor the ground-based survey costs include the cost of excavation.

Comparison of the airborne array to a ground-based towed array of magnetometers similar to MTADS may be more representative for several reasons:

- MTADS was deployed at several of the same sites as the airborne technology (as reflected in several IDA reports), which enables an easy comparison for broad-area search technology.
- USAESCH performed an assessment of costs associated with contractors that employ ground-based towed arrays for geophysical surveying at UXO sites.

The extent of coverage possible with an airborne system renders comparisons to handheld man-portable systems somewhat inappropriate.

Although both simplistic and generalized in nature, it is readily apparent that the advantage of airborne surveys over ground-based becomes greater as the area of concern becomes larger. These figures illustrate that man-portable platforms are most cost-effective for sites requiring <30 acres of actual coverage. Vehicular systems are most effective for 30-150 acres, and airborne systems are most effective for sites over 150 acres.

Costs for MTADS surveys may vary from those estimated in Table 6. The following was extracted from a relevant IDA report (Andrews et al., 2001): "For this demonstration, the MTADS total cost was $377,296. If the excavation costs of $169,096 and the reporting costs of $24,000 are removed, the MTADS costs for the deployment, survey, and analysis parts of this demonstration were $184,200. Note that this does not separate out the costs of the EMI work. The MTADS surveyed a total of more than 150 acres for a cost of $1,222 per acre." For the ORAGS-Arrowhead (which compare favorably with the costs for the vertical magnetic gradient system), the total costs for the demonstrations and surveys ranged from $159,096 to $348,080, for a cost of $86 to $704 per acre, including mobilization. According to the IDA report conclusions, "Cost estimates prepared by the performers indicate that the per acre cost of the MTADS is about 2–3 times higher that those of airborne systems. These figures are very rough estimates and may not accurately reflect the cost differences seen in operational surveys." The MTADS costs are summarized in Table 7.

Table 7. Representative Cost for MTADS Ground-Based Survey.

Cost Category	Subcategory	Costs ($)
Fixed Costs		
1. Capital costs	Mobilization/demobilization	6,614
	Planning/preparation/Health and Safety Plan (Mission Plan)	1,746
	Equipment	Included in survey cost
	Management support	Included in survey cost
Subtotal		**8,360**
Variable Costs		
2. Operation and maintenance	Ground-based survey	129,650
	Labor for data processing, analysis, and interpretation	37,800
	Instrument rental or lease	Included in survey cost
	Travel and miscellaneous materials	26,060
	Reporting	4,230
Subtotal		**197,740**

Table 7. Representative Cost for MTADS Ground-Based Survey (continued)**.**

Cost Category	Subcategory	Costs ($)
3. Other technology-specific costs	Excavation for ground-truthing and verification	Not included
	Geophysical prove-out	5,616
Subtotal		**5,616**
4. Miscellaneous costs	None noted	0
Total Costs		
Total Technology Cost		**211,716**
Throughput achievable (acres per hour)		**3**
Unit cost per acre		**735**

An even closer comparison of the Battelle VG-16 array costs are the costs associated with the previous ORAGS-Arrowhead and ORAGS-Hammerhead ESTCP demonstrations and DoD surveys. The cost factors involved in the Battelle VG-16, ORAGS-Hammerhead, and ORAGS-Arrowhead surveys are very similar. Apart from the learning curve associated with field experience, only the rate of survey coverage has changed significantly between the two generations of the technology. The ORAGS-Arrowhead and ORAGS-Hammerhead survey coverages were based on 12 m flight line spacing, which is virtually the same as the Battelle VG-16 system.

In Table 6, we provided costs for airborne surveys covering between 2% and 100% of the area of interest with ground-based surveys covering 2% of the area of interest. An unresolved question is where the equivalency would lie between airborne and ground-based technologies: Which is more valuable—a 10% airborne survey or a 2% ground-based survey. The answer would clearly lie in the detectability of the ordnance of interest at the site for both systems and the uncertainty about ordnance contamination in areas that are not surveyed. The greater sensitivity of ground-based systems must be balanced against the probability of ordnance contamination within areas that are not surveyed. The choice will likely vary from site to site. Ground-based systems have more cost constraints that are site-dependent than airborne systems (e.g., unnavigable terrain, vegetation that must be cleared, vibration-sensitive ordnance, etc.), and this may also affect the selection of approaches.

5.2.2.2 <u>VG-22 Cost Comparison</u>

VG-22 was designed as a more sensitive system for detecting individual ordnance items, and as such, it is appropriate to compare costing for VG-22 surveys to 100% ground-based surveys (Table 8). The costs for VG-22 are higher than those for VG-16 due to the 6 m swath width for VG-22 compared to a 12 m swath width for VG-16. Ground-based survey costs are based on Harbaugh et al. (2007), as with Table 6. Mobilizations are estimated in the same manner as in Table 6.

Table 8. Costs for 100% Coverage with VG-22 Airborne and Ground-Based Surveys.

Area (acres)	Airborne Cost ($/acre)	Airborne Total (k$)	Vehicular Towed (k$)	Man Portable (k$)
1,000	291	$291k	$575k	$1,585k
2,000	217	$ 434k	$1,075k	$3,125k
5,000	167	$835k	$2,575k	$7,745k
20,000	139	$2,780k	$10,075k	$30,845k
50,000	137	$6,850k	$25,075k	$72,545k

In Table 8, we have treated VG-22 as a surrogate for ground surveys. This may be appropriate where target ordnance items are large (e.g., 81 mm and larger), for which VG-22 P_d values are high, as indicated by the Kirtland tests. Alternatively, VG-22 might be used where a larger proportion of small ordnance must be detected in order to justify use of the airborne survey for WAA applications. In some cases, this might involve partial coverage of a site with VG-22, a scenario with costs that would be different from those estimated in Tables 6 and 8.

5.2.3 Cost Basis

The basis of cost for this analysis consists of the tasks and work elements necessary to provide a complete turnkey airborne geophysical survey of a current or former military site with the intended survey objective being UXO. The UXO survey objective includes detection and mapping of individual ordnance and ordnance-related artifacts, as well as clustered UXO represented by targets, impact areas, and firing fans. The operational survey criteria are assumed to be acceptable for low-altitude geophysical surveying, including relatively flat to gently sloping terrain; little to no vegetation exceeding 1 m in height; and few if any cultural artifacts or impediments (e.g., overhead power transmission lines). Additional survey criteria included in the cost basis are favorable weather conditions requiring no downtime (e.g., low wind, excellent visibility, high cloud ceiling, no precipitation).

The tasks and work elements included in the basis of cost include development of the survey Mission Plan (includes the Work Plan and Aviation Safety Plan); helicopter, survey equipment, and personnel mobilization and demobilization to the project site; geophysical prove-out (GPO) setup and mapping; data acquisition, QC, analysis, processing, analysis, and interpretation; project management; and reporting. Within these tasks and work elements, all labor, materials, travel, and other miscellaneous costs are fully addressed and accounted for.

5.2.4 Life-Cycle Costs

Life cycle costs for airborne technology are somewhat difficult to predict. This is based, in part, on how these costs are predicated on the usage and duty cycle of the boom structure, which is exposed to considerable stress during each survey application (including installation and de-installation). Our experience with the ORAGS-Arrowhead suggests that the replacement cycle for the boom components and mounting hardware is approximately 3 years based on six moderate-sized surveys per year. In addition, the cesium-vapor magnetometers require periodic recalibration (typically annually) and sensor refurbishment. Other components of the airborne system require little or no maintenance, including the GPS, navigation, laser altimeter, and data management system. These components have little cost associated with their life cycle beyond the investment of the original purchase.

Capital costs associated with this demonstration project were borne by Battelle and are in the range of $750,000. These capital costs include design, development, construction, testing, and flight certification costs. This last element, flight certification, is the single aspect within the life-cycle framework that requires regulatory approval (i.e., by FAA). This certification cost involves a determination of air worthiness, as well as the detailed weights and balances required for system operation. This is a single investment that is incurred before application of the survey technology as a survey project site. Aside from this initial regulatory involvement, no other regulatory or institutional oversight costs apply.

Operational costs as a part of the life-cycle cost assessment include the same elements addressed in the cost basis described in Section 5.2.3. These costs include development of the survey Mission Plan; helicopter, survey equipment, and personnel mobilization and demobilization to the project site; GPO setup and mapping; data acquisition, QC, analysis, processing, and interpretation; project management; and reporting. Within these tasks and work elements, all labor, materials, travel, and other miscellaneous costs are fully addressed and accounted for.

No liability costs are associated with the application of the airborne technology for a survey project site as far as life-cycle costs are concerned. The issue of liability for a survey project is associated with the liability of helicopter operation, which is a routine cost for which the helicopter services provider procures insurance. All other liability associated with the survey for UXO is typically indemnified by the U.S. government.

5.3 COST CONCLUSIONS

As demonstrated above, comparing costs of fundamentally different technology approaches is both difficult and inconclusive. The previously discussed cost comparison provided a range of answers to the same question, namely, what are the costs of deploying each technology over the same size area under the same conditions?

For consideration of DoD-wide application of the airborne technology, a number of factors must be considered when evaluating the appropriateness of the airborne technology and potential for substantial cost savings. While initially impressive, it is not possible to simply apply these types of cost savings across the entire DoD UXO program. Sites must be of sufficient geographic extent to warrant a deployment given the high costs associated with mobilization and demobilization. In addition, survey objectives, terrain, geology, vegetation, and cultural artifacts must also be considered for such a deployment. Extremely variable terrain and/or the presence of tall vegetation can greatly limit or impede the use of the airborne technology for the UXO objectives of interest. Finally, the project objective must be consistent with the detection limits and capabilities of the airborne system to make such a deployment feasible.

6.0 IMPLEMENTATION ISSUES

6.1 PERFORMANCE OBSERVATIONS

The primary performance objectives were largely exceeded in this project. Practical survey heights were as expected, allowing high resolution of the detected targets and anomalies. The geophysical calibration site was established and utilized with the objective of bracketing the detection capabilities of the system. The objective of this project was to demonstrate detection of ferrous targets, whether ordnance or nonordnance.

6.2 APPROACHES TO REGULATORY COMPLIANCE AND ACCEPTANCE

It is important to recognize the different aspects associated with the regulatory involvement in both the technology and the application of the technology to a UXO-contaminated site. With regard to the application of the technology, there are issues associated with regulatory drivers and involvement of both regulatory entities and other stakeholders that are relevant.

Although no specific regulatory drivers exist at this time for UXO-contaminated land, UXO clearance is generally conducted under CERCLA authority. Additionally, a draft Environmental Protection Agency (EPA) policy is currently under review. Regardless of a lack of specific regulatory drivers, many DoD sites and installations are aggressively pursuing innovative technologies to address a variety of issues associated with ordnance and ordnance-related artifacts (e.g., burial sites) that resulted from weapons testing and/or training activities. These issues include footprint reduction and site characterization, areas of particular focus for this technology demonstration and associated production surveys. In many cases, the prevailing concerns at these sites become a focus for the application of innovative technologies in advance of anticipated future regulatory drivers and mandates.

There are several types of sites where UXO contamination is an issue. These include closed, transferred, and transferring (CTT) ranges, such as formerly used defense sites (FUDS) and Base Realignment and Closure Act (BRAC) sites, as well as sites on active and inactive ranges that are not scheduled for closure. Where sites are designated for civilian reuse, it is important that the UXO be removed to the extent possible, and that proper safeguards be established where there is any possibility that live ordnance might still be in place. It is also important that a permanent record be maintained to document all measurements that are made to support clearance activities. Advanced technology, such as the airborne system, is expected to contribute to the performance of these activities in terms of effectiveness as well as cost.

6.3 LESSONS LEARNED

The primary benefit of this technology is in rapid reconnaissance of large open areas, or WAA. Cost analysis shows that costs per acre decrease significantly with the size of the project, whereas ground surveys tend to have a fixed cost per acre. These demonstrations and surveys have proven it prudent to survey as large an area as possible with each mobilization.

With regard to the technology, the only regulatory agency involved in the implementation of this technology is the FAA. Because the boom mounting structure is bolted directly to the hard-points of the aircraft, this installation becomes a modification to the airframe that requires FAA approval. These approvals were obtained in the form of an STC. This certificate was obtained by the aeronautics engineer at the time of manufacture, and permits the installation of this equipment in any standard Bell B206L Long Ranger aircraft.

6.4 OTHER SIGNIFICANT OBSERVATIONS

As mentioned previously, major factors in implementing or deploying the airborne system are topography and vegetation. Steep topographic variations make it difficult to achieve uniform altitude across many survey areas. Most topographic features will be coherent between lines, which makes them easy to identify and not confused with ordnance signatures. The impact on data quality is that the average altitude will increase, making it more difficult to detect smaller objects.

Vegetation has a similar effect on data quality in that it necessitates an increase in survey altitude. Isolated pockets of vegetation or single trees can be handled in two ways. The first is to fly over them and create a small pocket of lower resolution data. The second is to fly around them and create a minor gap in data coverage. Continuous stretches of vegetation or forest should be avoided. The VG-16 and VG-22 systems were designed, in part, to overcome some restrictions associated with vegetation and topography by exploiting the improved SNR performance of the VG architecture. However, these factors will continue to constrain all airborne systems, albeit at greater altitude than their predecessors.

Geologic influence is another factor impacting the technology implementation. The difficulty of detecting ordnance in highly magnetic environments is well documented and impacts the airborne system as it would a ground system. Battelle has developed an airborne time-domain system that can be employed as an alternative to magnetometer systems where geologic conditions are unsuitable for magnetometer surveys.

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