ESTCP
Cost and Performance Report

(MR-201002)

Autonomous Underwater Munitions and Explosives of Concern Detection System

March 2015

This document has been cleared for public release; Distribution Statement A

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAR 2015**	2. REPORT TYPE **Final**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Autonomous Underwater Munitions and Explosives of Concern Detection System**	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), 4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**	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 **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**51**	

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

COST & PERFORMANCE REPORT
Project: MR-201002

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

AIC	artificial intelligence crew
AS	analytic signal
AUV	Autonomous Underwater Vehicle
cm	centimeter
DERP	Defense Environmental Restoration Program
DoD	Department of Defense
DRMS	distance root mean squared
DVL	Doppler velocity log
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
ft	feet
FUDS	Formerly Used Defense Site
GPS	Global Positioning System
GUI	graphical user interface
GX	Geosoft Executable
Hz	Hertz
ID	identification
INS	inertial navigation system
IR	improvement ratio
kg	kilogram
kHz	kilohertz
km	kilometer
LAN	local area network
m	meter
m/s	meters per second
MEC	munitions and explosives of concern
MHz	megahertz
mm	millimeter
MMRP	Military Munitions Response Program
MRS	munitions response site
MTA	Marine Towed Array
nT	nanotesla

ACRONYMS AND ABBREVIATIONS (continued)

SBAS	satellite-based augmentation system
SRI	SRI International
USEMS	Underwater Simultaneous EMI and Magnetometer System
WAA	wide area assessment
WAAS	Wide Area Augmentation System
W-LAN	wireless local area network
XML	extensible markup language

ACKNOWLEDGEMENTS

Dr. Art Trembanis (University of Delaware) was the Autonomous Underwater Vehicle (AUV) Team Lead. Dr. Trembanis was responsible for mission planning and AUV deployment. He managed his AUV Team including Val Schmidt (University of New Hampshire) and Nicole Raineault (University of Delaware). Mr. Schmidt was the AUV engineer and AUV operations lead. Ms. Raineault provided AUV support.

George Tait (Geometrics, Inc.) was the hardware engineer. Mr. Tait was responsible for sensor operation and magnetometer module connectivity.

Misha Tchernychev (Geometrics, Inc.) was the geophysicist responsible for magnetic compensation.

Brian Junck (Weston Solutions, Inc.) was the geophysicist responsible for magnetic data processing and interpretation.

John Kloske (SRI International) was the marine operations lead. Mr. Kloske was responsible for planning and coordination of the research vessel *GH Gilbert* and the seeding program.

This page left blank intentionally.

EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The objective of Environmental Security Technology Certification Program (ESTCP) Project MR-201002, Autonomous Underwater Vehicle (AUV) Munitions and Explosives of Concern (MEC) Detection System, was to integrate an untethered and unmanned underwater vehicle with a total field magnetometer for underwater munitions detection and upgrade magnetic noise compensation software to reduce interference from electrical and dynamic influences such as vehicle heading, pitch and roll. The system was to also achieve data density, positional accuracy, and compensation improvement ratios necessary for wide area assessment and detailed characterization surveys.

TECHNOLOGY DESCRIPTION

The integrated AUV MEC Detection System consists of a high sensitivity Geometrics G-880AUV cesium vapor magnetometer integrated with a Teledyne-Gavia AUV and associated Doppler-enabled inertial navigation system, acoustic bathymetric, and side-scan imaging modules. Total field magnetic measurements are recorded with asynchronous time-stamped data logs that include position, altitude, heading, pitch, roll, and electrical current usage. Surveys are performed by using pre-planned mission information including speed, height above seafloor or depth, and lane or transect spacing.

Magnetic compensation software was concurrently developed to accept electrical current measurements directly from the Gavia AUV to address distortions from permanent and induced magnetization effects on the magnetometer. Maneuver and electrical current compensation terms can be extracted from the magnetic survey missions to perform post-process corrections.

In March 2012, the system was demonstrated in Tampa Bay near St. Petersburg, Florida. Two 100-meter (m) by 100-m test plots were established approximately 3 miles from shore in water 30 feet (ft) deep. Each test plot was seeded with inert munitions ranging from 60-millimeter (mm) mortars to 155mm projectiles. Data were collected with the AUV MEC Detection System at both test plots at 1.5-m, 2-m, and 3-m altitude above the sea floor and at 2-m line spacing.

DEMONSTRATION RESULTS

The AUV MEC Detection System showed reliable detection of 60mm mortars and larger munitions at 1.5-m altitudes, and 75mm projectiles and larger munitions at altitudes over 2-m. Average offsets between the known and measured locations of seed items ranged between 0.7-m and 1.8-m depending on the mission design and is a function of mission planning software at the time of the demonstration. Offsets were less than 0.5-m where survey lines crossed seed item locations. No net drift of the navigation solution was observed during survey missions thus confirming target positional accuracy of less than 1-m is achievable. Vehicle dynamic performance objectives for bottom keeping, pitch, roll and along-line data density were achieved.

Considerable suppression of system noise was realized using upgraded compensation software. The most prominent magnetic distortions in the survey data correlated with vehicle pitch and heading. Post-process corrections yielded improvement ratios from 5.1 to 7.6 in the calibration grid and 11 to 12.4 in the blind grid.

Daily operational costs for this demonstration totaled approximately $5,300/hectare of survey data collection and processing. A daily recurring cost of $400 was needed for instrument setup and preparation.

IMPLEMENTATION ISSUES

Several advantages were attained as a result of the modular design, autonomous capabilities, and rapid deployment of the AUV MEC Detection System, including ease of use and application in a broad range of environments as compared to current towed array marine detection systems. This autonomous and self-contained system shows the capability to provide cost savings over current systems by reducing the mobilization/demobilization effort, requiring less manpower for operation, and reducing the need for a large surface support vessel altogether. This commercial off-the-shelf AUV MEC Detection System shows improved efficiency, safety, and cost savings compared to current systems for wide area assessment (WAA) and detailed characterization surveys.

The components used to develop the mag module are primarily commercially available; however, their integration and operation was customized for the purposes of this demonstration. Issues including excess survey coverage to achieve full coverage requirements and across-line spacing limitations associated with commercially available mission planning software need careful consideration when selecting this technology and developing missions. A quality control program specific to underwater surveys that verifies navigation accuracy, detection capabilities, and system operation will need to be created for regulatory approval.

Due to the operational complexities associated with the operation of the Gavia AUV, personnel require specialized training in properly assembling, configuring, and operating the equipment to perform detection surveys. Mission plan creation, data transfer, and communication with the AUV, and as well as monitoring of the AUV during surveys are all tasks that require specialized training.

1.0 INTRODUCTION

1.1 BACKGROUND

Reports indicate that thousands of active and former Department of Defense (DoD) sites spanning millions of acres of near-shore coastal, off-shore ocean, swamps, rivers, and lakes potentially contain munitions from past military training and weapons testing activities. To respond to munitions-contaminated underwater environments, modern land-based geophysical survey techniques and technologies are being integrated and deployed with waterborne crafts, platforms, and sensors to detect munitions.

Underwater detection technologies currently demonstrated at constructed test plots and munitions response sites (MRS) use geophysical sensor (magnetometer and/or time domain electromagnetic) arrays mounted to rigid semi-buoyant platforms tethered to a surface water vessel that tows the sensor system through the water body. Logistical issues regarding maximum sensor deployment depths, topside vessel support, manpower requirements for implementation, and associated high costs are some of the limiting factors with current systems.

ESTCP Project MR-201002, *Autonomous Underwater Vehicle (AUV) Munitions and Explosives of Concern (MEC) Detection System*, integrates an untethered and unmanned underwater vehicle with a total field magnetometer. The magnetometer is self-contained within the vehicle providing added agility when deployed for underwater MEC detection. Magnetic noise compensation software has been upgraded to reduce interference from electrical influences and vehicle dynamics such as pitch and roll. The modular construction of the AUV allows the system to be easily shipped using standard package carriers. The AUV MEC Detection System is illustrated in Figure 1.

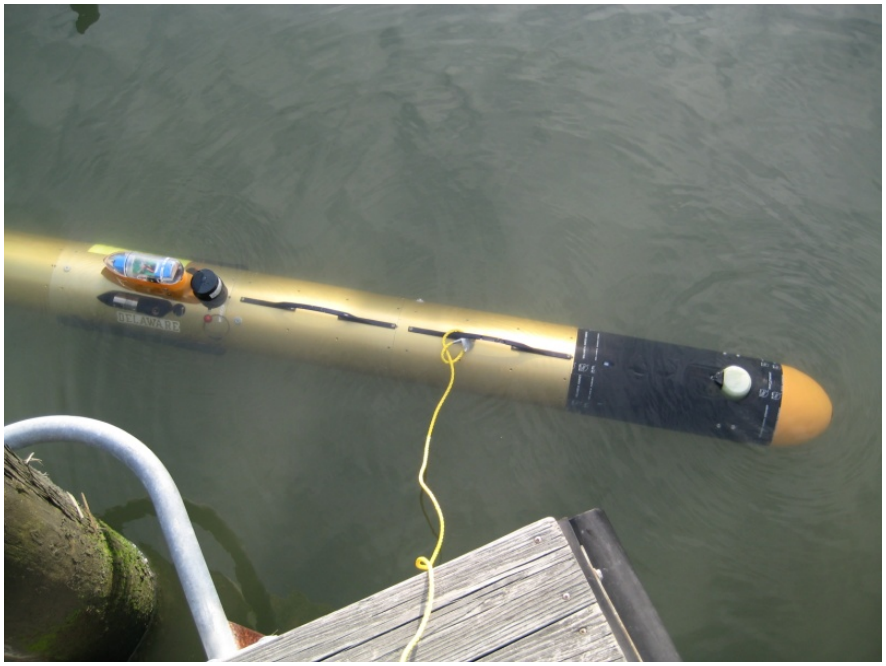


Figure 1. AUV MEC Detection System.

1.2 OBJECTIVE OF THE DEMONSTRATION

The goal of this demonstration was to validate the ability of the AUV MEC Detection System to detect individual munitions items in an underwater environment. The system was demonstrated at an underwater test plot seeded with inert munitions items. Individual objectives that were tested to achieve the goal of this demonstration included the following:

- Validate the system's ability to achieve data density, coverage, and positional accuracy requirements for underwater MEC detection.
- Verify improvement ratios between raw and compensated magnetic data to reduce electrical and dynamic interference.
- Evaluate system performance against other underwater detection systems by measuring cost, production rates, and constraints of use.

Vehicle dynamic performance objectives for bottom keeping, pitch, roll and along-line data density were achieved by the AUV MEC Detection System. Coverage and positional accuracy objectives were not met during the demonstration. Average offsets between the known and measured locations of seed items ranged between 0.7-m and 1.8-m versus the 0.5-m offset requirement. The failure was dependent upon mission design and is a function of limitations associated with mission planning software at the time of the demonstration. Offsets were less than 0.5-m where survey lines crossed seed item locations.

Considerable suppression of system noise was realized using upgraded compensation software. The most prominent magnetic distortions in the survey data correlated with vehicle pitch and heading. Post-process corrections yielded improvement ratios from 5.1 to 7.6 in the calibration grid and 11 to 12.4 in the blind grid. The system showed reliable detection of 60 millimeter (mm) mortars and larger munitions at 1.5-m altitudes and 75mm projectiles and larger munitions at altitudes over 2-m.

Daily operational costs for this demonstration totaled approximately $5,300/hectare including vehicle rental, survey data collection and data processing. A daily recurring cost of $400 was needed for instrument setup and preparation.

1.3 REGULATORY DRIVERS

Regulations for underwater military munitions are currently being evaluated. Current Defense Environmental Restoration Program (DERP) guidance classifies properties where military munitions are more than 100 yards seaward of the mean high-tide point as ineligible for the Formerly Used Defense Site (FUDS) program. No guidance exists for active DoD component Military Munitions Response Program (MMRP) sites. Proposed guidance is risk based, stating that underwater munitions at depths greater than 120 feet (ft) will be considered to have a physical constraint equivalent to a barrier that prevents direct access and to be beyond the depth of potential human exposure. In addition, Public Law 109-364, Section 314, National Defense Authorization Act, Research on Effects of Ocean Disposal of Munitions, involves the identification and evaluation of military munitions disposal sites. Technology will need to accommodate the wide range of underwater scenarios involving military munitions and support existing and developing regulatory policy.

This page left blank intentionally.

2.0 TECHNOLOGY

This section provides an overview of the AUV MEC Detection System technology that was demonstrated.

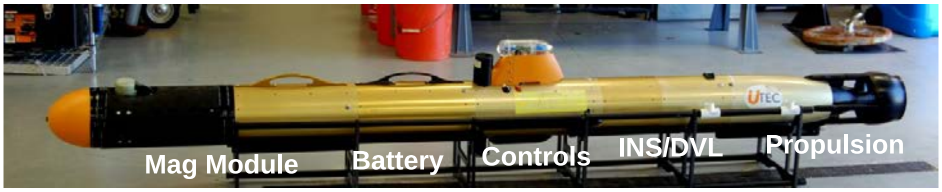
2.1 TECHNOLOGY DESCRIPTION

The AUV MEC Detection System consists of the following primary components:

- Teledyne-Gavia model autonomous underwater vehicle,
- Magnetometer module, and
- Magnetic compensation.

2.1.1 Teledyne-Gavia Model AUV

The Gavia AUV is a modular underwater robotic system that follows a pre-programmed course, collecting environmental data in situ. Missions are planned using a graphical user interface (GUI) to specify waypoints or survey lines, prescribed depths or altitudes, and desired sensor configurations. The Gavia base vehicle is a mobile sensor platform that can be user-configured on deck for a particular task or operating condition by the addition of one or more sensor, navigation, or battery modules; these items are inserted into the vehicle and locked in place with a unique twist lock system. Figure 2 presents the Gavia AUV specifications.



- Fully modular, two person portable
- 2.7 m (long), 77 kg (weight in air)
- 500 m depth rating
- INS/DVL Nav System (Kearfott T-24 SeaNAV)
- Side-scan sonar (900/1800 kHz)
- 2 mega-pixel color camera/strobe
- Geoswath phase-measuring bathy sonar (500 kHz)
- 10-20 kHz chirp sub-bottom profiler (optional)
- Wireless local area network (W-LAN), acoustic modem and satellite comms

Figure 2. Gavia AUV specifications

The Gavia AUV is navigated by a Kearfott T-24 "SEANAV" inertial navigation system (INS). While on the surface, a Wide Area Augmentation System (WAAS)-capable Global Positioning System (GPS) in the AUV's sail provides position fixes to the INS. In addition, when within range of the bottom (< 40 meters [m]), an RD Instruments 1,200 kilohertz (kHz) Workhorse Navigator Doppler velocity log (DVL) measures velocity of the vehicle over the seafloor and provides these measurements to the INS.

The Gavia AUV has a maximum depth rating of 500 m. Additional standard sensors aboard the AUV include speed-of-sound, temperature, salinity (derived), dissolved oxygen, chlorophyll-a, and turbidity, as well as a 900 kHz/1,800 kHz side-scan sonar. Other modules available to the AUV include a sub-bottom profiler, downward-looking camera with strobe, and bathymetric side-scan sonar.

2.1.2 Magnetometer Module

The magnetometer module design schematic is presented in Figure 3. The module flooded section houses the G-880AUV total field magnetometer (Figure 4). The G-880AUV is secured by the sensor clamp and supported by M6 aluminum threaded assembly support rods. The sealed pressure vessel contains the G-880AUV electronics and Applied Physics 539 fluxgate compass (fluxgate) (Figure 4). The sensors are interfaced with the magnetometer module circuitry, which is necessary to provide internal electrical power and communication with the vehicle's control system through the AUV microcontroller "rabbit board."

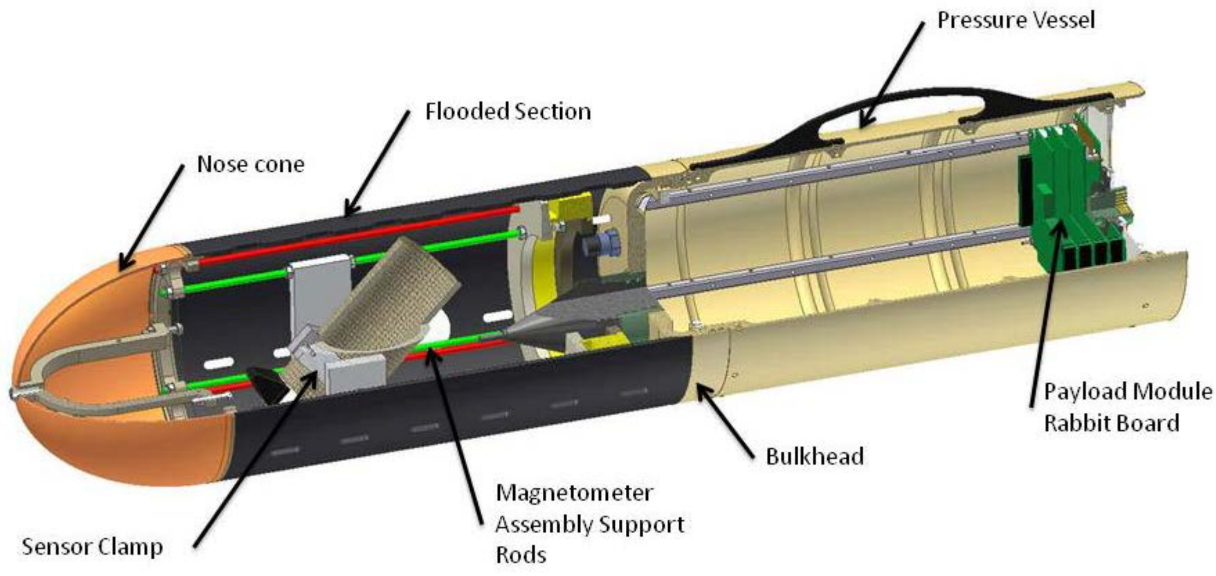


Figure 3. Magnetometer module design.

A relief slot cut in the flooded section is used to facilitate G-880AUV sensor orientation requirements (Figure 4). The relief slot permits the sensor to be rotated forward to a vertical position. The magnetometer module can be installed on the Gavia AUV using the same interlocking system as the other Gavia AUV sensor modules. Whereas endurance of the Gavia AUV is sensor module-makeup specific, tests with the magnetometer module suggest a 4-hour operational time on a single battery corresponds to approximately 22 kilometers (km) of travel. Although the AUV may operate with two batteries, this is often unnecessary. Alternatively, a second standby battery can be at the ready for swap out in the field for quick turnaround operations (approximately 20 to 30 minutes).

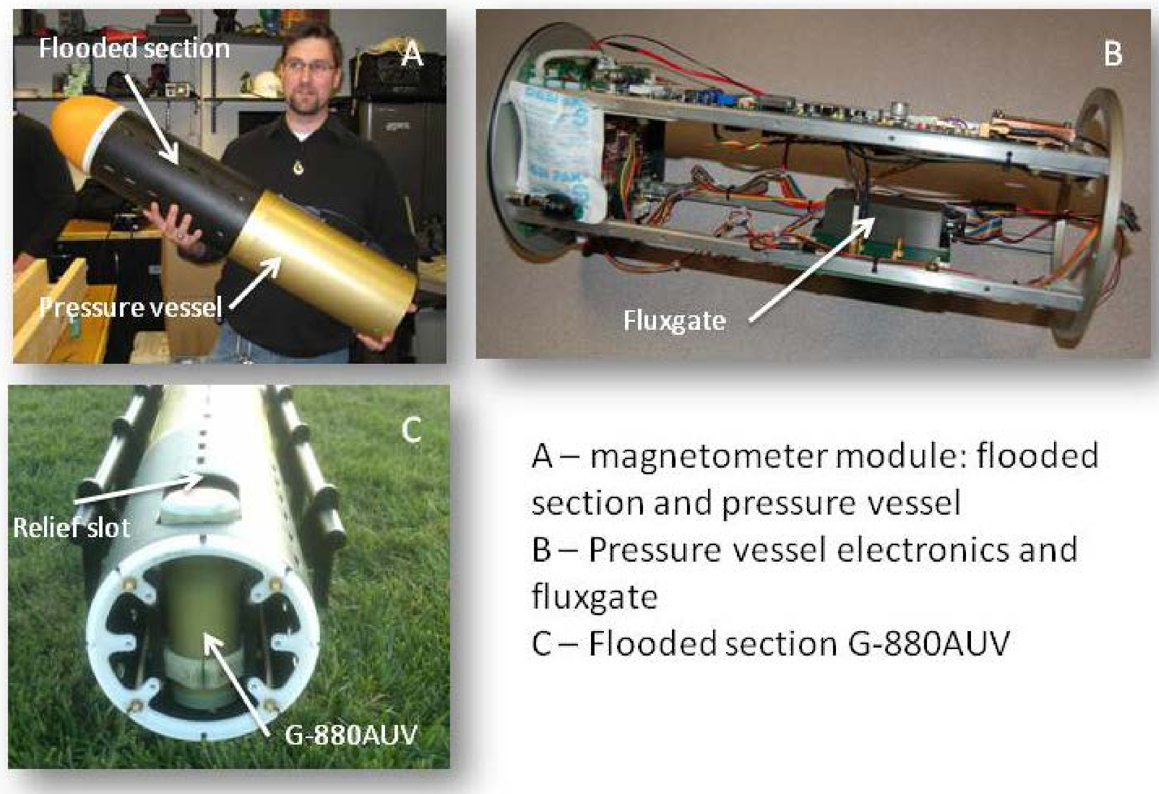


Figure 4. Magnetometer module components.

2.1.3 Magnetic Compensation

Magnetic field measurements on a moving platform are sensitive to permanent and induced field sources and to electrical currents generated on the platform. To reduce the influence of these sources on total field magnetic measurements, the method first proposed in Leliak (Leliak, 1961) is typically used for magnetic sensors mounted on an aircraft. This method addresses distortions resulting from permanent and induced magnetization of the parts of the aircraft as well as from eddy current effects from aircraft acceleration in the Earth's magnetic field. This approach has proven very successful and has been used in the airborne magnetometry industry for decades.

However, other aspects of magnetic distortion, such as magnetic fields resulting from permanent or slowly changing electrical currents, are not addressed. These sources are typically found in platforms such as AUVs. It can be shown that their influence is very similar to the permanent field effects but with variable amplitude. To enable corrections for this kind of distortion, the typical electrical currents of a platform should be recorded along with platform orientation.

Geometrics has developed software based in part on MagComp source code to accept electrical current compensation terms. During missions, the AUV can simultaneously capture current measurements, G880AUV magnetic measurements, and vehicle dynamic/orientation information from the fluxgate. Compensation coefficients can be derived and applied to the total field magnetic data to reduce the influence from magnetic field distortions caused by vehicle movement and changing electrical currents. The upgraded MagComp GUI allows the user to select the appropriate computational code, define electrical current variables, and define computational variables for the dataset. Test results using the new computational libraries demonstrate that compensation software that includes current terms can considerably improve the compensation solution. The magnetic compensation development and testing is described in more detail in Section 2.1.4.

2.1.4 Technology Development Chronology

ESTCP Project No. MR-201002 was awarded in August 2010. Magnetometer module assembly and system integration such as design, material procurement, mechanical and electrical engineering, crew member development and communications testing were completed prior to the Saint Petersburg, Florida demonstration in March 2012. The magnetometer module was also deployed at the United States Naval Academy in October 2011 and at the University of Delaware, Lewes, Delaware Campus in December 2011 for preliminary testing. Magnetic compensation software upgrades were completed concurrently with magnetometer module design and build.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Several advantages were attained as a result of the modular design, autonomous capabilities, and rapid deployment of the AUV MEC Detection System, including ease of use and application in a broad range of environments as compared to current towed array marine detection systems. This autonomous and self-contained system shows the capability to provide cost savings over current systems by reducing the mobilization/demobilization effort, requiring less manpower for operation, and reducing the need for a large surface support vessel altogether. This commercial off-the-shelf AUV MEC Detection System shows improved efficiency, safety, and cost savings compared to current systems for munitions response investigation and removal projects.

The AUV can be operated only by skilled personnel, which can be a limitation to system deployment. A clear understanding of the underwater environment and conditions is necessary to prevent system damage or loss. Additional geophysical and imaging surveys (which can be accomplished by the AUV using alternate configurations) may be necessary prior to magnetic surveys to ensure missions could be successfully planned.

3.0 PERFORMANCE OBJECTIVES

The following performance objectives are from the Demonstration Plan. They provided the basis for evaluating the performance and costs of the technology. The demonstration performance objectives and results are listed in Table 1. The performance objectives and results are further discussed in Section 7, Performance Assessment.

Table 1. Performance objectives.

Performance Objective	Metric	Data Required	Success Criteria	Results
Quantitative Performance Objectives – Vehicle Dynamics				
Depth keeping and height above bottom are maintained for terrain-following surveys	Standard deviation of requested depth or height above bottom	AUV Navigator and INS/DVL logs with depth and altimetry	$\sigma \leq 0.25$ m	Pass: $\sigma \leq 0.25$ m
Vehicle roll is constant	Maximum expected roll from typical 5 degree (°) ballast	AUV Navigator and INS/DVL logs with roll	± 10°	Pass: within ± 10°range
Vehicle pitch is maintained	Maximum expected pitch	AUV Navigator and INS/DVL logs with pitch	± 10°	Pass: within ± 10°range
Quantitative Performance Objectives – Survey Specifications				
Along-line measurement spacing	Point-to-point measurement separation provides adequate data density on targets of interest	• Magnetic measurement locations from dynamic surveys • AUV Navigator and INS/DVL logs with positioning information • Separation of data points along-line for WAA surveys • Separation of data points per dataset for areas intended for full coverage surveys	95% of point-to-point measurements are ≤ 0.25 m for areas intended to achieve full coverage or as required to ensure detection of intended areas of interest for WAA surveys	Pass: 95% of measurements ≤ 0.25 m
Survey coverage	Separation of survey lines provides adequate data density on targets of interest	• Magnetic measurement locations from dynamic surveys • AUV Navigator and INS/DVL logs with positioning information • Spatial analysis of gridded data	95% of the survey coverage is ≤ 1.00 m for areas intended to achieve full coverage or as required to ensure detection of intended areas of interest for WAA surveys	Fail: Survey lines had a separation > 1.00 m. Due to a limitation in the mission planning software, the minimum transect spacing that could be programmed into the vehicle mission file was approximately 1.7 m. As a result of this limitation, line spacing ranged from 1.5 m to 2.6 m.

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Required	Success Criteria	Results
Measurements are positioned accurately	Average error and standard deviation in northing and easting for seed items	• Locations of seed items within the verification strip for wide area assessment surveys and for surveys intended to achieve full coverage • Locations of seed items in production areas intended for full coverage surveys • Magnetic measurements from dynamic surveys • AUV Navigator and INS/DVL logs with positioning information • Target locations for selected anomalies along verification strip • Target locations/dig list for full coverage surveys	)N and)E ≤ 0.50 m)N and)E ≤ 1.00 m	Fail: 18% of detected seed items had a)N and)E ≤ 0.50 m. Fail: 60% of detected seed items had a)N and)E ≤ 1.00 m. The average)N was 0.42 m, and the)E was 0.61 m.
Acquire site-specific calibration coefficients for magnetic compensation	Variation between point-to-point magnetic measurements	• Vehicle orientations • Electrical current • Magnetic measurements captured during testing • AUV Navigator and INS/DVL logs with vehicle altitude • Mag module compass log	≤ 0.5 nT	Pass: Point to point magnetic measurements in background areas were ≤ 0.5 nT
Noise reduction performance using magnetic compensation	Improvement ratio between raw and compensated data	• Raw magnetic measurements from dynamic surveys • Maneuver and electrical current coefficients	Improvement ratio ≥ 5	Pass: Improvement Ratios ranged from 5.1 to 12.3 across missions
Detection of all seed items	Percent detected of seed items	• Locations of seed items within the verification strip for WAA surveys and for surveys intended to achieve full coverage • Locations of seed items in production areas intended for full coverage surveys • Target locations/dig list for full coverage surveys	Detect all seed items placed in the verification strip and full coverage survey areas with an offset of ≤ 1.0 m (0.5 m + ½ of the line spacing)	Fail: 25% of seed items traversed in the calibration grid were detected with an offset ≤1.0 m; 65% of the seed items traversed were detected with an average offset of 1.4 m

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Required	Success Criteria	Results
Qualitative Performance Objectives				
Mission planning	Vehicle and team prepared to execute survey following mobilization	Mission plan XML files	Survey plans and logistics are complete prior to mobilization	Pass: Survey plans and logistics were complete prior to mobilization
System performance	Efficient and effective deployment	• Observe and log daily preparatory steps • Observe and log issues with mission • Observe and log battery changes and data downloads	Information required to assess system performance is logged in detail accurate to 15 minutes	Pass: Information required to assess system performance was logged in detail
Completeness of dataset	Record integrated data streams from system components for analysis	• Magnetic measurements • Navigational information • System dynamics (roll, pitch, yaw) • Electrical current • Navigator logs, INS/DVL logs, Mag Module logs	All data streams have been captured by the primary crew member	Pass: All data streams were captured
Cost	Actual survey costs	• Logistics and preparation • Mobilization • Deployment and support details • Demobilization • Data analysis and dig list development	Costs are detailed by task and easily comparable to system performance and production rate evaluations	Pass: Costs are detailed by task
Production rate	Number of acres of data collection per day	Log of field work	Field log is detailed and accurate to 15 minutes	Pass: Field log is detailed and accurate to 15 minutes

Notes:
nT = nanotesla
WAA = wide area assessment
XML = extensible markup language

This page left blank intentionally.

4.0 SITE DESCRIPTION

The demonstration was conducted in Tampa Bay near St. Petersburg, Florida (Figure 5). Facilities operated by SRI International (SRI) were used for preparation, staging, and deployment of the system during the demonstration. The research vessel SeaSub II (Figure 6) was used to deploy the AUV at the grid locations.

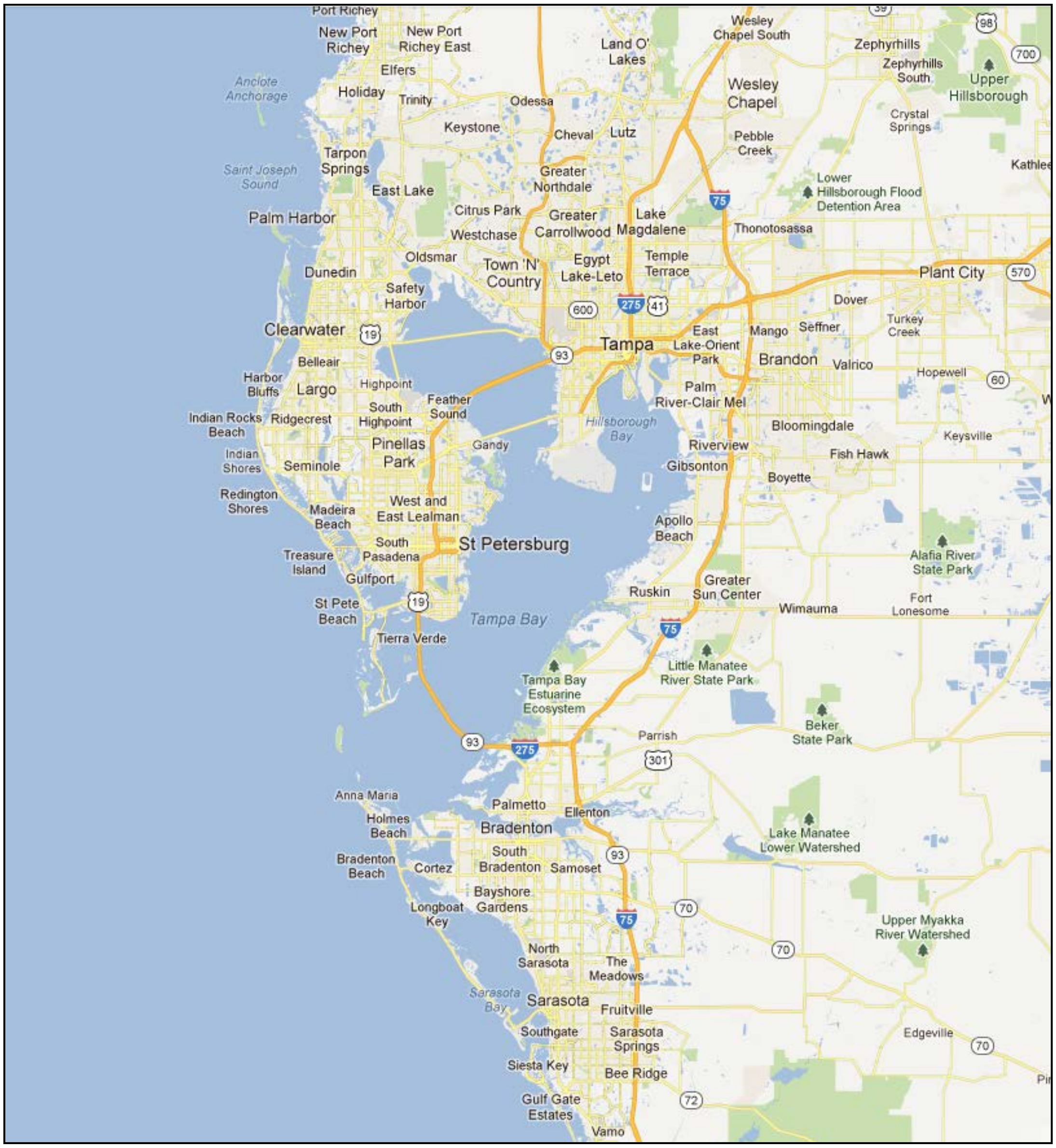


Figure 5. Regional location map of demonstration site.

Figure 6. SeaSub II support vessel.

4.1 SITE SELECTION

The test grids were placed about 3 miles from the SRI dock in water approximately 30 ft deep (Figure 7).The grids were located in a flat mud bottom area operated by SRI. Available high-resolution multi-beam and sonar surveys of this area were reviewed prior to site selection and showed that no clutter was visible. This same location was used previously for a Naval Surface Warfare Center Panama City Division Remote Environmental Monitoring Unit Series AUV field study of munitions targets and thus selected for this demonstration (Dr. M. Richardson, personal communication).

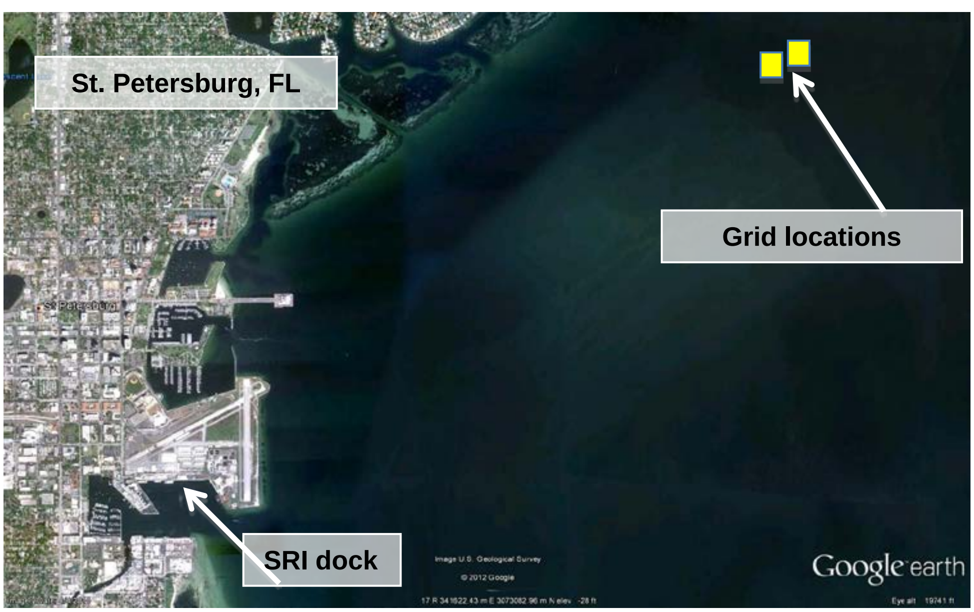


Figure 7. Demonstration location.

4.2 SITE HISTORY

Tampa Bay is a primary shipping route. It is routinely dredged to keep navigation channels open for cargo carrying vessels. Many of the near shore areas are protected from marine traffic to preserve habitat.

4.3 SITE GEOLOGY

The Tampa Bay region is dominated by carbonate deposition. Overlying the limestone is a veneer of unconsolidated sediment composed of a mixture of carbonates and siliciclastics, with a minor amount of phosphatic material. The regional geology and depositional history suggest minimal amounts of ferrous material.

4.4 MUNITIONS CONTAMINATION

No historical munitions-related activities have occurred at this site. A seeding program was implemented as part of this demonstration.

This page left blank intentionally.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The conceptual experimental design included the construction of two separate underwater test plots each seeded with inert munitions items ranging from 60mm mortars to 155mm projectiles. One test plot was used as a calibration grid, and the seed item types and locations were made available to the project team. The second test plot was used as a blind evaluation grid, and the seed item types and locations were not made available until after the magnetic data analysis had been completed.

Each test plot was surveyed with the AUV MEC Detection System at various altitudes and directions using parallel line spacing. Magnetic data analysis was performed to determine the system's geolocation accuracy by comparing the measured and actual seed item locations. Each survey was reviewed against the quantitative and qualitative performance objectives listed in Table 1.

5.2 SITE PREPARATION

Two underwater test plots, including a calibration grid and blind evaluation grid, were emplaced at the demonstration site. The footprint for the test plots was approximately 100 m by 100 m. The calibration grid was seeded with 24 inert munitions items and the blind evaluation grid was seeded with 23 inert munitions items. Seed items were separated by a minimum of 5 m to avoid overlapping signals. Water depths ranged from 30 to 36 ft.

Only a portion of each grid was surveyed during the demonstration due to time constraints, and as a result, not all seed items fell within the survey area footprint. Seed type, location, unique identification (ID), and survey coverage of each grid are presented in Figure 8.

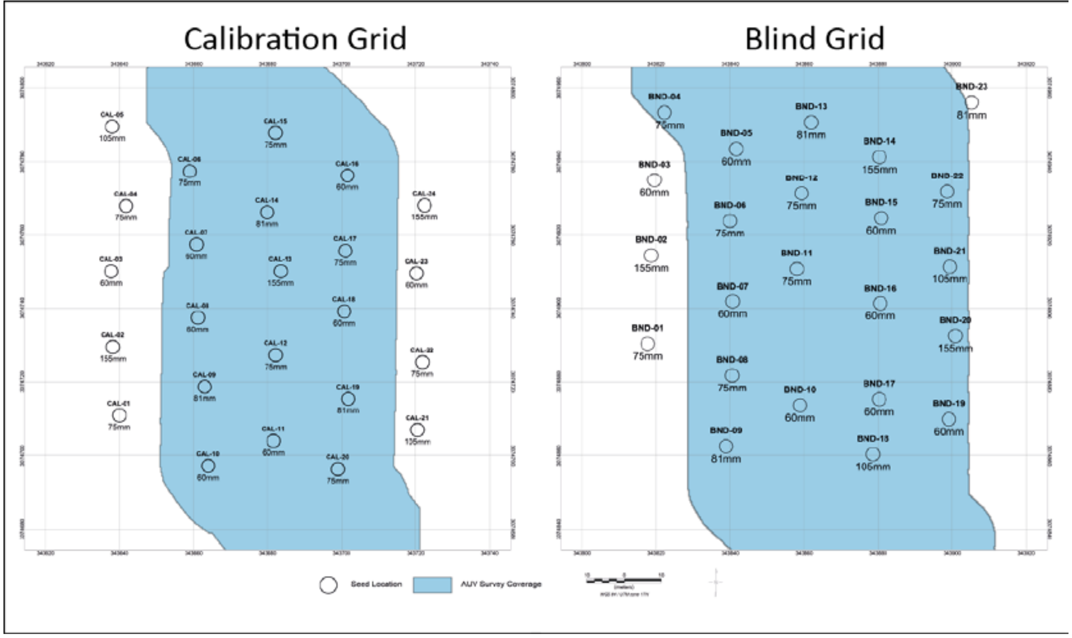


Figure 8. Test plot schematic and survey footprint for each grid.

The seeds were placed proud on the surface using frames as shown in Figure 9. A 6-inch-diameter Styrofoam crab float with pop-up link and recovery line was attached to each frame. The final location of the seed items was confirmed using a site-calibrated 1.35-megahertz (MHz) MB sonar system deployed by the research vessel *GH Gilbert*. The location of each seed item was surveyed to decimeter-level horizontal accuracy.

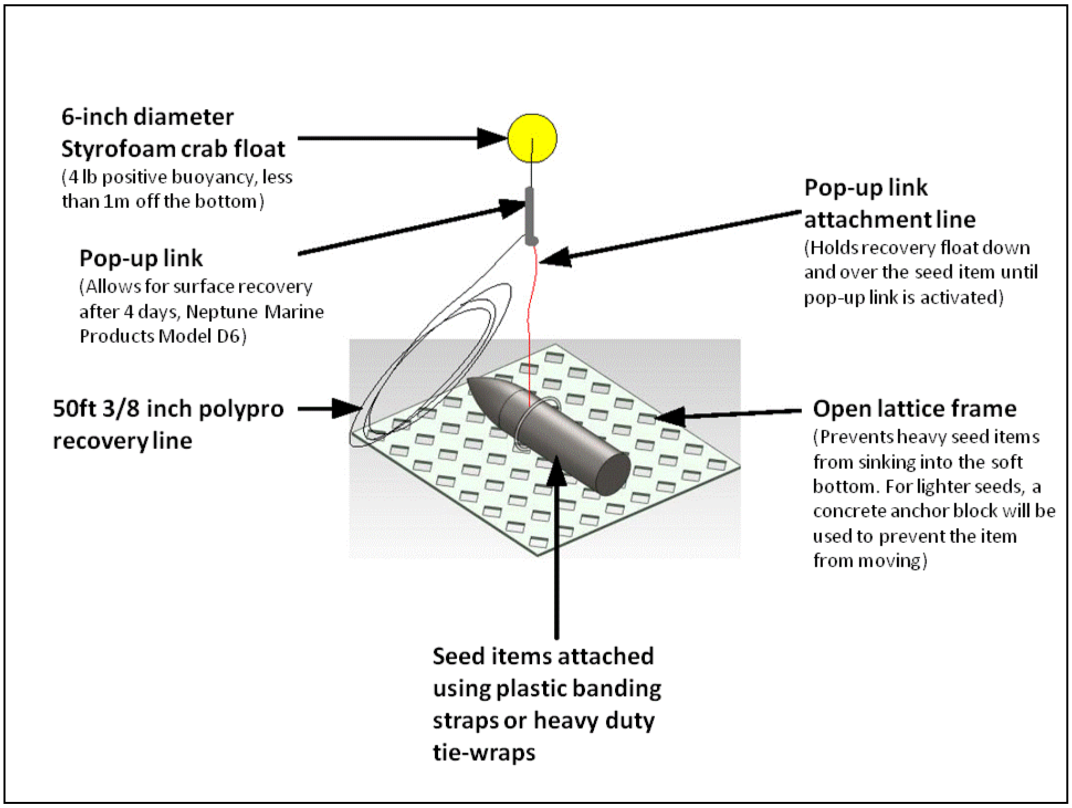


Figure 9. Seed item deployment and recovery system.

Seed item type and location for the calibration grid was provided to the project team by SRI. The seed item type and location for the blind evaluation grid was held by SRI until the demonstration data were analyzed.

5.3 SYSTEM SPECIFICATION

The AUV MEC Detection System was described in Section 2. Applicable system component sampling rates are described in the following sections. A sensor summary with corresponding sampling frequencies is provided in Table 2.

Table 2. Sensor sampling frequencies.

Sensor	Sampling Frequency (Hz)	Spacing (cm) @ survey speed (1.5 m/s)
G-880AUV	10	15
Fluxgate	15	10
Temperature	1	150
Salinity	1	150
Camera	4	37.5
Swath Bathy	15	10

Notes:
cm = centimeter
Hz = Hertz
m/s = meters per second

5.3.1 Total Field Magnetometer

The Geometrics style G-880AUV cesium vapor magnetometer is internally integrated within the magnetometer module and is powered through the vehicle control system. Magnetic measurements are sampled at 10 Hz.

5.3.2 Fluxgate Compass

Located in the magnetometer module pressure vessel, the fluxgate compass measures vehicle pitch, roll, and yaw at 15 Hz. Orientation information is evaluated against the AUVs INS and subsequently used in the compensation solution.

5.3.3 Positioning

The AUV positioning systems, including the INS and GPS, are nominally logged at 1 Hz. The AUV is equipped with a satellite-based augmentation system (SBAS)/WAAS-capable GPS to navigate on the surface and to remove biases from the INS solution. This GPS has a positional uncertainty of 3 m with 95% circular error probability (CEP). CEP of 3 m at 95% means that there is a 95% probability that the AUV lies inside a circle with a radius of 3 m. When submerged, the AUV navigates with a Kearfott T-24 INS with an integrated DVL. The published drift rate for the INS with an integrated DVL during submerged operation is 0.1% of distance traveled, indicating that the INS solution would likely drift beyond the positioning accuracy limit after 500 m.

5.3.4 Current

A dedicated artificial intelligence crew (AIC) member assigned to the battery module maintains a log of the current load and voltage being supplied by the battery to the vehicle at a nominal logging rate of 1 Hz.

5.4 DATA COLLECTION PROCEDURES

Surveys were performed at the blind evaluation grid. The blind evaluation grid was constructed as described in Section 5.2 using inert munitions items. Type and location information for the seeds was held by SRI and was not provided to the project team until the magnetic data were analyzed and interpreted.

5.4.1 Scale

The blind evaluation grid area was approximately 100 m by 100 m. A total of 24 blind seeds were placed within the grid area. Multiple missions were conducted to develop a robust dataset.

5.4.2 Sample Density

Multiple missions were performed at the blind evaluation grid. Each mission was set at a constant altitude above bottom. The first mission was set at 3-m altitude and subsequent missions were at 2 m and 1.5 m above bottom. The higher altitude missions (3 m and 2 m above bottom) were used to develop sonar image mosaics to identify abrupt changes in bed topography or obstructions that may require changes in mission planning for lower altitude surveys (2 m and 1.5 m).

The blind evaluation grid was traversed at a 2-m line spacing for each mission. The AUV was set to travel along-line at 1.5 m/s, equating to a magnetic measurement every 14.5 cm. The along-line sample density performance objective is 0.25 m (standard deviation). Each planned mission altitude of operation (i.e., 3 m, 2 m, and 1.5 m) is within DVL lock range, reducing variation in positional accuracy.

The performance objectives listed in Table 1 were analyzed separately for each of the three missions planned at 3 m, 2 m, and 1.5 m above bottom. Performance objective success criteria for all objectives in Table 1 were only applied to the 2 m and 1.5 m altitude missions. Although performance objectives associated with data density and coverage are achievable with the 3-m altitude mission, objectives associated with seed item detectability are likely near or beyond the limit of what is possible at this altitude.

5.4.3 Quality Checks

System operation is monitored through the W-LAN and wired local area network (LAN) network connection prior to mission deployment. The functionality of each sensor and reading stability is verified prior to submerging the AUV. Magnetic data are gathered statically and transferred to MagLogNT for evaluation of sensitivity and signal.

5.4.4 Data Summary

Several calibration and pre-survey activities were performed prior to demonstrating the AUV MEC Detection System at the blind evaluation grid discussed above.

5.4.4.1 Compensation Coefficient Development

The first set of missions planned for the demonstration was to establish compensation coefficients to reduce the effects of the vehicle's magnetic properties on the G-880AUV. These coefficients are attitude dependent and, therefore, must be established in a low magnetic field gradient area with orientations of the vehicle similar to that experienced during the survey. Boxshaped missions were conducted over 100-m to 300-m segments at constant and varying altitudes to introduce heading, pitch and roll to the magnetic data. Vehicle orientation (heading, pitch, and roll) from the fluxgate compass and the total field magnetometer measurements are required for processing into the MagComp compensation software.

5.4.4.2 Data Logging Latencies

A single seed item from the calibration grid was chosen for a set of trials to measure any data logging latencies. Any constant data logging latency resulted in a shift of the signal when plotted as a function of distance from a known point. The AUV was run in repeated reciprocal lines over a high amplitude anomaly (large seed item). Based on the test results, a time bias was calculated for correcting magnetic measurements such that reciprocal anomalies align. This time bias can then be used for correcting subsequent data.

5.4.4.3 Calibration Grid Missions

The AUV MEC Detection System traversed the 100-m by 100-m grid using a 2-m-lateral-line spacing. Survey speed was set to achieve an along-line magnetic measurement spacing of less than or equal to 0.25 m. The calibration grid was surveyed three times, each with a different constant altitude. The first survey was performed at a constant 3-m altitude. Subsequent surveys were completed at 2-m and 1.5-m altitudes, respectively. Magnetic measurements, geolocation, orientation (pitch, roll, heading), and current were logged concurrently during the mission. Results from the calibration grid were used to further optimize mission parameters. Lessons developed from the calibration grid were applied to the subsequent demonstration at the blind evaluation grid.

This page left blank intentionally.

6.0 DATA ANALYSIS AND PRODUCTS

6.1 PREPROCESSING

At the end of each survey day, the raw geophysical field data were downloaded from the AUV. The mission data in XYZ format were imported into a Geosoft® Oasis montaj database for further processing. Quality control on the data was also performed within Oasis montaj. As part of the data validation process, any data corresponding to a magnetometer sensor dropout or spike were removed from the dataset or dummied with a null value. Diurnal variations in the total field magnetic data were corrected through the use of magnetic base station data collected near the survey site, if possible, or else through a separate data leveling process involving a non-linear drift correction.

After the initial data import had been performed, latency corrections were applied using the values calculated from the data logging latencies and repeatability mission. The total field magnetic data were gridded using the minimum curvature gridding method. The analytic signal was calculated from the total field magnetic data and gridded using the same minimum curvature method.

Background noise levels were calculated from survey data using the statistics (UCENOISEST.GX) and subwindow statistics (UCEWINDOWSTATS.GX).

Quality control metrics, including velocity and sample separation, were calculated at each sample point. Distance between sample points (meters) and velocity (miles per hour) were calculated using the velocity calculation Geosoft Executable (GX) (UCEVELOCITY.GX). This GX populates a database channel with the distance between each sample (sample separation) and the reported velocity at each sample. Line spacing was analyzed for each dataset using a scripted routine that spatially analyzes the gridded data and flags areas in which line spacing exceeds the line separation metric detailed in Section 3. These metrics were analyzed to ensure data requirements were being met.

6.2 TARGET SELECTION FOR DETECTION

The gridded total field and analytic signal data collected at the test plot were used for target selection. Analytic signal (AS) target selection was performed using the Blakely peak algorithm (UXPARSE.GX). Magnetic dipole selection was performed using the magnetic dipole selection GX (UCEPEAKDIPOLES.GX). Initial target picking thresholds were calculated as 2.5x the standard deviation of the background noise level as determined by the subwindow statistics GX.

Targets were further analyzed by calculating size, signal strength, and signal-to-noise ratio of each target using the SNR/Size tool (UCEANALYSETARGET.GX). Target easting and northing locations were compared to the actual seed item locations by calculating offset distance and direction using a WESTON-developed GX (COITARGET.GX); the locations of all anomalies within a specified radius of a seed item are then compared to the location of the seed item. The GX generates a merged target database detailing the seed ID, seed location, unique target ID, target location, offset distance, offset direction, and target response.

Target characteristics (response, target size) calculated from the test plot data were compared to characteristics of similar items as measured from previous geophysical investigations or predicted values measured from response curves to determine whether the system is performing properly.

A final target database and geophysical anomaly map was generated that will detail target detection performance and measured target characteristics.

6.3 DATA PRODUCTS

The Gavia AUV records location and actions as well as measurements from all of the onboard sensors. Each system sensor is commanded by a unique AIC that creates an extensible markup language (XML) log file with a common time stamp allowing for integration and comparison to other vehicle sensor information. Data samples include field intensity, sensor amplitude, and orientation measurements. Field-intensity is the magnetic field intensity sensed by the G-880AUV magnetometer. Data are transferred from the AUV to the control computer through the wireless and wired LAN network connection for each mission. The common time sync basis between the AUV attitude sensors (INS) and the magnetometer allowed the team to perform an interpolation between the vehicle attitude and the magnetometer measurements. The contoured analytic signal data collected during the 1.5-m altitude mission one survey at the Blind Grid is presented in Figure 10.

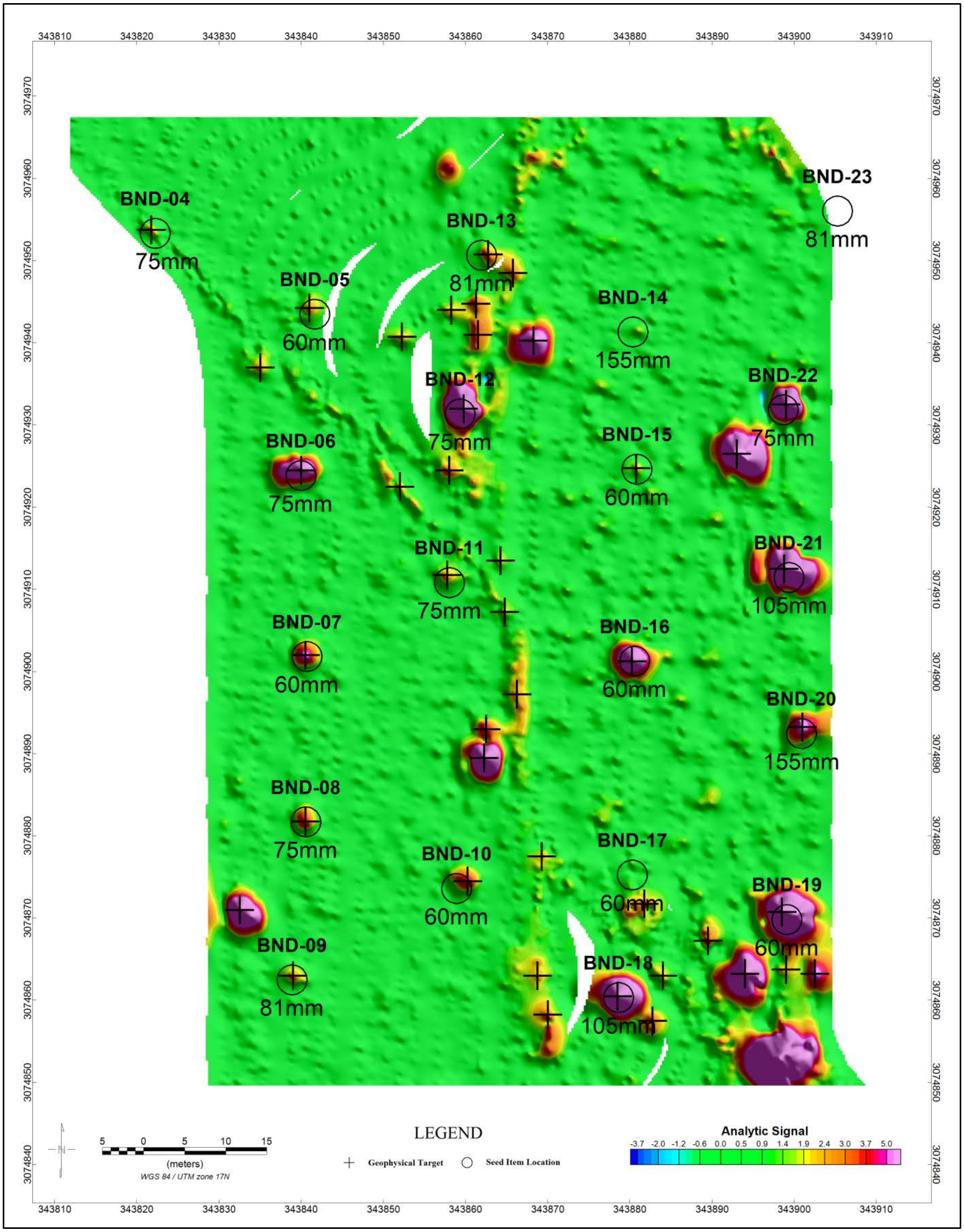


Figure 10. Mission 1 contoured analytic signal data collected at the blind grid survey area at an altitude of 1.5 m.

This page left blank intentionally.

7.0 PERFORMANCE ASSESSMENT

7.1 MAINTAIN A CONSTANT HEIGHT ABOVE BOTTOM

The altitude of the AUV is monitored by the on board DVL, which allows the AUV to adjust its position in real time to maintain a consistent height above the seafloor. Analysis of the altitude data captured during both calibration and blind grid surveys showed slight variations in altitude from what was specified in the mission plans uploaded to the AUV. The performance objective is met if the vehicle operates with excursions less than or equal to a standard deviation of 0.25 m when operating over a flat seafloor. Typical variations in altitude did not exceed 0.21 m standard deviations within the grid survey area.

Because the sensor response falls off at the inverse of the cubed distance between the magnetometer and a metallic object, it is important to maintain a constant height above the seafloor and to stay as close as possible to targets of interest. Variations in altitude above the seafloor due to abrupt changes in the terrain can have a direct effect on the detectability of an item. Items positioned flush with the seafloor or within low spots in the terrain where the terrain-following mode of the AUV cannot adequately compensate for them will be further from the sensor resulting in a lower response amplitude. It is possible that an item would be undetected if it was positioned in a deep enough depression.

7.2 OBJECTIVE: MAINTAIN CONSTANT PITCH AND ROLL

The AUV stores pitch and roll data to internal log files throughout the duration of the survey. The data are used as part of the INS solution for vehicle navigation and can be used in post-mission magnetic compensation or as a means of comparison to the onboard fluxgate magnetometer.

Logged pitch and roll values observed during grid surveys were all within the quantitative performance objective of +/- 10° during both straight-line navigation and turn-around maneuvers. However, consistent variations in roll values were observed between straight-line navigation data and data in which the vehicle was performing turn-around maneuvers. Roll angles in straight-line navigation were typically within +/-2° of zero, whereas turn-around maneuvers could exhibit roll angles of up to +/-6°, but still well within the optimal sensor orientation of the on-board magnetometer.

AUV pitch and roll values for a typical traverse are plotted together in Figure 11. Fluctuations in pitch angles are most likely due to the AUV compensating for uneven seafloor terrain. Consistent variations in roll values are observed between straight-line navigation and turn-around maneuvers because of the slight banking involved during the turns; however, pitch does not vary greatly between straight-line and turn-around navigation.

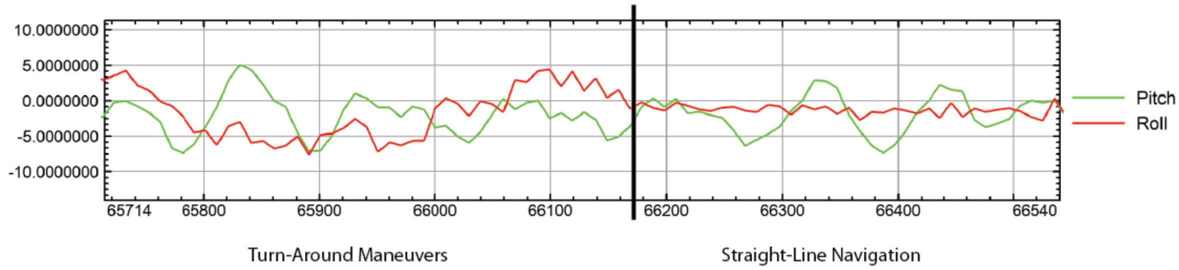


Figure 11. AUV pitch and roll along a single traverse.

7.3 OBJECTIVE: ALONG-LINE MEASUREMENT SPACING

Along-line measurement spacing for the Gavia AUV is a function of the velocity of the vehicle combined with the 10-Hz sampling frequency of the onboard magnetometer. The target velocity at which the AUV will traverse the survey area is programmed into the mission file. Each onboard sensor samples at a fixed frequency, thus the programmed mission velocity directly determines what the approximate sample separation for each onboard sensor will be.

Slight fluctuations in velocity were observed throughout the surveys; however, they occurred primarily during turn-around maneuvers. Mean velocities were consistent across all of the test grid surveys, and velocities observed during straight-line navigation were generally uniform across the traverses. Figure 12 is a velocity profile comprising two traverses across a test grid area. Velocities during straight-line navigation portions ranged between 1.48 and 1.56 m/sec during both traverses, whereas the velocities during the turn-around maneuvers varied between 1.32 and 1.54 m/sec, depending on where in the turn the vehicle was positioned.

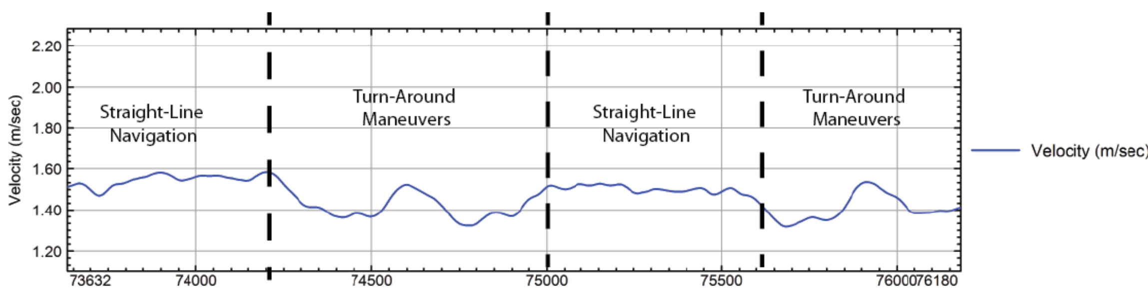


Figure 12. Velocity profile of a typical AUV survey area traversal.

This performance objective is met when 95% of the mean along-track data spacing is less than or equal to 0.25 m. Mean sample separation for the onboard magnetometer was 0.15 m for all missions.

7.4 OBJECTIVE: SURVEY COVERAGE

Missions were designed to survey the test plots using a sliding box pattern to achieve full coverage across the seeded areas. This sliding box pattern has the advantage of limited amounts of survey overlap to ensure that no lines are directly repeated during the survey. To achieve full coverage in a bounded survey area, excess data must be surveyed outside the designated survey area.

The success criteria for this objective is that 95% of the across line spacing is less than or equal to 1.0 m. The mission planning software limits the minimum transect spacing that can be programmed into the vehicle mission file to approximately 1.7 m, and the line spacing range is limited to between 1.5 and 2.6 meters. The variation in line spacing observed was due to vehicle navigation drift occurring around turns when the vehicle was attempting to line itself up with the planned straight-line traverse. Due to the limitations of the mission planning software, this performance objective was not met.

7.5 OBJECTIVE: MEASUREMENTS ARE POSITIONED ACCURATELY

The metric for this performance objective is based on the average error and standard deviation of the known location of seeded targets of interest compared to the location measured through analysis of the magnetic data collected by the AUV. Success criteria for this objective is a positional error (offset) of less than 0.5 m, with a standard deviation (Distance Root Mean Squared [DRMS]) of less than or equal to 1.0 m. A summary of the detection results is provided in Table 3. Detection percentages are calculated based on the number of seed items within the survey footprint of each mission.

Table 3. Summary of seed detection results for calibration and blind grids.

	Calibration Grid		Blind Grid				
	Mission 1	Mission 2	Mission 1	Mission 2	Mission 3	Mission 4	Mission 5
Overall Detection %	71%	64%	89%	74%	50%	42%	58%
% Offset < 0.5	20%	33%	29%	14%	0%	0%	9%
% Offset < 2.0	90%	100%	100%	64%	50%	88%	82%
% DRMS < 1.0	30%	44%	47%	14%	0%	0%	27%
% DRMS < 2.0	90%	100%	94%	29%	50%	50%	55%

Notes:
% = percent

Overall detection percentages ranged from 42% to 89%. The measured locations of the detected seed items rarely met the success criteria of 0.5-m offset (1-m standard deviation/DRMS) due to the wide transect separation used during the grid surveys, which was a result of limitations in the mission planning software. However, the majority of seed items detected had a recorded offset of less than 2 m, which is less than the average transect spacing observed during the surveys.

7.6 OBJECTIVE: ACQUIRE SITE-SPECIFIC CALIBRATION COEFFICIENTS FOR MAGNETIC COMPENSATION

Uncompensated maneuver sample-to-sample noise tends to be approximately 3 nT as shown in Figure 13. The performance objective is met if point-to-point magnetic measurements are less than or equal to 0.5 nT during compensation coefficient development. Compensated data sample-to-sample noise is approximately 0.5 nT. Sample-to-sample noise analysis was performed at a location where no magnetic anomalies were apparent.

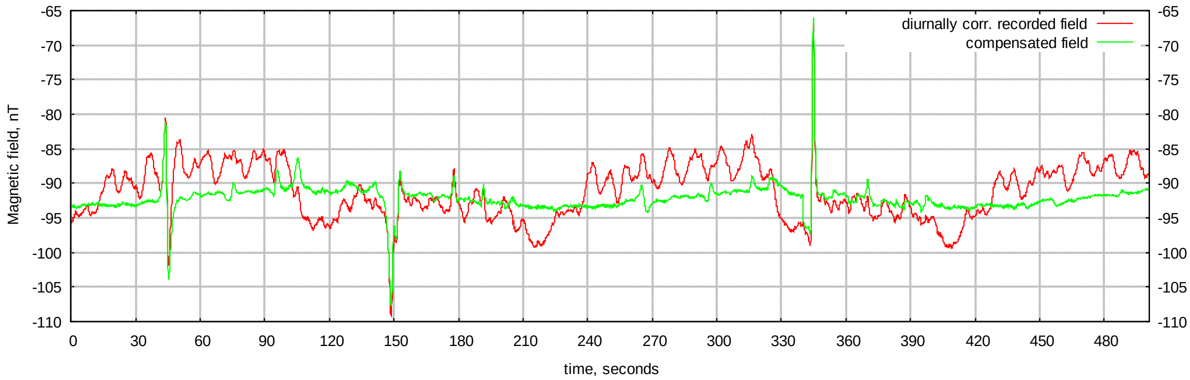


Figure 13. Example production survey compensation results.

7.7 OBJECTIVE: NOISE REDUCTION PERFORMANCE USING MAGNETIC COMPENSATION

The performance objective is considered met if an overall improvement ratio (IR) of greater than or equal to five is observed following compensation corrections for orientation and electrical current. IRs for data collected on March 28 2012 ranged from 5.1 to 7.6 when all terms were used. IRs for data collected on March 29 2012 ranged from 11 to 12.4 when all terms were used. As a result of unexpected changes in magnetic characteristics from changing or recharging batteries, it was necessary to gather a set of compensation coefficients for each mission. The best results were achieved when all survey data were used to generate the compensation coefficients. However, survey data cannot always be used to generate compensation coefficients because this technique requires a relatively uniform magnetic field in the survey area, as was the case in the demonstration area.

Current compensation was more difficult than preliminary testing because the effect on the measured magnetic field was generally less than 0.5 nT for short-term current changes. Some empirically-determined testing with survey data indicated that there is a real effect on compensation as the battery charge state varies during a mission. Results of experimenting with current terms indicate it may be possible to generate a single compensation calibration set for each battery and apply current terms to achieve long-term stability of compensation calibration coefficients.

7.8 OBJECTIVE: DETECTION OF ALL SEEDED ITEMS

Grid surveys were performed over 2 days (March 28 and 29, 2012) during the demonstration. On the first day, two surveys were performed over the seeded calibration grid where the seed locations and types were known. On the second day, five surveys were performed over the blind seeded survey grid where the seed locations and types were blind (unknown) to the survey crew. Only seed items traversed as part of the demonstration were included in the performance objective assessment.

The performance objective is considered met if all detectable seeds are identified and are accurately selected in the total field magnetic data. The AUV MEC Detection System showed reliable detection of 60mm mortars and larger munitions at 1.5-m altitudes and 75mm projectiles and larger munitions at altitudes over 2 m; however, not all seed items were detected during each mission. Line spacing limitations due to mission planning software was one of the major contributing factors to seed item detection. Where large horizontal and vertical (altitude) offsets from seed items were encountered, the detection capability of the system decreased. In instances where offsets were less than 1 m from actual seed item locations, detection capability of the system increased.

The grid surveys, corresponding mission numbers, and seed item detection results are summarized in Table 4.

Table 4. AUV mission descriptions.

Calibration Grid

	Survey Date	Survey Design	Altitude	Survey Direction	Targets Traversed	Targets Detected
Mission 3	3/28/2012	Sliding Box	2 m	N-S	14	10
Mission 4	3/28/2012	Sliding Box	2 m	N-S	15	9

Blind Grid

	Survey Date	Survey Design	Altitude	Survey Direction	Targets Traversed	Targets Detected
Mission 1	3/29/2012	Sliding Box	1.5 m	N-S	19	17
Mission 2	3/29/2012	Sliding Box	1.5 m	N-S	19	14
Mission 3	3/29/2012	Lawnmower	3 m	N-S	4	2
Mission 4	3/29/2012	Sliding Box	2 m	N-S	18	8
Mission 5	3/29/2012	Sliding Box	2 m	N-S	18	11

Notes: N-S = north-south

This page left blank intentionally.

8.0 COST ASSESSMENT

8.1 COST MODEL

The cost model for this demonstration is based upon site preparation, mobilization and demobilization, and survey production costs. Cost elements and the data that were captured during the AUV MEC Detection System demonstration are listed in Table 5. These elements were used to support the development of a technology cost model.

Table 5. Cost model for the AUV MEC Detection System.

Cost Element	Data Tracked	Estimated Cost
Instrument cost	Component and integration costs: • Engineering estimates based on current development • Lifetime estimate • Consumables and repairs	Capital purchases and magnetometer integration: $180,000 Noise reduction and compensation optimization: $120,000
Mobilization and demobilization	Cost to mobilize/demobilize to/from site: • Derived from demonstration costs	$13,000
Site preparation	Test plot emplacement: • Seed item preparation • Seed item deployment	$40,000
Instrument setup costs	Unit: $ cost to set up and calibrate Data requirements: • Hours required • Personnel required • Frequency required	Initial: $22,000 (2 days, 3 personnel, one time) Reoccurring: $400 (1 hr, 3 personnel, daily)
Survey costs	Unit: $ cost per hectare Data requirements: • Hours per hectare • Personnel required	$4,500 (3.5 hrs, 3 personnel)
Detection data processing costs	Unit: $ per hectare as function of anomaly density Data Requirements: • Time required • Personnel required	$800 (3.5 hrs, 2 personnel)

8.2 COST DRIVERS

The primary cost drivers for the AUV MEC Detection System demonstration are the labor costs associated with the survey, the mobilization and demobilization costs, and the site preparation costs. Site preparation includes the preparation of seed items and the actual deployment of seed items. Seed item deployment costs include vessel support costs, geolocation surveys, and processing and analysis costs totaling $40,000. Initial surveys were needed to develop compensation coefficients prior to production surveys as well as research vessel preparation ($22,000). Reoccurring costs were realized during deployment to the sites and performing operational checklists ($400/day). Mobilization and demobilization were directly derived from the demonstration and totaled $13,000. The magnetometer module and vehicle are easily shippable to and from the site location limiting fluctuation in mobilization and demobilization costs. Daily costs are also significantly driven by the rental of vessel support charters and accompanying crew.

8.3 COST BENEFIT

The AUV MEC Detection System is an alternative to marine geophysical systems that are typically cable-towed or tethered to a surface vessel and, thus, limited in the areas where they can perform surveys due to water depth, surface vessel access, or underwater obstacles that may be difficult to navigate from the surface.

System purchase, system setup, and daily survey costs were compared to two other mapping and detection systems that utilize magnetic or electromagnetic induction (EMI) sensors. The Underwater Simultaneous EMI and Magnetometer System (USEMS) (Siegel, 2010) and Marine Towed Array (MTA) (McDonald, 2009) systems are underwater mapping and detection systems capable of operating in water 3.7 m and approximately 10 m deep, respectively. The Gavia AUV is rated to 500-m.

The Gavia AUV system is commercially available; however, its base cost of over $750,000 could make it cost prohibitive when compared to other cable-towed or rigid boom systems that may be procured or assembled for less. The USEMS had an instrument cost of approximately $238,000, and the MTA report lists a total system cost of over $800,000. Neither the USEMS nor MTA system is commercially available at the present time.

The Gavia AUV system is relatively compact and can be easily freighted. Mobilization of the Gavia AUV and the field team was estimated at approximately $13,000, which is directly comparable to the USEMS with an estimated mobilization cost of $14,000. Due to the compact size of both systems, neither requires heavy equipment at the loading or receiving end. Mobilization and demobilization costs for the crew and the MTA system were estimated at $72,000; and due to the size of the array, heavy equipment is required at the loading and receiving end to handle the system.

Daily system setup costs were comparable between the Gavia AUV and USEMS systems. The Gavia AUV has a recurring daily setup cost of approximately $400, whereas the USEMS has a reported daily setup cost of $550. Initial setup of the Gavia AUV system during the demonstration was higher than would be anticipated for a typical production site, because many additional tests were performed to evaluate system survey readiness and to develop compensation coefficients. No daily or initial setup costs were broken out for the MTA.

The Gavia AUV cost per hectare was estimated at $4,500, whereas the USEMS was estimated at $1,440 per hectare. Data collection rates were comparable, with the Gavia AUV requiring approximately 3.5 hours per hectare, and the USEMS requiring 3.3 hours per hectare. The MTA cost per hectare was reported at $8,500, with each hectare requiring approximately 0.65 hours for data collection.

9.0 IMPLEMENTATION ISSUES

9.1 REGULATORY ISSUES

A quality control program specific to underwater surveys that verifies navigation accuracy, detection capabilities, and system operation will need to be created for regulatory approval. The magnetometer design utilized by Geometrics is already recognized by the regulatory community as an accepted technology for MEC detection; therefore, no issues are anticipated with its approval.

9.2 END USER ISSUES

The end users are most likely commercial munitions response service firms. The components used to develop the mag module are primarily commercially available; however, their integration and operation was customized for the purposes of this demonstration.

Several issues were observed during survey design and mission planning. To achieve full coverage in a bounded survey area, like a 100-m by 100-m grid as an example, excess survey coverage is required outside of the designated survey area. The additional survey coverage reduces system efficiency and increases cost. When planning live production surveys, care must be taken to optimize the survey area to realize the system's full potential. During turns, elevation changes may help optimize the horizontal travel distance.

Mission planning software issues prevented achieving the across-line data metric. The mission planning software limits the minimum transect spacing that can be programmed into the vehicle mission file to approximately 1.7 m. Users need to consider across-line spacing implications based on the site conceptual site model and munitions detection performance requirements. Commercial versions of the mission planning software may be applicable for WAA but will have limitations during detailed characterization surveys.

9.3 AVAILABILITY OF THE TECHNOLOGY

The magnetometer module is available for use and is functional with most Gavia module AUVs.

9.4 SPECIALIZED SKILLS

The Gavia AUV is a complex instrument that utilizes several navigation and detection technologies during operation and data collection. Personnel require specialized training in properly assembling, configuring, and operating the equipment to perform detection surveys. Mission plan creation, data transfer, communication with the AUV, and monitoring of the AUV during mapping surveys are all tasks that require specialized training.

The sensor data are stored in XML format, thus knowledge of XML file parsing is necessary to pre-process the data into a format that can be recognized by data processing software. After data are converted to a standard format, the data processing procedure is similar to that used for terrestrial magnetometer surveys.

This page left blank intentionally.

10.0 REFERENCES

Breiner, S., 1999. *Applications Manual for Portable Magnetometers*. Geometrics Inc.

Leliak, P., 1961. Identification and Evaluation of Magnetic Field Sources of Magnetic Airborne Detector Equipped Aircraft. *IRE Transactions on Aerospace and Navigational Electronics*. 8, 95-105.

McDonald, J., 2009. Marine Towed Array Technology Demonstration Blossom Point Research Facility. ESTCP Project MM-0324.

Siegel, R., 2010. Underwater Simultaneous EMI and Magnetometer System (USEMS). ESTCP Project MR-200733.

This page left blank intentionally.

APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role In Project
Ryan Steigerwalt	Weston Solutions, Inc. 1371 Brass Mill Road Suite N Belcamp, MD 21017	Phone: 410.612.5900 Fax: 410.612.5901 E-Mail: Ryan.Steigerwalt@westonsolutions.com	Principal Investigator
Dr. Art Trembanis	109 Penny Hall University of Delaware Newark, DE 19716	Phone: 302-831-2498 E-Mail: art@udel.edu	AUV Team Leader
George Tait	Geometrics, Inc. 2190 Fortune Drive San Jose, CA 95131	Phone: 408 954-0522 E-Mail: George@geometrics.com	Hardware Engineer
Val Schmidt	Center for Coastal and Ocean Mapping University of New Hampshire 24 Colovos Road Durham, NH 03820	Phone: 614 286-3726 E-Mail: vschmidt@ccom.unh.edu	AUV Lead Engineer
Nicole Raineault	109 Penny Hall University of Delaware Newark, DE 19716	Phone: 860-301-7292 E-Mail: nrain@udel.edu	AUV Operations Support
Misha Tchernychev	Geometrics, Inc. 2190 Fortune Drive San Jose, CA 95131	Phone: 408 954-0522 E-Mail: misha@geometrics.com	Geophysicist–Compensation
Brian Junck	Weston Solutions, Inc. 1400 Weston Way West Chester, PA 19380	Phone: 610.701.3926 Fax: 410.612.5901 E-Mail: Brian.Junck@westonsolutions.com	Geophysicist–Data Processing
John Kloske	SRI International 450 8th Avenue SE St. Petersburg, FL 33701	Phone: 727.252.6477 E-Mail: john.kloske@sri.com	Marine Operations

ESTCP Office
4800 Mark Center Drive
Suite 17D08
Alexandria, VA 22350-3605
(571) 372-6565 (Phone)
E-mail: estcp@estcp.org
www.serdp-estcp.org