DEMONSTRATION REPORT

AUTONOMOUS UNDERWATER VEHICLE MUNITIONS AND EXPLOSIVES OF CONCERN DETECTION SYSTEM

ESTCP Project MR-201002

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LIST OF ACRONYMS

°	degree
µT	microtesla
AIC	artificial intelligence crew member
AS	analytic signal
AUV	Autonomous Underwater Vehicle
C	Celsius
CEP	circular error probability
cm	centimeter
DERP	Defense Environmental Restoration Program
DoD	Department of Defense
DRMS	Distance Root Mean Squared
DVL	Doppler velocity log
EMI	electromagnetic interference
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
mA	milliampere
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
rms	root mean square
RTK	real time kinematic
SBAS	satellite-based augmentation system
SRI	SRI International
USEMS	Underwater Simultaneous EMI and Magnetometer System
UTM	Universal Transverse Mercator
VDC	volt direct current

WAA	wide area assessment
WAAS	Wide Area Augmentation System
W-LAN	wireless local area network
XML	extensible markup language

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- 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.
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- 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.

EXECUTIVE SUMMARY

ES1 OBJECTIVES

The objective of Environmental Security Technology Certification Program (ESTCP) Project Number 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.

ES2 TECHNICAL APPROACH

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.

ES3 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 reoccurring cost of $400 was needed for instrument setup and preparation.

ES4 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 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. 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.

Environmental Security Technology Certification Program (ESTCP) Project Number 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 1-1**.

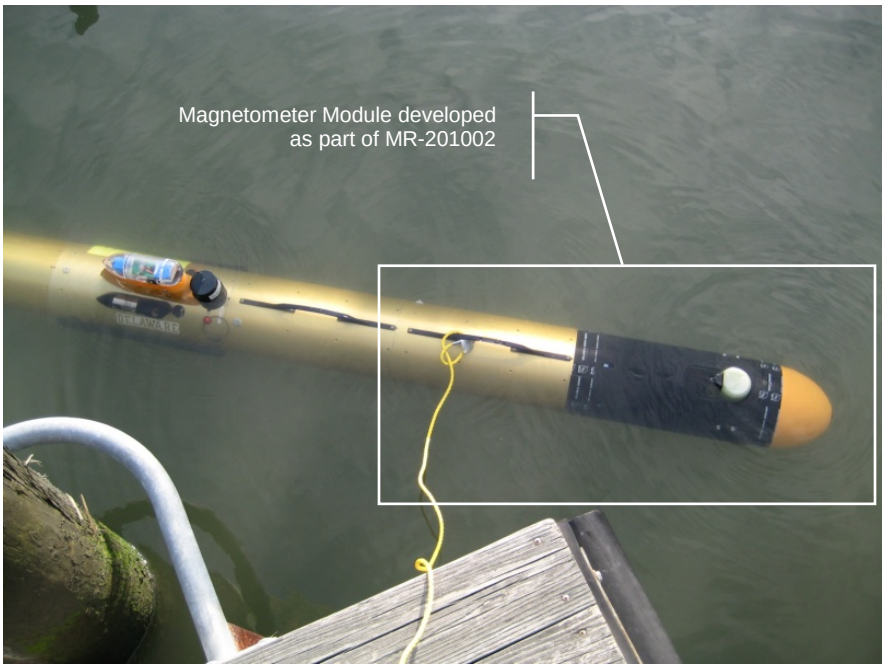


Figure 1-1 AUV MEC Detection System

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.

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.

2. TECHNOLOGY

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

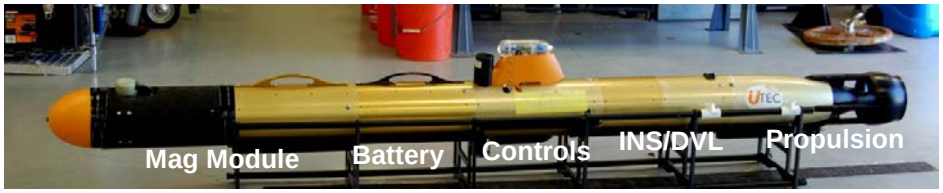
2.1 TECHNOLOGY DESCRIPTION

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

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

2.1.1 Teledyne-Gavia Model Autonomous Underwater Vehicle

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, which are inserted into the vehicle and locked in place with a unique twist lock system. **Figure 2-1** presents the Gavia AUV specifications.



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

Figure 2-1 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. Navigational drift of the system while submerged is approximately 0.1% of the linear distance traveled.

The AUV has the capability of descending close to the seabed and maintaining a set elevation track conforming to the shape of the seabed in "terrain following mode." In terrain following mode, the vehicle uses the precise altitude data from the DVL to measure the distance to the bottom below the AUV. Control algorithms within the vehicle automatically adjust the position of the AUV based on the commanded terrain altitude offset and in response to changes in the seabed geometry. Typical terrain following performance of the vehicle is to maintain position within ± 10 centimeter (cm) of the set point altitude over a flat seafloor. Precise terrain following improves data quality and survey efficiency by helping to maintain even survey swath coverage.

Prior to the beginning of a deployment, the INS runs through an initialization phase (typically 15 to 20 minutes) that allows the INS to measure the Earth's rotation and discern True North. The AUV obtains GPS positional fixes on the surface, which are passed on to the recursive filter of the INS. When the vehicle submerges, the INS integrates accelerometer measurements with DVL bottom tracking to maintain a close estimation of vehicle position.

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 2-2**. The module flooded section houses the G-880AUV total field magnetometer (**Figure 2-3**). 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 2-3**). 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."

<u>G-880AUV Total Field Magnetometer Specifications</u>: The G-880AUV is a self-oscillating split-beam cesium vapor (non-radioactive Cs133) total field magnetometer with automatic hemisphere switching. Operating temperature is from -30 degrees Celsius (°C) to +50 °C. Noise is 0.004 nanoteslas (nT) per square root Hertz (√Hz). Operating range is from 17,000 nT to 100,000 nT. Sample rates are user selectable from 1 Hz to 100 Hz. The G-880AUV draws 400 to 850 milliampere (mA) current from +24 to +32 volt direct current (VDC). Custom options installed on the instrument delivered for this project increase the operating voltage range to +20 to +35 VDC.

<u>Model 539 3-Axis Fluxgate Magnetometer Specifications</u>: The Applied Physics model 539 is a high-speed digital 3-axis vector magnetometer. Accuracy is ± 1% full scale. Range is ± 65 microteslas (µT). Current is 50 mA at +4.95 to +9.0 VDC. Operating temperature is -25 °C to +70 °C.

A relief slot cut in the flooded section is used to facilitate G-880AUV sensor orientation requirements (**Figure 2-3**). 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).

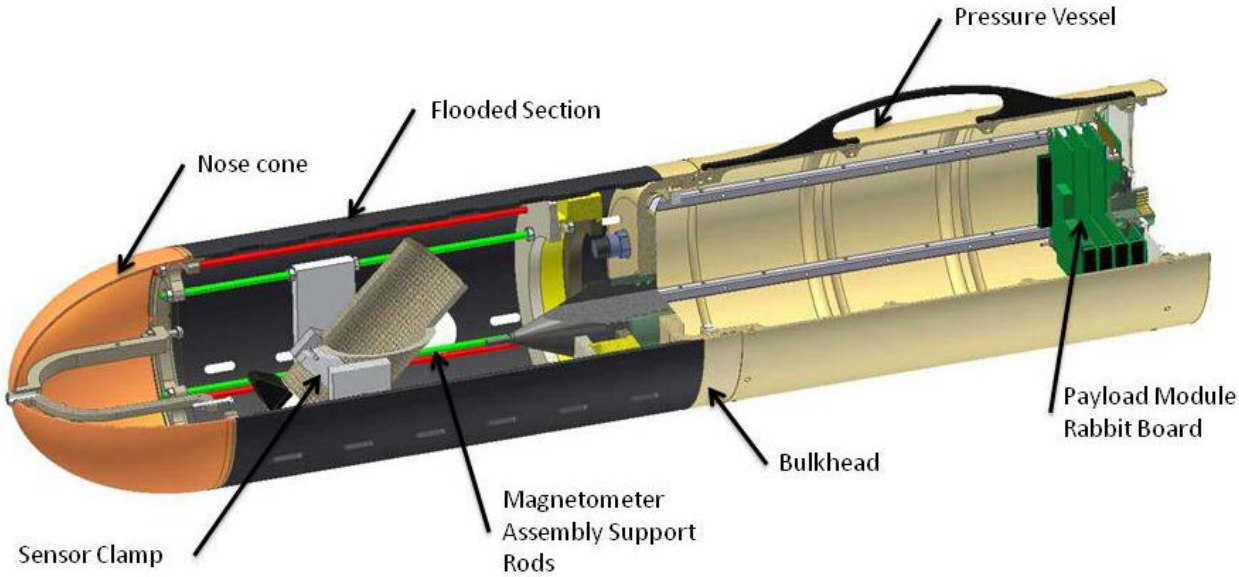


Figure 2-2 Magnetometer Module Design

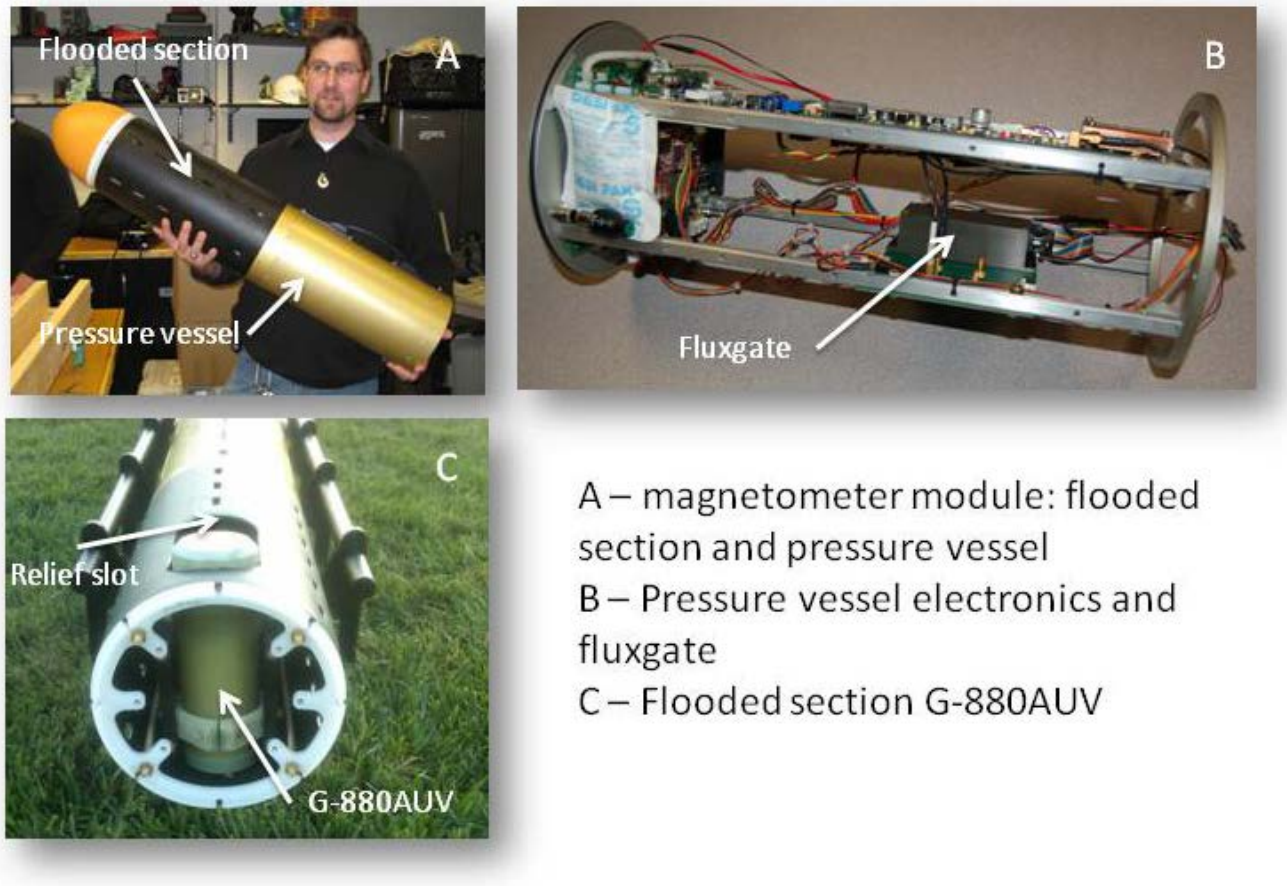


Figure 2-3 Magnetometer Module Components

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, G-880AUV 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

In preparation for the demonstration, the G-880AUV electronics were initially fitted with a lower power sensor driver circuit board and an efficient voltage boost circuit board. Mechanical and electrical engineering was performed to provide electrical power and communications between the G-880AUV and fluxgate and the AUV microcontroller (rabbit board). The G-880AUV sensor was successfully installed in the payload module flooded section. The G-880AUV electronics and the fluxgate were installed in the pressure vessel section of the payload module. A small custom artificial intelligence crew member (AIC), which forms the basis of all Gavia AUV sensors and vehicle operations, was first scripted and installed on a personal computer to test communications with each installed sensor. Next, a custom AIC was scripted in Python using a manufacturer-supplied template. This crew member was initially configured with the task of performing the RS-232 communication to each sensor and time stamping all of the sensor response communications.

During the pre-demonstration testing, it was found that as a result of size constraints, the G-880AUV sensor was limited to a range of vertical motion by the plastic fairing around the flooded section of the module. A relief slot was cut in the flooded section to facilitate G-880AUV sensor orientation. The relief slot permitted the G-880AUV to be rotated forward to a vertical position. Access holes were also drilled to facilitate tightening the sensor swivel screws.

The payload module was also found to be very light for its volume, making the unit positively buoyant by approximately 4 kgs. Calculations of module buoyancy under likely water densities were conducted to determine the needed size and placement of internal weights. Non-magnetic lead ballast strips were installed in the pressure vessel to serve as internal ballast weights to allow the module to have weight integration that was balanced to the rest of the AUV. The lead ballast pieces were shaped to conform closely to the inside diameter of the pressure vessel. The lead ballast pieces were permanently installed by gluing the pieces in place with Epoxy Pax EP7432A, a non-magnetic epoxy, which is slightly flexible when cured. The epoxy was cured at 50 °C as directed by Epoxy Pax and the assembly was allowed to cool to room temperature. Two temperature cycles were run to verify that the epoxy bond was sufficient. There was no indication of separation after the temperature cycles.

The initial magnetic compensation phase of work was performed concurrent with the magnetometer module development. Geometrics developed software, based in part on MagComp source, to accept electrical current compensation terms. To test the software, a low magnetic signature cart was constructed with a high sensitivity cesium vapor magnetometer, fluxgate, two adjustable sine-wave current sources connected to two coils oriented along and perpendicular to the cart, and a lithium polymer battery power source. The purpose of the cart was to record data

(magnetometer, fluxgate, and current) as it would be collected during a marine survey to generate compensation coefficients. The cart was slowly turned over a 360-degree-range to include all possible platform yaw orientations. Magnetometer measurements were sampled at 10 Hertz (Hz). Orientation of the cart relative to the Earth's magnetic field was sampled at 20 Hz using the fluxgate compass. Compensation corrections were then applied to the magnetic data using current terms from active coil 1, active coil 2, and combined active coils 1 and 2.

Improvements (improvement ratios between 7.1 and 10.3, depending on the coil) were observed over traditional compensation (improvement ratios between 2.1 and 4.7, depending on the coil) that uses no current terms. This demonstration showed that compensation software that includes current terms can considerably improve the compensation solution. This finding suggested that magnetic compensation for electrical current terms provide improvements in the acquired magnetic data from the magnetometer payload module.

New compensation libraries were merged into previous code. Testing indicated that the new libraries functioned correctly. When the original computational code was chosen to operate on known data sets, testing indicated that none of the software changes had caused any difference in results. Improved results on a test data set were obtained by changing high pass filter parameters, improving axis annotation handling when small data values were present, finishing a current terms definition dialog box, and further integrating current terms into the application. The program was able to store, use, and recall current terms when the new compensation code was selected. A run with this version of MagComp against data from the magnetometer test cart produced results comparable to those achieved with the command line program.

The magnetometer module was deployed at the United States Naval Academy in October 2011 and at the University of Delaware, Lewes, Delaware Campus in December 2011. The primary objective of these tests was to confirm connectivity between the magnetometer module sensors and the rest of the Gavia AUV. Repeatable magnetic responses were observed where survey line locations were rerun.

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. 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 are listed in **Table 3-1**.

Table 3-1 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° 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

Table 3-1 Performance Objectives (Continued)

Performance Objective	Metric	Data Required	Success Criteria	Results
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.
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	ΔN and $\Delta E \leq 0.50$ m σN and $\sigma E \leq 1.00$ m	Fail: 18% of detected seed items had a ΔN and $\Delta E \leq 0.50$ m. Fail: 60% of detected seed items had a σN and $\sigma E \leq 1.00$ m. The average σN was 0.42 m, and the σE was 0.61 m.

Table 3-1 Performance Objectives (Continued)

Performance Objective	Metric	Data Required	Success Criteria	Results
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
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

Table 3-1 Performance Objectives (Continued)

Performance Objective	Metric	Data Required	Success Criteria	Results
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:

WAA = wide area assessment
XML = extensible markup language

3.1 OBJECTIVE: MAINTAIN A CONSTANT HEIGHT ABOVE BOTTOM

The AUV system's ability to maintain a constant height above the seafloor is important for anomaly detection because the magnetic response signal falls off at roughly one over the cube of the distance to that object. Although the altitude of the vehicle is measured from the seafloor, comparison of overlapping data is simplified when the data are measured at a constant height. Thus, the goal is to minimize the excursions from the nominal altitude set point.

3.1.1 Metric

The standard deviation of the AUV's altitude compared to the mission set point serves as the metric.

3.1.2 Data Requirements

The AUV's DVL provides an altitude measurement at approximately 1-Hz intervals.

3.1.3 Success Criteria

The 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.

3.2 OBJECTIVE: MAINTAIN CONSTANT PITCH AND ROLL

The sensitivity of a cesium vapor magnetometer is dependent, in part, on its orientation to the Earth's ambient magnetic field. Thus, instruments must be installed on survey platforms in known configurations and surveys planned to maximize the response of the sensor. For the demonstration site, the optimal orientation of the sensor is vertical, which is illustrated by the symmetric green circle indicating uniform signal response at all headings (**Figure 3-1**). However, when the sensor is rotated just 10°, the signal level decreases for the westerly heading, as shown by the malformed green circle in **Figure 3-2**. Any deformation observed at the edge of the green circle is representative of the proportional decrease in signal level at a specific heading when the sensor is rotated away from vertical. For these reasons, maintaining vehicle stability during the mission allows optimization of the mission configuration for local conditions.

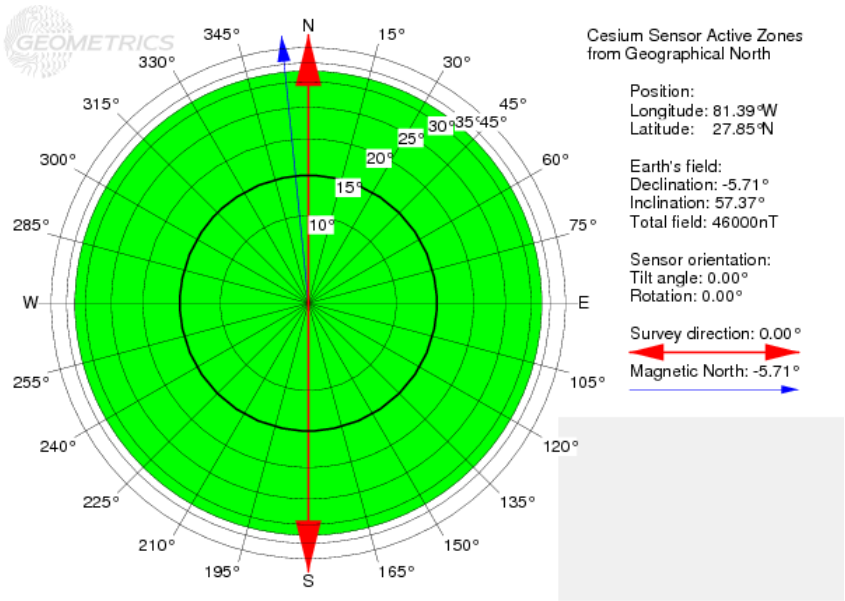


Figure 3-1 Optimal Sensor Orientation

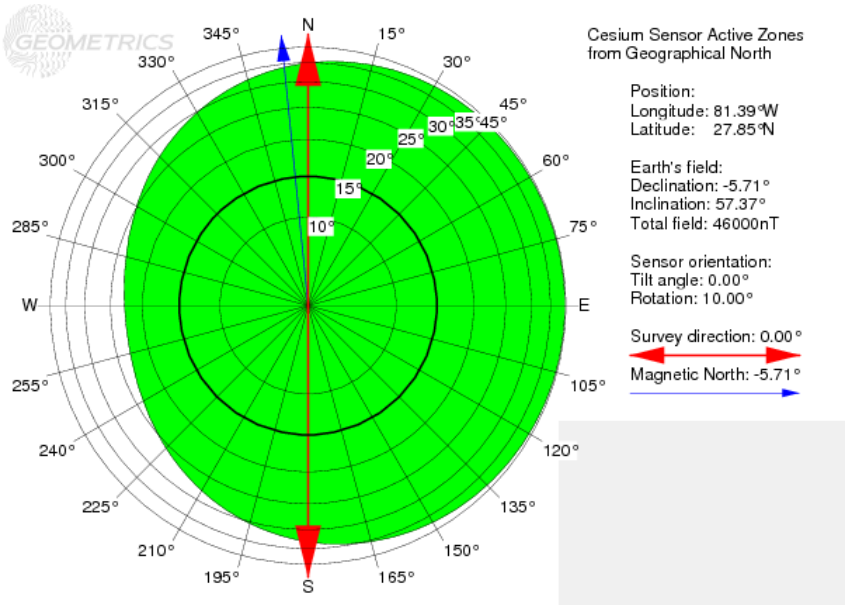


Figure 3-2 Magnetometer Effect Based on Rotation

3.2.1 Metric

The metric for vehicle stability is the root mean square (rms) value of pitch and roll during straight-line operations at a constant depth.

3.2.2 Data Requirements

Pitch and roll data are logged at 1-Hz increments by the AUV INS log.

3.2.3 Success Criteria

An rms value less than 10° is desired to mitigate the effects of sensor orientation on the survey.

3.3 OBJECTIVE: ALONG-LINE MEASUREMENT SPACING

An appropriate data density is needed to successfully detect targets of interest. In general, the length of the anomaly is 1 to 3 times the distance to the object (Breiner, 1999). Vehicle velocity and magnetic sample measurements are maintained to achieve the data density requirements.

3.3.1 Metric

The metric for along-track data spacing is the average physical sample-to-sample spacing measured over a representative portion of the survey.

3.3.2 Data Requirements

To calculate the along-track data spacing, the magnetometer sample rate, measured as the difference in successive sample time stamps (samples/second), is divided by the AUV survey speed (meters/second), providing a sample per meter value. This value may be averaged over a survey or portion of a survey to assess the mean along-track data spacing.

3.3.3 Success Criteria

This objective is met when 95% of the mean along-track data spacing is less than or equal to 0.25 m.

3.4 OBJECTIVE: SURVEY COVERAGE

An appropriate data density is needed to successfully detect targets of interest. The separation between survey lines is as important as along-line data density to reduce signal degradation and increase the detectability of targets of interest.

3.4.1 Metric

This metric is established both procedurally and empirically. AUV missions are planned with 1–m lateral line spacing to meet the objective.

3.4.2 Data Requirements

Latitude and longitude (or Universal Transverse Mercator [UTM] Northings and Eastings) of each data point are required. Spatial analysis can be performed on the gridded magnetic data to evaluate coverage and determine data gap locations and cumulative area.

3.4.3 Success Criteria

The success criteria for this objective is that 95% of the across line spacing is less than or equal to 1 m.

3.5 OBJECTIVE: MEASUREMENTS ARE POSITIONED ACCURATELY

The AUV is equipped with a satellite-based augmentation system/wide area augmentation service (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 a 95% circular error probability (CEP). When submerged, the AUV navigates with a Kearfott T-24 INS with an integrated DVL. The published drift rate for the INS 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.

In an effort to remove biases from the onboard low-accuracy GPS, the AUV's position is fixed, both prior to launch and on recovery, with a standalone real time kinematic (RTK) GPS capable of estimating positions to less than 10 millimeters (mm) rms. In addition, post-mission GPS fixes allow assessment of the navigational drift rate and propagation of a correction to this drift back through the navigation. As an additional precaution, a downward-looking camera is attached to measure the AUV's navigational drift rate directly by locating targets (whether natural or manmade) imaged in overlapping lines.

3.5.1 Metric

The metric is based on the average error and standard deviation of the known location compared to the measured location of seeded targets of interest.

3.5.2 Data Requirements

Data required include AUV navigation and uncertainty estimates from the INS as logged by the AUV, post mission GPS position fixes logged by the AUV, pre- and post-mission RTK GPS fixes logged externally with associated time stamps, and seed item locations. Camera imagery for navigation drift assessment is also required.

3.5.3 Success Criteria

The success criteria for this objective is an average positional error of less than or equal to 0.5 m with a standard deviation of less than or equal to 1 m.

3.6 OBJECTIVE: ACQUIRE SITE SPECIFIC CALIBRATION COEFFICIENTS FOR MAGNETIC COMPENSATION

Missions were performed prior to the demonstration to develop site-specific coefficients based on vehicle orientation (heading, roll, pitch) and electrical current. An area of low magnetic gradient is necessary to effectively develop these coefficients.

3.6.1 Metric

The metric is based on the variation between point-to-point magnetic measurements.

3.6.2 Data Requirements

Sensor measurements from the G-880AUV, fluxgate compass, INS/DVL logs, and internal vehicle compass are integrated and applied to the compensation solution.

3.6.3 Success Criteria

Point-to-point magnetic measurements are less than or equal to 0.5 nT during compensation coefficient development.

3.7 OBJECTIVE: NOISE REDUCTION PERFORMANCE USING MAGNETIC COMPENSATION

Compensation coefficients are applied to the raw total field magnetic data to improve the overall signal-to-noise ratio for targets of interest.

3.7.1 Metric

Orientation and current induced interference from the vehicle to the magnetic measurements are reduced following application of the derived compensation solution. The reduction in magnetic noise interference is calculated as an improvement ratio.

3.7.2 Data Requirements

Sensor measurements from the G-880AUV, fluxgate compass, INS/DVL logs, and internal vehicle compass are integrated and applied to the compensation solution.

3.7.3 Success Criteria

An overall improvement ratio of greater than or equal to 5 is observed following compensation corrections for orientation and electrical current.

3.8 OBJECTIVE: DETECTION OF ALL SEEDED ITEMS

Known and blind seeds were emplaced at two test plots to evaluate detection and positional accuracy capabilities. Positive detection within the total field magnetic data is needed to assess positional accuracy between the measured and the actual seed item locations.

3.8.1 Metric

Following the test plot surveys, the number of detected seed items was compared to the final total number of seed items to determine percent detected.

3.8.2 Data Requirements

The quantity, type, and location of seed items placed within the test plots is needed to derive the performance evaluation.

3.8.3 Success Criteria

The surveys are successful if all detectable seeds are identified and are accurately selected in the total field magnetic data.

4. SITE DESCRIPTION

The demonstration was conducted in Tampa Bay near St. Petersburg, Florida (**Figure 4-1**). 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 4-2**) was used to deploy the AUV at the grid locations.

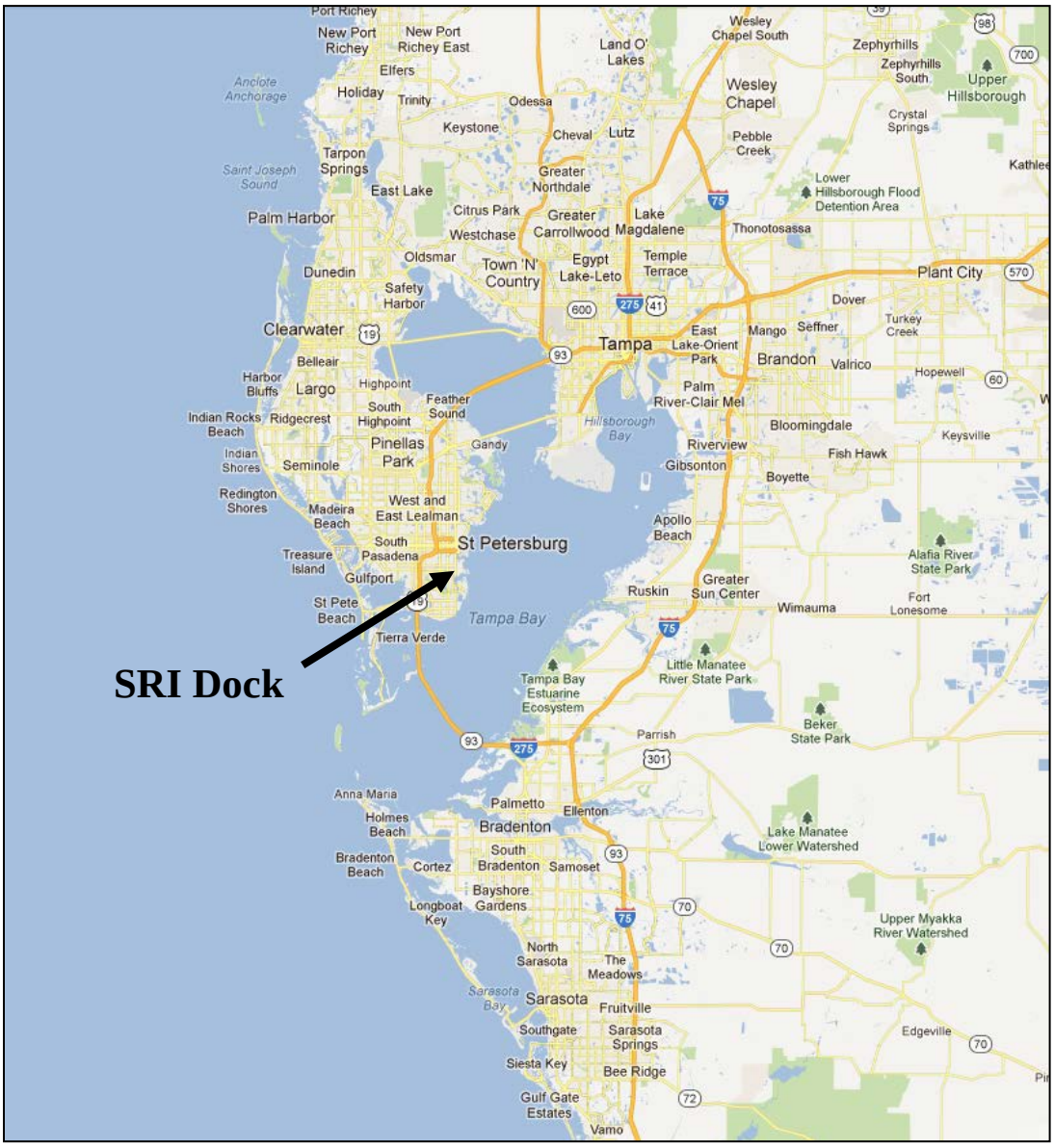


Figure 4-1 Regional Location Map of Demonstration Site

Figure 4-2 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 4-3**).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 Research Laboratory field study of munitions targets and thus selected for this demonstration (Dr. M. Richardson, personal communication).

Figure 4-3 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.

5. 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 3-1**.

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 5-1**. The inert munitions items used for seeding and their respective locations are listed in **Tables 5-1 and 5-2**.

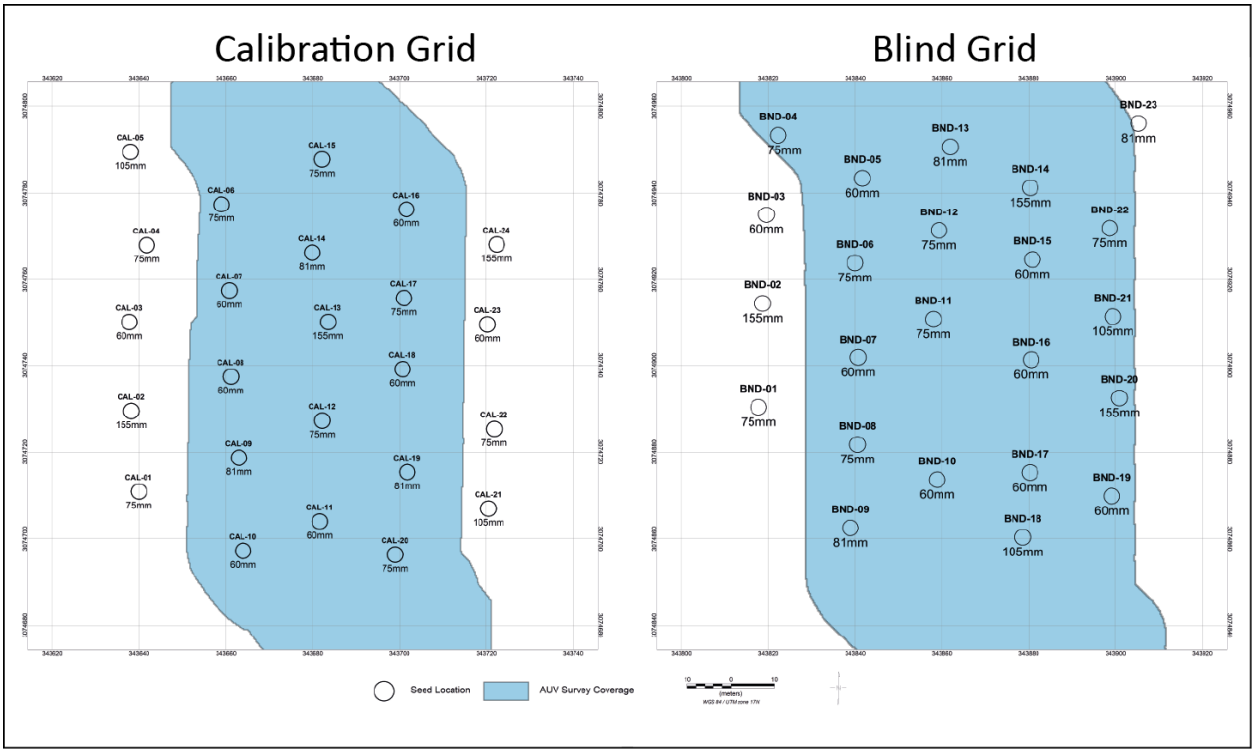


Figure 5-1 Test Plot Schematic and Survey Footprint for Each Grid

Table 5-1 Seed Item Descriptions, Calibration Grid

Calibration Grid

Unique ID	Item Description	Easting	Northing
CAL-01	75mm	343639.93	3074710.89
CAL-02	155mm	343638.17	3074729.45
CAL-03	60mm	343637.70	3074750.19
CAL-04	75mm	343641.72	3074767.94
CAL-05	105mm	343637.97	3074789.53
CAL-06	75mm	343658.92	3074777.45
CAL-07	60mm	343660.79	3074757.45
CAL-08	60mm	343661.15	3074737.40
CAL-09	81mm	343662.99	3074718.67
CAL-10	60mm	343663.93	3074697.20
CAL-11	60mm	343681.59	3074703.98
CAL-12	75mm	343682.17	3074727.26
CAL-13	155mm	343683.53	3074750.21
CAL-14	81mm	343679.87	3074766.21
CAL-15	75mm	343682.13	3074787.82
CAL-16	60mm	343701.59	3074776.29
CAL-17	75mm	343701.02	3074755.72
CAL-18	60mm	343700.71	3074739.12
CAL-19	81mm	343701.78	3074715.36
CAL-20	75mm	343698.98	3074696.34
CAL-21	105mm	343720.50	3074706.95
CAL-22	75mm	343721.83	3074725.34
CAL-23	60mm	343720.25	3074749.65
CAL-24	155mm	343722.40	3074768.10

Table 5-2 Seed Item Descriptions, Blind Grid

Blind Grid

Unique ID	Item Description	Easting	Northing
BND-01	75mm	343817.70	3074890.34
BND-02	155mm	343818.67	3074914.50
BND-03	60mm	343819.53	3074935.03
BND-04	75mm	343822.23	3074953.32
BND-05	60mm	343841.64	3074943.49
BND-06	75mm	343839.96	3074923.84
BND-07	60mm	343840.70	3074901.83
BND-08	75mm	343840.55	3074881.72
BND-09	81mm	343838.88	3074862.49
BND-10	60mm	343858.91	3074873.61
BND-11	75mm	343858.04	3074910.84
BND-12	75mm	343859.33	3074931.36
BND-13	81mm	343861.95	3074950.66
BND-14	155mm	343880.36	3074941.33
BND-15	60mm	343880.86	3074924.64
BND-16	60mm	343880.59	3074901.29
BND-17	60mm	343880.29	3074875.25
BND-18	105mm	343878.62	3074860.34
BND-19	60mm	343899.11	3074869.83
BND-20	155mm	343900.89	3074892.46
BND-21	105mm	343899.36	3074911.45
BND-22	75mm	343898.65	3074931.85
BND-23	81mm	343905.27	3074956.04

The seeds were placed proud on the surface using frames as shown in **Figure 5-2**. 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.

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.

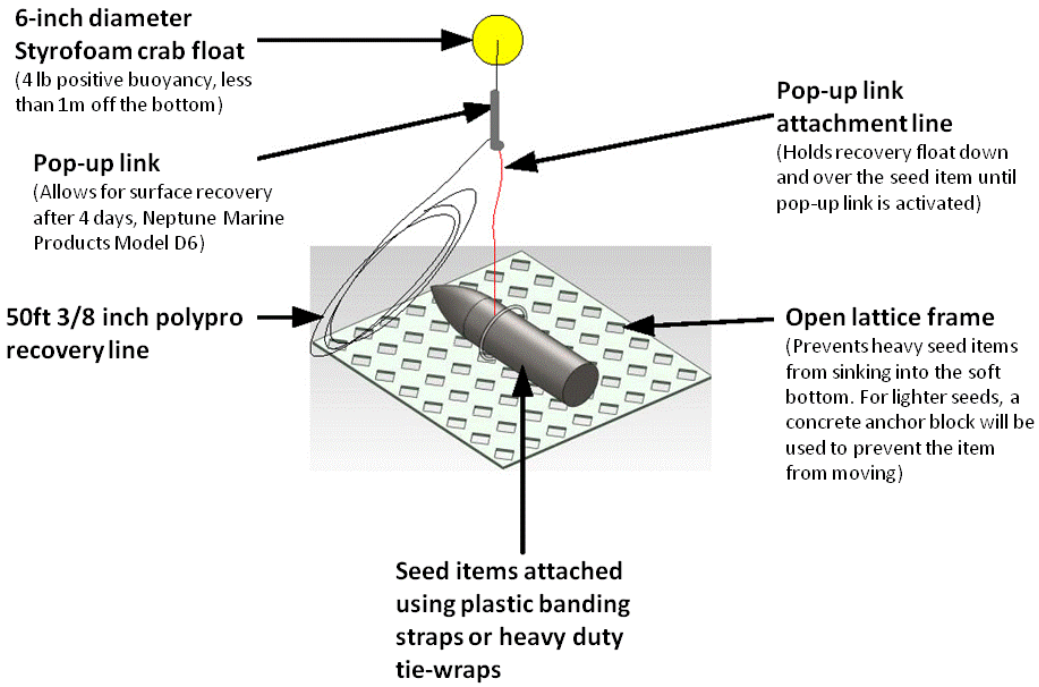


Figure 5-2 Seed Item Deployment and Recovery System

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 5-3**.

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 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% 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.

Table 5-3 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:
m/s = meters per second

5.3.4 Current

A dedicated AIC crew 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 CALIBRATION ACTIVITIES

Several calibration and pre-survey activities were performed prior to demonstrating the AUV MEC Detection System at the blind evaluation grid. A description of these activities is provided in the following sections.

5.4.1 Derive Maneuver Compensation Coefficients

The noise level of the G-880AUV is dependent, in part, on the magnetic properties of the vehicle on which it is deployed and the magnetometer sensor's orientation with respect to the Earth's magnetic field. Compensation coefficients were established 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. The first set of missions planned for the demonstration was to establish these compensation coefficients.

5.4.1.1 *Compensation Coefficients Mission 1 (Heading, Roll)*

A box-shaped mission was conducted over a low magnetic gradient area with lines extending between 200 m and 300 m in length at 2-m constant depth in water 5 m or greater. The mission was performed at an altitude high enough off the bottom to minimize the magnetic gradient but

deep enough to prevent surface wave interaction. Survey speed was set to achieve an along-line magnetic measurement spacing of less than or equal to 0.25 m.

5.4.1.2 *Compensation Coefficients Mission 2 (Heading, Roll, Pitch)*

A box-shaped mission was conducted over a low magnetic gradient area with lines extending to 100-meter segments. Each segment requires depth changes from 2-m depth to 3-m altitude over approximately 10 m. Survey speed was set to achieve an along-line magnetic measurement spacing of less than or equal to 0.25 m.

5.4.1.3 *Compensation Coefficients Development*

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. These measurements are logged asynchronously and must be interpolated to the magnetometer's temporal reference frame. 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. Compensation coefficients were evaluated based on the point-to-point magnetic measurement with a change of less than or equal to 0.5 nT. An improvement ratio (IR) is calculated by the process with a target value greater than or equal to 5.

5.4.2 Determine 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.

5.4.2.1 *Data Logging Latencies and Repeatability Mission*

The AUV was run in repeated reciprocal lines over a high amplitude anomaly (large seed item) at speeds ranging from 1.5 meters per second (m/s) to 2.5 m/s, not to exceed an along-line magnetic measurement spacing of 0.25 m. The AUV was run at a constant depth of approximately 2 m.

5.4.2.2 *Latency Correction*

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.

5.4.3 Positional Accuracy

To constrain positional accuracy, a series of missions were performed to quantify navigation precision and drift. Side-scan sonar and camera imagery were used to estimate the location of a known target of opportunity, such as a seed item or other known feature, which is adjacent to the survey area. Side-scan sonar acoustic imagery has the advantage of allowing identification of objects up to 30 m from the vehicle; however, it does not allow precise positioning of targets relative to the AUV. Camera imagery, in contrast, is limited to a field of view directly beneath the AUV and can provide much more precise positioning of targets. Because the AUV's native camera cannot be deployed with the magnetometer, an external strap-on camera (HD Go Pro Hero camera) was used.

5.4.3.1 *Positional Accuracy Mission*

A sliding box survey design was used for the positional accuracy mission (**Figure 5-3**). A 50-m by 20-m area located over a known target was surveyed at a 2-m line spacing. One meter line spacing was planned but not achievable because of the precision of the mission planning software. Survey speed was set to achieve an along-line magnetic measurement spacing of less than or equal to 0.25 m. The target was identifiable in 900 kHz side-scan data and also optically by the camera. The sonar system has a variable ping rate, whereas, the camera's frame rate is 3.75 Hz, providing approximately 1/3 overlap frame-to-frame at the AUV's nominal speed.

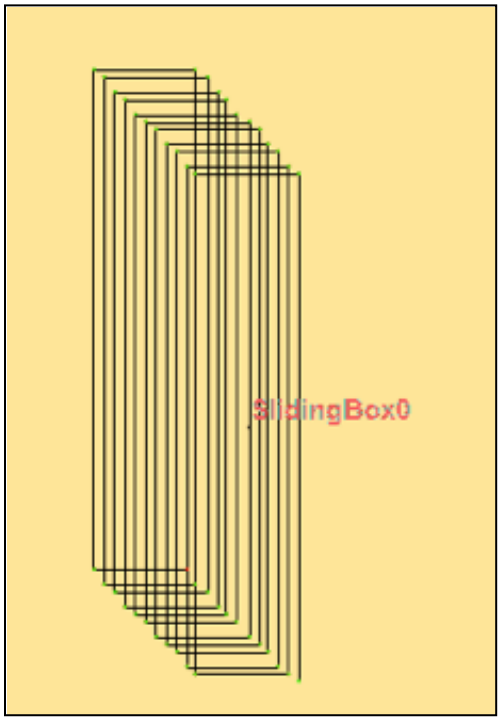


Figure 5-3 Example Sliding Box Survey

5.4.3.2 *Navigation Solution Drift Correction*

The location of the known features can be tracked across overlapping survey lines during calibration tests. A navigation solution drift rate can then be established and used to adjust the navigation in post-processing, as needed.

5.4.4 Calibration Grid Survey

Following completion of the initial compensation coefficient and latency correction missions, the calibration grid was surveyed. The calibration grid seed item types and locations were made available to the project team.

5.4.4.1 *Calibration Grid Mission*

The AUV MEC Detection System traversed the 100-m by 100-m grid using a 1-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.

5.4.4.2 *Calibration Grid Results*

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.

5.5 DATA COLLECTION PROCEDURES

Following system calibration, 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 International and was not provided to the project team until the magnetic data were analyzed and interpreted.

5.5.1 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.

5.5.2 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 3-1 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 3-1 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.

5.5.3 Quality Checks

System operation is monitored through the wireless 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.

5.5.4 Data Handling

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 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.

5.6 VALIDATION

Validation was not performed during this demonstration. A seeding program was used to evaluate system performance.

6. 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) in which the locations of all anomalies within a specified radius of a seed item are 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 PARAMETER ESTIMATION

This task is not applicable for this demonstration.

6.4 TRAINING

This task is not applicable for this demonstration.

6.5 CLASSIFICATION

This task is not applicable for this demonstration.

6.6 DATA PRODUCT SPECIFICATION

The Gavia AUV records location and actions as well as measurements from all of the onboard sensors. It is important that the data are saved and managed consistently. This outline describes the steps in saving, parsing, and plotting the data. Enthought (for Python) and Matlab are required software for proper data management.

The files are written into a folder called “db” in the control center folder. Within the db folder, there are other folders with campaign names. The files are written to a folder with the same name as the current campaign in the control center. After each mission, the data are downloaded from the Gavia AUV onto the Toughbook computer. The folder should be named using the following convention: YYYYMMDD_Location. From there, it is transferred onto two portable hard drives. One of these drives is a permanent archive, and no one should ever have write access to these files. The other drive is intended for downloading the data and working with the data locally.

Each of the logs is parsed from the format in which it comes from the Gavia AUV. The extract_logs function is used for the parsing. This file requires three variables: directory, type of log, and a Boolean for Matlab or Python. It is much faster to parse using Python rather than Matlab. Matlab is the default, so be sure to set the third variable to 1*.

6.7 WORKFLOW

AUV log processing workflow **(Figure 6-1**):

1. Prior to departing for the mission, copy the template directory tree for processed data to the shared data drive.

2. Directory name is /DORA_AUV_PRODUCTS/adminscripts/templates/directorytree/

Note: To quickly copy the directory tree, execute the rsync command from the terminal as follows:
rsync -rav <pathtodataproducts/adminscripts/templates/directorytree> \ /Volumes/shareddrive/ \ /Volumes/DORA_AUV_PRODUCTS/adminscripts/templates/directorytree/db/dataproducts/adminscripts/templates/directorytree

3. After the campaign, extract data from Gavia AUV to the Toughbook computer (using Control Center or manually for Geoswath).

4. Backup data to archival drive.

5. Backup data to shared data drive.

6. Copy compressed xml logs to the campaign folder: /gaviaxmllogs/unzipped/

7. Uncompress the xml logs by opening a terminal window, cd to /unzipped/ directory. Execute gunzip *.gz

8. In Matlab, parse the logs into standard structure names (nav, col, gps, depth, flntu, eng, sea, (mmgr TBA)) using the extract_logs script.

9. Save each log in its own .mat file: save('nav','nav'), save('col','col').

10. Save each log in /parsed/ directory for that campaign.

11. Generate nav plot and science plot and save these as jpgs in: gaviaxmllogs/plots/.

12. Generate kml plots using the following plot commands (adjust for specific date names and desired decimation) level for depth: ge_scatter_orig('Gavia082610totDepthDECall.kml'), nav.longitude(1:10:length(nav.depth)), nav.depth(1:10:length(nav.depth))+nav.altitude(1:10:length(nav.depth))); for temp: ge_scatter_orig('Gavia082610tempDECall.kml', nav.longitude(1:10:length(nav.depth)), nav.latitude(1:10:length(nav.depth)), nav.temperature(1:10:length(nav.depth))); for salinity: ge_scatter_orig('Gavia082610salinityDECall.kml'), nav.longitude(1:10:length(nav.depth)), nav.latitude(1:10:length(nav.depth)), nav.salinity(1:10:length(nav.depth))); and save these in: kml/

13. Generate "cnc" FM animation file.

14. Generate "Winfrog" file using the script winfrog_navigator.m winfrog_navigator(filename.nav) [Note: be sure to change the latitude/longitude range to match the extent of the mission data and select the correct UTM zone to get the plot right)

15. Generate animated Google Earth mission file. Use the makeFlightTrackKml.py function as follows. This function should be fixed to use the actual vehicle heading at some point instead of the kludge, which performs a point-to-point fix differencing routine.

/makeFlightTrackKml.py-i /Users/arttrembanis/desktopstuff/UDel/UD_grants/Pavillion09/PLRP10plans/UD_GAVIA_WINFROG_MISSIONS/20100628UDGavia.nmea -o /Users/arttrembanis/desktopstuff/UDel/UD_grants/Pavillion09/PLRP10plans/UD_GAVIA_WINFROG_MISSIONS/20100628UDGavia.kml -v udgav –a

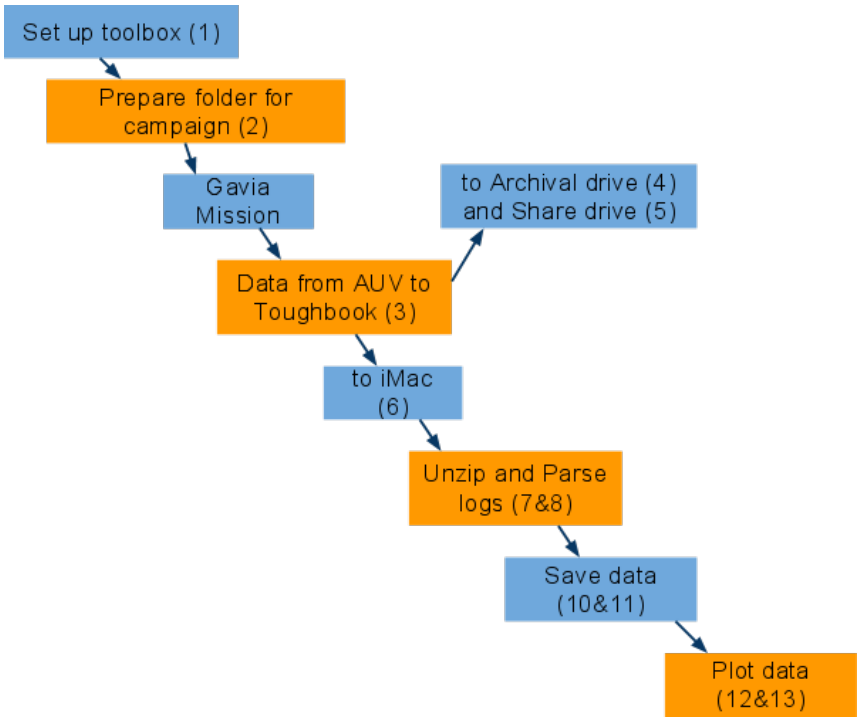


Figure 6-1 Work Flow

6.7.1 Mag Module Data Description

Data samples include field intensity, sensor amplitude, and orientation measurements. Field-intensity is the magnetic field intensity sensed by the G-880AUV magnetometer. The magnetic field intensity is in nT units and normal values can be anywhere from 30,000 to 75,000, depending on the user's location and the amount of magnetically susceptible material nearby. When the vehicle is stationary in a magnetically quiescent place, noise is minimal, varying not much more than +/-1 nT. Ambient noise levels during production surveys will vary from site to site, based on local conditions. System noise induced by sensor orientation and current is reduced during post-processing using magnetic compensation software.

The G-880AUV emits a signal that is generated with frequency that is proportional to the magnetic field intensity. The amplitude of that signal (sensor-amplitude) is a measure of the signal-to-noise ratio of the magnetic field measurement. When the sensor is in a severe magnetic gradient because of some local anomaly, the sensor amplitude reduces to < 100nT, often less than 50nT. Normal values range from 1,000nT to 2,000nT.

Field Intensity Example

Example file: mag-20111025-222345.xml
Sample rate: 10Hz


```
<? xml version="1.0"?>
<log xmlns:gavia="http://www.gavia.is/namespace">
  <entry timestamp="1319581425.2230238914" time="2011 10 25 22:23:45.223">
    <field-intensity>51382.171</field-intensity>
    <sensor-amplitude>1260</sensor-amplitude>
  </entry>
  <entry timestamp="1319581425.3196249008" time="2011 10 25 22:23:45.319">
    <field-intensity>51382.124</field-intensity>
    <sensor-amplitude>1257</sensor-amplitude>
  </entry>
  <entry timestamp="1319581425.4270679951" time="2011 10 25 22:23:45.427">
    <field-intensity>51382.149</field-intensity>
    <sensor-amplitude>1257</sensor-amplitude>
  </entry>
```


Sensor Amplitude Example

Same file: magfg-20111025-222345
Sample Rate: 15Hz (approx)
Data Sample:


```
<?xml version="1.0"?>
<log xmlns:gavia="http://www.gavia.is/namespace">
  <entry timestamp="1319581425.1786630154" time="2011 10 25 22:23:45.178">
    <x>-0.15817</x>
    <y>+0.11981</y>
    <z>-0.47573</z>
  </entry>
  <entry timestamp="1319581425.2347071171" time="2011 10 25 22:23:45.234">
    <x>-0.15820</x>
    <y>+0.11981</y>
    <z>-0.47573</z>
  </entry>
```


Flux-Gate Compass Example

These measurements are the vector components of the magnetometer's flux-gate compass in Gauss. (Note: There are 100,000 nT to the Gauss). The calculation for the norm of this vector and its conversion to nT is as follows:

$$A = \mathrm{sqrt}(x^2 + y^2 + z^2) * 1e5$$

7. 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 very slight variations in altitude from what was specified in the mission plans uploaded to the AUV. Typical variations in altitude did not exceed 0.21 standard deviations within the grid survey area.

The expected and mean altitude per mission; the offset between the mean and expected altitudes; and the standard deviation of the altitude, as recorded during data collection; are presented in **Table 7-1**.

Table 7-1 AUV Mission Altitudes

	Calibration Grid		Blind Grid				
Mission ID	M3	M4	M1	M2	M3	M4	M5
Expected Altitude (m)	2.00	2.00	1.50	1.50	3.00	2.00	2.00
Mean Altitude (m)	1.95	1.96	1.38	1.39	3.19	2.25	2.22
Mean Altitude Offset (m)	0.05	0.04	0.12	0.11	-0.19	-0.25	-
Standard Deviation (σ)	0.18	0.21	0.21	0.19	0.13	0.20	0.12

Slight variations in altitudes (+/- 20cm) were observed throughout each mission. These altitude variations are most likely due to slight undulations in the seafloor terrain that were so small or abrupt that the terrain-following functionality of the AUV could not compensate for them.

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.

Pitch and roll values were consistent throughout the missions, with no anomalous or out of spec values observed during survey area traversal. A summary of pitch and roll values observed for each grid survey is detailed in **Table 7-2**.

Table 7-2 AUV Pitch and Roll RMS Values

	Calibration Grid		Blind Grid				
Mission ID	M3	M4	M1	M2	M3	M4	M5
Expected Range (°)	Pitch and Roll +/-10°						
RMS (Pitch)	3.27	3.34	1.73	1.86	1.51	1.42	1.71
RMS (Roll)	3.52	3.83	3.95	3.58	2.26	3.37	3.03

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. **Figure 7-1** is a profile plot of roll values for a typical AUV traverse. The first half of the profile consists of roll values for the turn-around portion of the traverse, and the second half consists of roll values for the straight-line navigation portion.

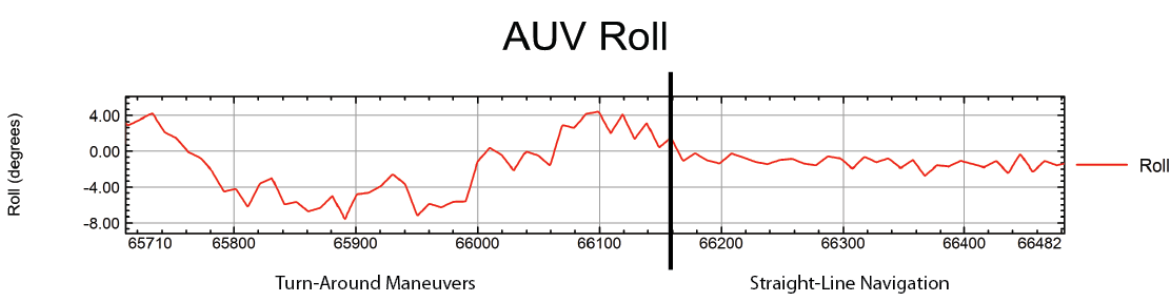


Figure 7-1 AUV Roll Along a Single Traverse

AUV pitch and roll values for a typical traverse are plotted together in **Figure 7-2**. 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.

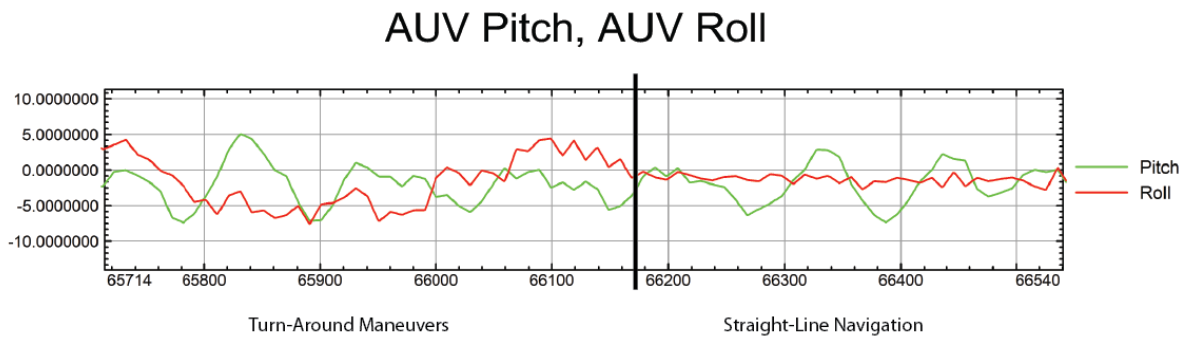


Figure 7-2 AUV Pitch and Roll Along a Single Traverse

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.

Sensor data are logged and time-stamped independently of INS position logs and must be merged during post-processing based on matching timestamps. The INS logs positions at a 1-Hz frequency, so the positioning of higher frequency sensor data must be interpolated between data with common timestamps.

Table 7-3 details the mean sample separation and mean velocity for each test plot survey mission. Mean sample separation for the onboard magnetometer was 0.15 m for all missions. Mean velocities for all missions were between 1.47 and 1.52 m/sec.

Table 7-3 Mean AUV Mission Sample Separations and Velocities

	Calibration Grid		Blind Grid				
Mission ID	M3	M4	M1	M2	M3	M4	M5
Mean Sample Separation (m)	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Mean Velocity (m/s)	1.47	1.50	1.47	1.47	1.52	1.49	1.49

Figure 7-3 depicts a sample separation profile showing the minute fluctuations in sample separation values along a typical section of survey transect. The profile represents approximately 20 seconds of data. Sample separations range from approximately 0.14 m to 0.18 m.

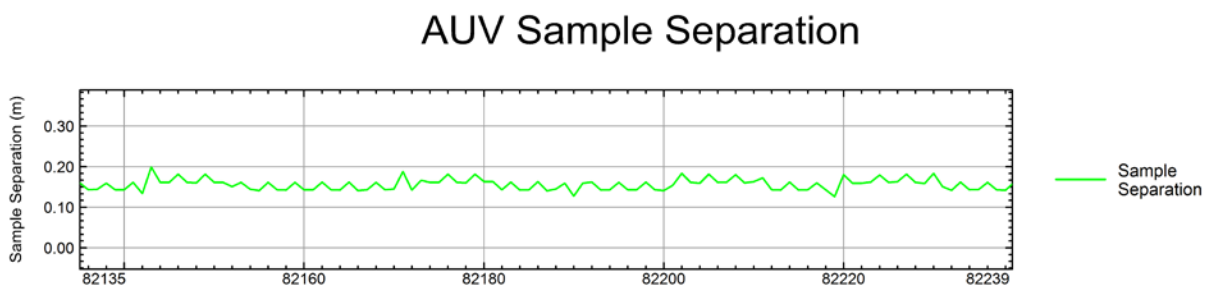


Figure 7-3 Sample Separation Along a 20-Second Segment of a Typical Survey Line

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 7-4** 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.

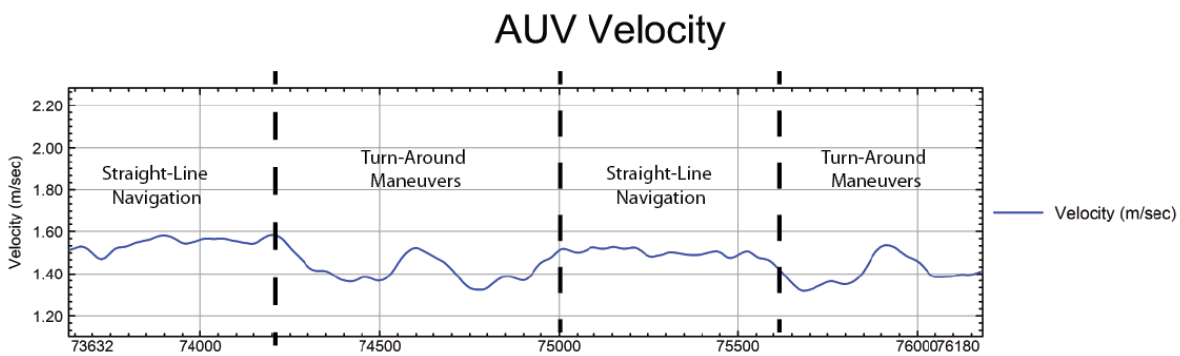


Figure 7-4 Velocity Profile of a Typical AUV Survey Area Traversal

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. **Figure 7-5** shows a uniform sliding box survey pattern designed to achieve full coverage across a bounded survey area.

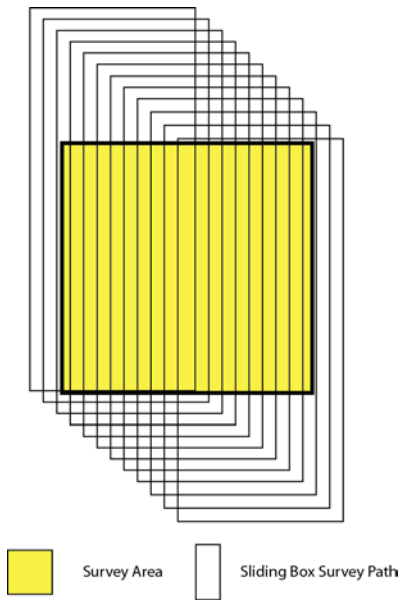


Figure 7-5 Example Sliding Box Survey Pattern in Relation to a Square Survey Area

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 limit 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.

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.

Positional information as measured by the AUV is detailed in **Table 7-4** for the calibration grid seed items and in **Table 7-5** for the blind grid seed items. These data points include offset, standard deviation of each northing and easting measurement and the DRMS of each measured coordinate.

Table 7-4 Calibration Grid Seed Item Detection Information by Mission

		Mission 3				Mission 4			
Seed ID	**Item Type**	**Offset (m)**	**σN**	**σE**	**DRMS**	**Offset (m)**	**σN**	**σE**	**DRMS**
CAL-06	75mm	1.43	0.72	0.71	1.98	1.10	0.74	0.23	1.52
CAL-07	60mm	-	-	-	-	-	-	-	-
CAL-08	60mm	2.63	0.28	1.84	3.64	-	-	-	-
CAL-09	81mm	0.33	0.23	0.00	0.45	1.10	0.76	0.17	1.53
CAL-10	60mm	1.23	0.56	0.66	1.70	0.21	0.14	0.05	0.30
CAL-11	60mm	-	-	-	-	-	-	-	-
CAL-12	75mm	0.54	0.36	0.12	0.75	0.99	0.70	0.06	1.37
CAL-13	155mm	0.41	0.21	0.20	0.56	1.51	0.92	0.55	2.09
CAL-15	75mm	-	-	-	-	1.13	0.66	0.45	1.56
CAL-16	60mm	1.85	0.68	1.12	2.57	-	-	-	-
CAL-17	75mm	1.15	0.37	0.72	1.59	0.27	0.02	0.19	0.38
CAL-18	60mm	-	-	-	-	-	-	-	-
CAL-19	81mm	1.10	0.28	0.73	1.52	1.10	0.28	0.73	1.52
CAL-20	75mm	1.53	0.06	1.08	2.11	0.28	0.12	0.16	0.39
Mean Values		1.22	0.38	0.72	1.69	0.85	0.48	0.29	1.18

Notes:

E = easting
N = northing

Table 7-5 Blind Grid Seed Item Detection Information by Mission

		Mission 1				Mission 2				Mission 3				Mission 4				Mission 5			
Seed ID	**Item Type**	**Offset (m)**	**σN**	**σE**	**DRMS**	**Offset (m)**	**σN**	**σE**	**DRMS**	**Offset (m)**	**σN**	**σE**	**DRMS**	**Offset (m)**	**σN**	**σE**	**DRMS**	**Offset (m)**	**σN**	**σE**	**DRMS**
BND-04	75mm	0.64	0.30	0.34	0.89	1.02	0.05	0.72	1.42	-	-	-	-	-	-	-	-	-	-	-	-
BND-05	60mm	1.00	0.54	0.46	1.38	1.68	0.36	1.14	2.33	-	-	-	-	-	-	-	-	0.66	0.18	0.43	0.91
BND-06	75mm	0.66	0.46	0.03	0.91	0.16	0.11	0.03	0.22	-	-	-	-	-	-	-	-	1.29	0.07	0.91	1.79
BND-07	60mm	0.26	0.12	0.14	0.36	2.34	0.29	1.63	3.24	-	-	-	-	0.84	0.59	0.04	1.16	-	-	-	-
BND-08	75mm	0.06	0.02	0.04	0.09	2.02	0.38	1.38	2.8	-	-	-	-	-	-	-	-	-	-	-	-
BND-09	81mm	0.52	0.36	0.08	0.73	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BND-10	60mm	1.61	0.63	0.95	2.23	-	-	-	-	2.20	0.28	1.56	3.1	1.36	0.96	0.07	1.89	1.64	0.28	1.13	2.28
BND-11	75mm	0.96	0.65	0.20	1.33	2.72	0.12	1.92	3.77	-	-	-	-	-	-	-	-	-	-	-	-
BND-12	75mm	0.77	0.45	0.30	1.06	0.78	0.28	0.47	1.07	1.40	0.07	0.92	1.81	0.91	0.43	0.47	1.26	2.61	1.32	1.29	3.62
BND-13	81mm	0.81	0.06	0.57	1.12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BND-14	155mm	-	-	-	-	2.24	0.47	1.51	3.1	-	-	-	-	-	-	-	-	-	-	-	-
BND-15	60mm	0.16	0.08	0.08	0.22	1.93	0.26	1.34	2.67	-	-	-	-	-	-	-	-	-	-	-	-
BND-16	60mm	0.34	0.03	0.24	0.48	1.67	0.15	1.17	2.32	-	-	-	-	1.30	0.91	0.11	1.8	0.79	0.56	0.06	1.1
BND-17	60mm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.02	1.41	0.21	2.8
BND-18	105mm	0.20	0.12	0.09	0.28	0.36	0.24	0.09	0.5	-	-	-	-	1.71	1.12	0.44	2.36	1.84	1.30	0.09	2.55
BND-19	60mm	1.10	0.65	0.43	1.53	1.90	0.12	1.34	2.63	-	-	-	-	2.66	0.83	1.69	3.69	1.28	0.65	0.63	1.77
BND-20	155mm	0.79	0.56	0.08	1.1	1.88	0.20	1.32	2.61	-	-	-	-	-	-	-	-	0.12	0.03	0.08	0.16
BND-21	105mm	1.22	0.74	0.43	1.68	-	-	-	-	-	-	-	-	1.91	0.21	1.33	2.65	1.66	0.21	1.16	2.31
BND-22	75mm	0.74	0.46	0.25	1.02	2.44	0.46	1.66	3.38	-	-	-	-	1.85	1.16	0.60	2.57	0.61	0.07	0.42	0.84
Mean Values		0.70	0.37	0.28	0.97	1.65	0.25	1.12	2.29	1.80	0.18	1.24	2.45	1.57	0.78	0.59	2.17	1.32	0.55	0.58	1.83

A summary of the detection results is provided in **Table 7-6**. Detection percentages are calculated based on the number of seed items within the survey footprint of each mission.

Table 7-6 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 7-6**. Compensated data sample-to-sample noise in areas where no anomalies are present is approximately 0.6 nT. Sample-to-sample noise analysis was performed at a location where no magnetic anomalies were apparent.

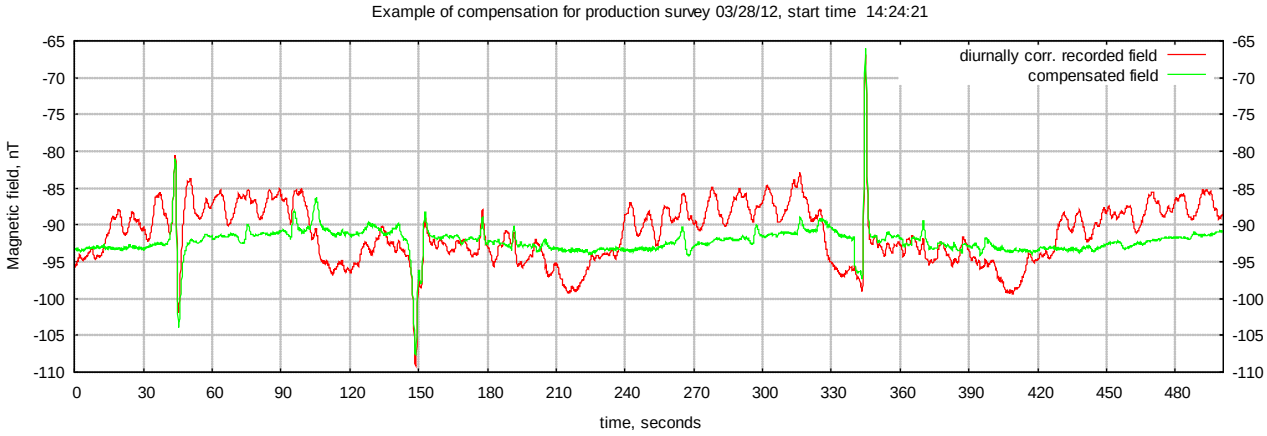


Figure 7-6 Example Production Survey Compensation Results

7.7 OBJECTIVE: NOISE REDUCTION PERFORMANCE USING MAGNETIC COMPENSATION

IRs for data collected on 28 March 2012 ranged from 5.1 to 7.6 when all terms were used. IRs for data collected on 29 March 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 Field 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. Either a more accurate measurement of current or a different mathematical treatment of measured current may be required to differentiate long-term from short-term current changes.

7.8 OBJECTIVE: DETECTION OF ALL SEEDED ITEMS

Grid surveys were performed over 2 days (28 and 29 March, 2012) during the AUV field 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. The grid surveys and corresponding mission numbers are detailed in **Table 7-7**.

Table 7-7 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

7.8.1 Calibration Grid Surveys

Both surveys over the calibration grid (Missions 3 and 4 for the day) were collected at an altitude of 2 m, and both used the same mission plan design. Because of time constraints, a mission length was used for both missions that only allowed 14 seeds within the calibration grid to be surveyed.

7.8.1.1 *Mission 3 – 2-m Altitude*

Figure 7-7 is an analytic signal contour plot of magnetic data collected during Mission 3 over the calibration grid. Of the 14 targets traversed during the survey, 10 were detected; however, not all were detected within the 1-meter offset metric. The response of 13.7 nT noted in the data for seed item CAL-10, a 60mm mortar, is not consistent with responses observed from other seed items within the calibration test bed and is most likely indicative that the item is being masked by a larger existing anomaly.

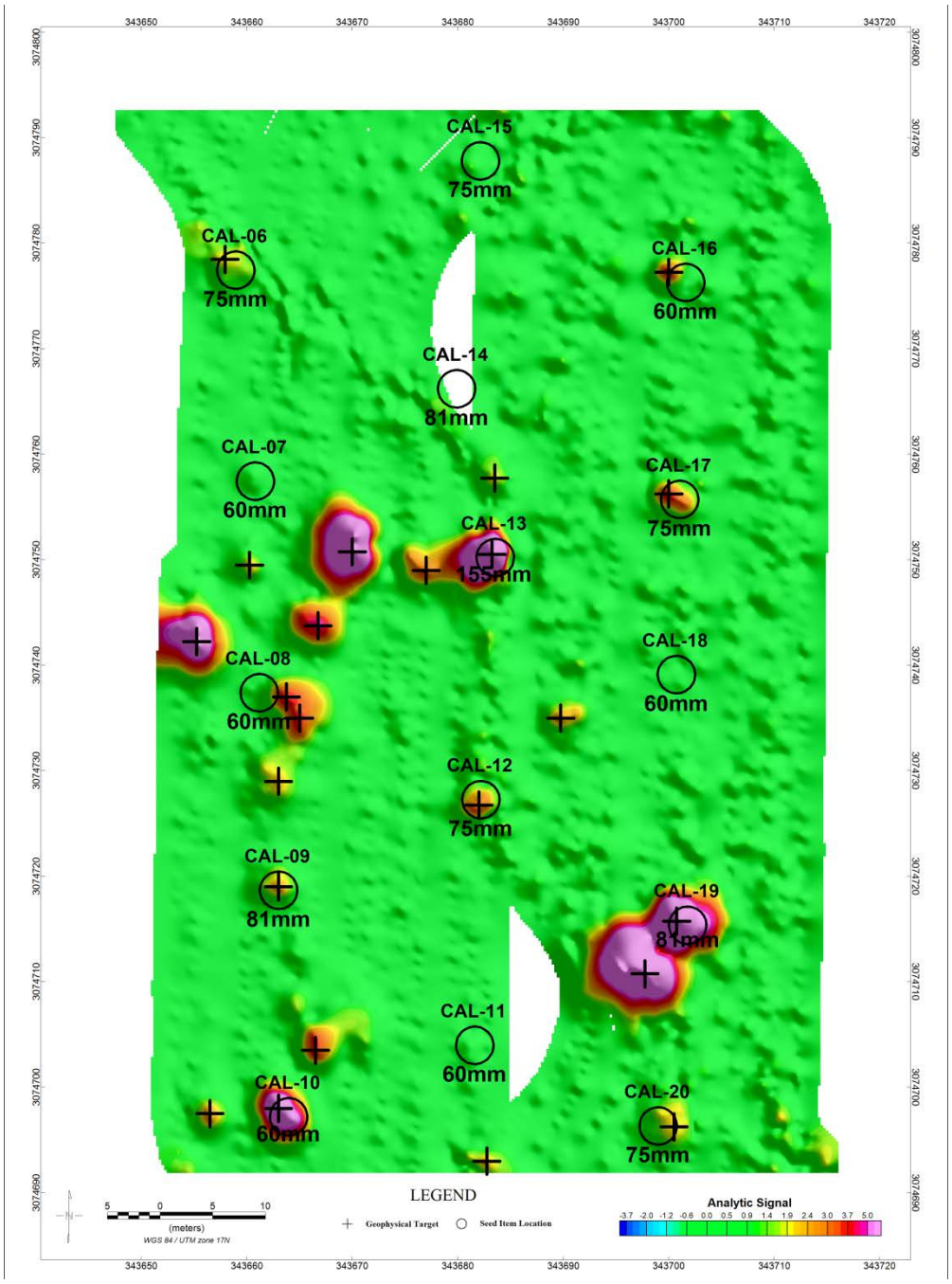


Figure 7-7 Mission 3 Contoured Analytic Signal Data Collected at the Calibration Grid Survey Area at an Altitude of 2 Meters

Detection results for each seed item traversed during Mission 3 are detailed in **Table 7-8.** Two areas within the AUV survey footprint were not surveyed because of the sliding box pattern that was used in the mission program. As a result, seed item CAL-14 is excluded from the detection results table because it is located within one of the areas not covered during the survey.

Table 7-8 Detection Results for Mission 3 - Calibration Grid Survey

Calibration Grid - Mission 3 – 2-m Altitude									
Seed ID	**Item Type**	**Detect/Non-Detect**	**Offset (m)**	**Response (nT)**	**Altitude (m)**	**ΔN**	**ΔE**	**σN**	**σE**
CAL-06	75mm	Detect	1.43	1.95	2.01	1.02	1.00	0.72	0.71
CAL-07	60mm	Non-Detect							
CAL-08	60mm	Detect	2.63	3.80	1.8	0.40	2.60	0.28	1.84
CAL-09	81mm	Detect	0.33	2.51	1.88	0.33	0.01	0.23	0.00
CAL-10	60mm	Detect	1.23	13.68	1.68	0.80	0.93	0.56	0.66
CAL-11	60mm	Non-Detect							
CAL-12	75mm	Detect	0.54	2.99	1.81	0.51	0.17	0.36	0.12
CAL-13	155mm	Detect	0.41	23.68	1.77	0.29	0.28	0.21	0.20
CAL-15	75mm	Non-Detect							
CAL-16	60mm	Detect	1.85	3.80	1.59	0.96	1.59	0.68	1.12
CAL-17	75mm	Detect	1.15	3.87	2.05	0.53	1.02	0.37	0.72
CAL-18	60mm	Non-Detect							
CAL-19	81mm	Detect	1.10	30.85	1.99	0.39	1.03	0.28	0.73
CAL-20	75mm	Detect	1.53	2.09	1.84	0.09	1.52	0.06	1.08
Summary		10/14 Detected	Mean Values						
			1.22	n/a	1.84	0.53	1.01	0.38	0.72

Of the 14 items traversed during the survey, 10 were detected within the magnetic data, and of those 10 items, only 2 were detected within the 0.5-m offset metric. These offset exceedances are most likely a result of the 1.5-m to 2.7-m line spacing, which was wider than planned and limits the lateral resolution of the survey, restricting the accuracy of the target detection. The AUV traversed directly over seed items CAL-09, CAL-12, and CAL-13; consequently, these items have the smallest detection offset distances.

7.8.1.2 *Mission 4 – 2-m Altitude*

Figure 7-8 is an analytic signal contour plot of magnetic data collected during Mission 4 over the calibration grid. The mission plan used for Mission 4 was the same plan used for Mission 3; however, seed item CAL-14 was traversed during this survey because of the variation between the planned and actual AUV survey paths. A total of 15 seed items were traversed during the survey, 9 of which were detected during the survey. CAL-10 was again detected at a much higher response than would be expected from a 60-mm mortar at this survey altitude. Detection results for seed items traversed during Mission 4 are detailed in **Table 7-9**.

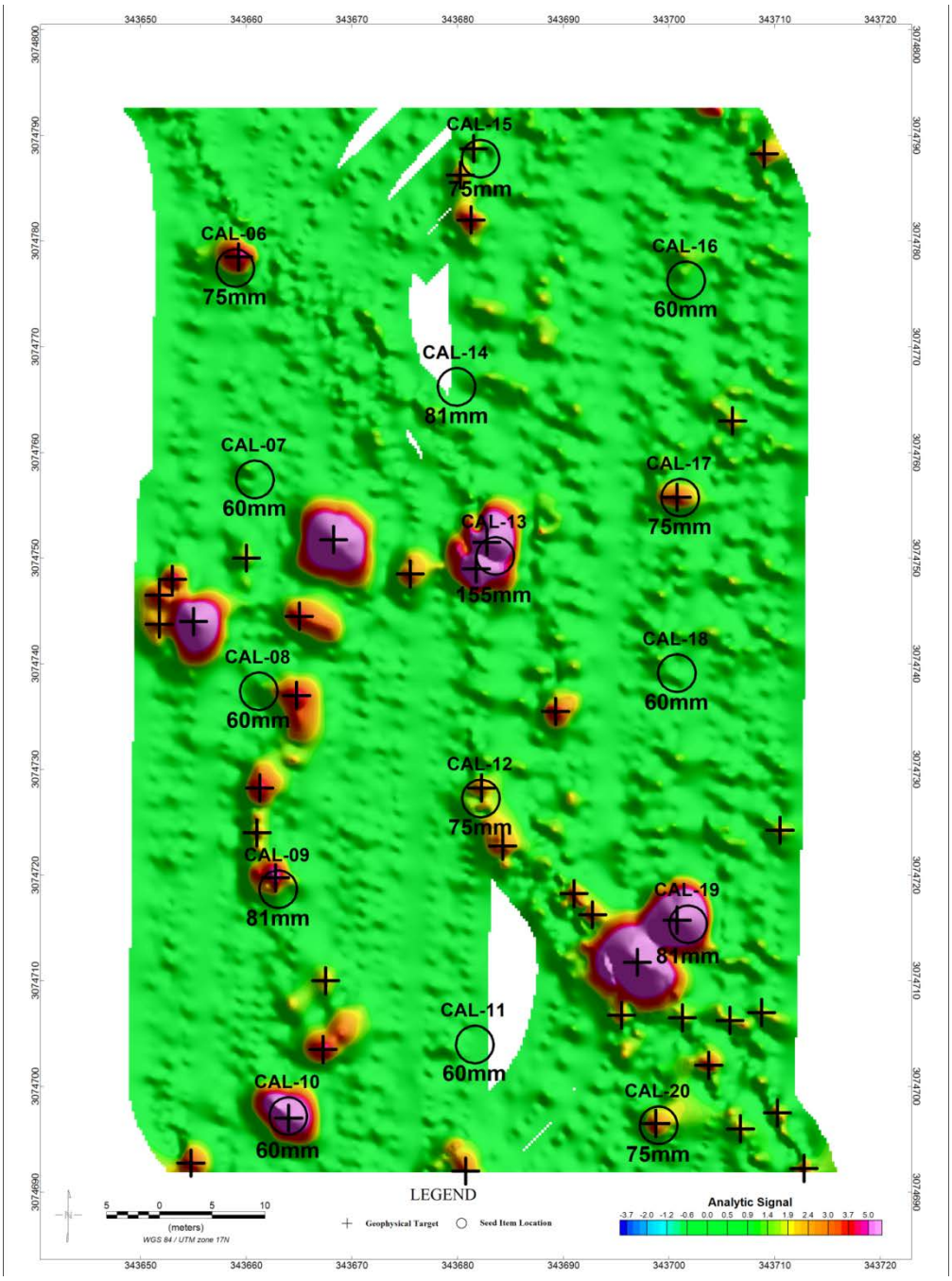


Figure 7-8 Mission 4 Contoured Analytic Signal Data Collected at the Calibration Grid Survey Area at an Altitude of 2 Meters

Table 7-9 Detection Results for Mission 4 - Calibration Grid Survey

Calibration Grid - Mission 4 – 2-m Altitude									
Seed ID	**Item Type**	**Detect/Non-Detect**	**Offset (m)**	**Response (nT)**	**Altitude (m)**	**ΔN**	**ΔE**	**σN**	**σE**
CAL-06	75mm	Detect	1.10	4.63	2.17	1.05	0.33	0.74	0.23
CAL-07	60mm	Non-Detect							
CAL-08	60mm	Non-Detect							
CAL-09	81mm	Detect	1.10	6.64	1.53	1.08	0.24	0.76	0.17
CAL-10	60mm	Detect	0.21	11.63	1.90	0.20	0.07	0.14	0.05
CAL-11	60mm	Non-Detect							
CAL-12	75mm	Detect	0.99	2.64	2.04	0.99	0.08	0.70	0.06
CAL-13	155mm	Detect	1.51	26.44	1.76	1.29	0.78	0.92	0.55
CAL-14	81mm	Non-Detect							
CAL-15	75mm	Detect	1.13	2.25	2.17	0.93	0.63	0.66	0.45
CAL-16	60mm	Non-Detect							
CAL-17	75mm	Detect	0.27	3.27	1.83	0.03	0.27	0.02	0.19
CAL-18	60mm	Non-Detect							
CAL-19	81mm	Detect	1.10	38.89	2.07	0.39	1.03	0.28	0.73
CAL-20	75mm	Detect	0.28	3.17	2.04	0.16	0.23	0.12	0.16
Summary		9/15 Detected	**Mean Values**						
			0.85	n/a	1.95	0.68	0.41	0.48	0.29

Of the 15 items traversed during the survey, 9 were detected within the magnetic data and of those 9, 3 were detected within the 0.5-m offset metric. As with Mission 3, the offset exceedances are likely due to the limited lateral resolution caused by the 1.5-m to 2.7-m transect spacing. Seed items that were directly in line with the AUV path were detected within 0.5 m of the actual location (CAL-10, CAL-17, CAL-20).

7.8.2 Blind Grid Surveys

7.8.2.1 *Mission 1 – 1.5 m-Altitude*

Figure 7-9 is an analytic signal contour plot of magnetic data collected during Mission 1 over the blind grid survey area. Data were collected at a planned altitude of 1.5 m using a sliding box survey pattern. A total of 19 seed items were traversed during the survey, 17 of which were detected. Detection results for seed items traversed during Mission 1 are detailed in **Table 7-10**.

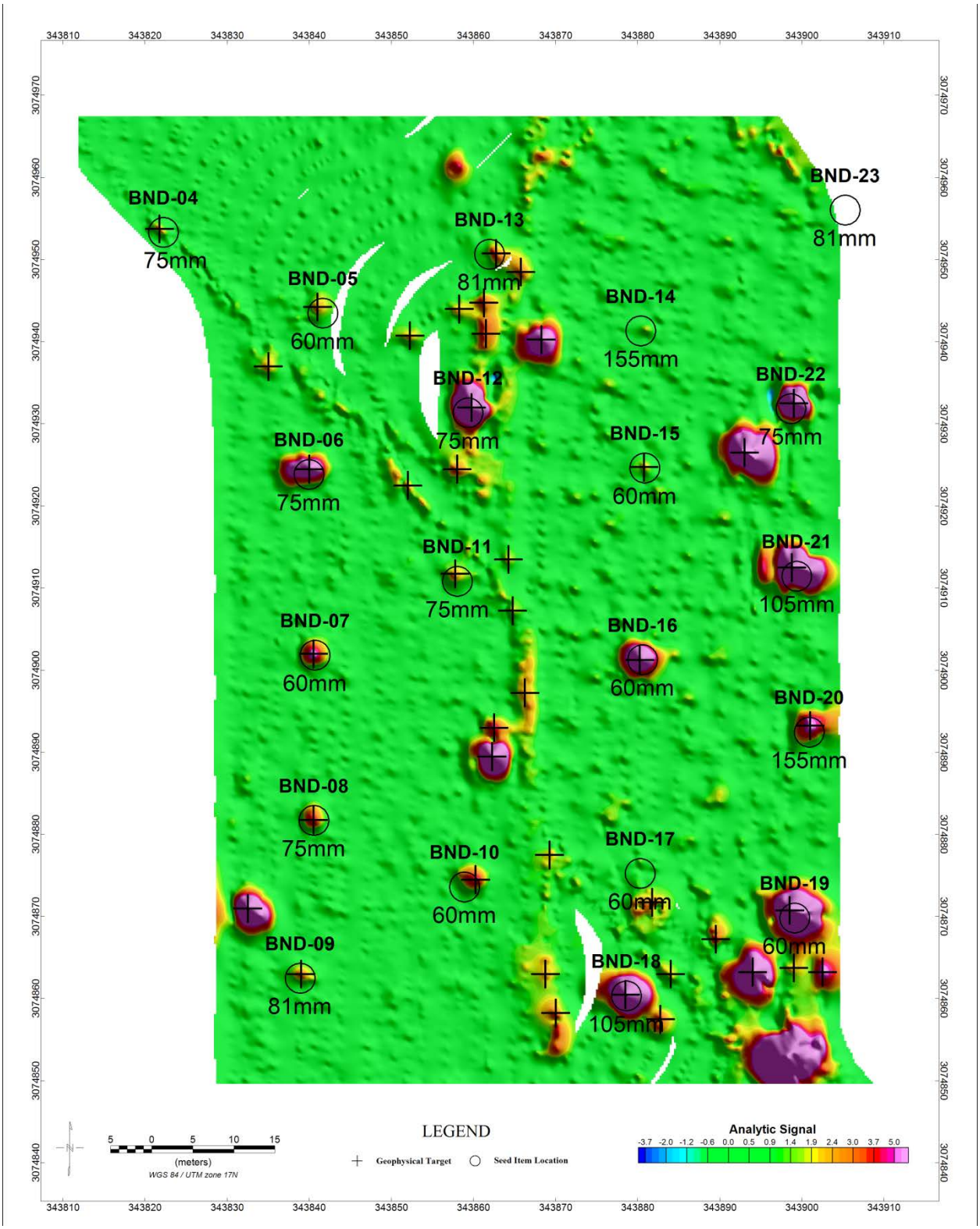


Figure 7-9 Mission 1 Contoured Analytic Signal Data Collected at the Blind Grid Survey Area at an Altitude of 1.5 Meters

Table 7-10 Detection Results for Mission 1 - Blind Grid Survey

Blind Grid - Mission 1 to 1.5-m Altitude									
Seed ID	**Item Type**	**Detect/Non-Detect**	**Offset (m)**	**Response (nT)**	**Altitude (m)**	**ΔN**	**ΔE**	**σN**	**σE**
BND-04	75mm	Detect	0.64	2.63	1.59	0.43	0.48	0.30	0.34
BND-05	60mm	Detect	1.00	2.57	1.67	0.76	0.64	0.54	0.46
BND-06	75mm	Detect	0.66	14.69	1.13	0.66	0.04	0.46	0.03
BND-07	60mm	Detect	0.26	6.30	1.15	0.17	0.20	0.12	0.14
BND-08	75mm	Detect	0.06	4.48	1.13	0.04	0.05	0.02	0.04
BND-09	81mm	Detect	0.52	2.98	1.22	0.51	0.12	0.36	0.08
BND-10	60mm	Detect	1.61	4.38	1.27	0.89	1.35	0.63	0.95
BND-11	75mm	Detect	0.96	2.64	1.13	0.91	0.29	0.65	0.20
BND-12	75mm	Detect	0.77	90.17	1.05	0.64	0.42	0.45	0.30
BND-13	81mm	Detect	0.81	3.52	1.20	0.09	0.80	0.06	0.57
BND-14	155mm	Non-Detect							
BND-15	60mm	Detect	0.16	2.33	1.54	0.11	0.11	0.08	0.08
BND-16	60mm	Detect	0.34	19.37	1.26	0.04	0.34	0.03	0.24
BND-17	60mm	Non-Detect							
BND-18	105mm	Detect	0.20	48.20	1.56	0.16	0.12	0.12	0.09
BND-19	60mm	Detect	1.10	35.05	1.23	0.92	0.61	0.65	0.43
BND-20	155mm	Detect	0.79	6.31	1.17	0.79	0.11	0.56	0.08
BND-21	105mm	Detect	1.22	68.05	0.96	1.05	0.61	0.74	0.43
BND-22	75mm	Detect	0.74	67.97	0.89	0.65	0.35	0.46	0.25
Summary		17/19 Detected	**Mean Values**						
			0.70	n/a	1.14	0.52	0.39	0.37	0.28

Of the 19 items traversed during the survey, 17 were detected within the magnetic data, and of the 17 items, 5 were detected within 0.5 m of the seed location, 8 were detected between 0.5 and 1 m, and 4 were outside 1 m.

7.8.2.2 *Mission 2 – 1.5-m Altitude*

Mission 2 is a repeat of Mission 1 and used the same mission plan. Data were collected at a planned altitude of 1.5 m using a sliding box survey pattern. **Figure 7-10** is an analytic signal contour plot of magnetic data collected during Mission 2 over the blind grid survey area. A total of 19 seed items were traversed during the survey, 14 of which were detected. Detection results for seed items traversed during Mission 2 are detailed in **Table 7-11**.

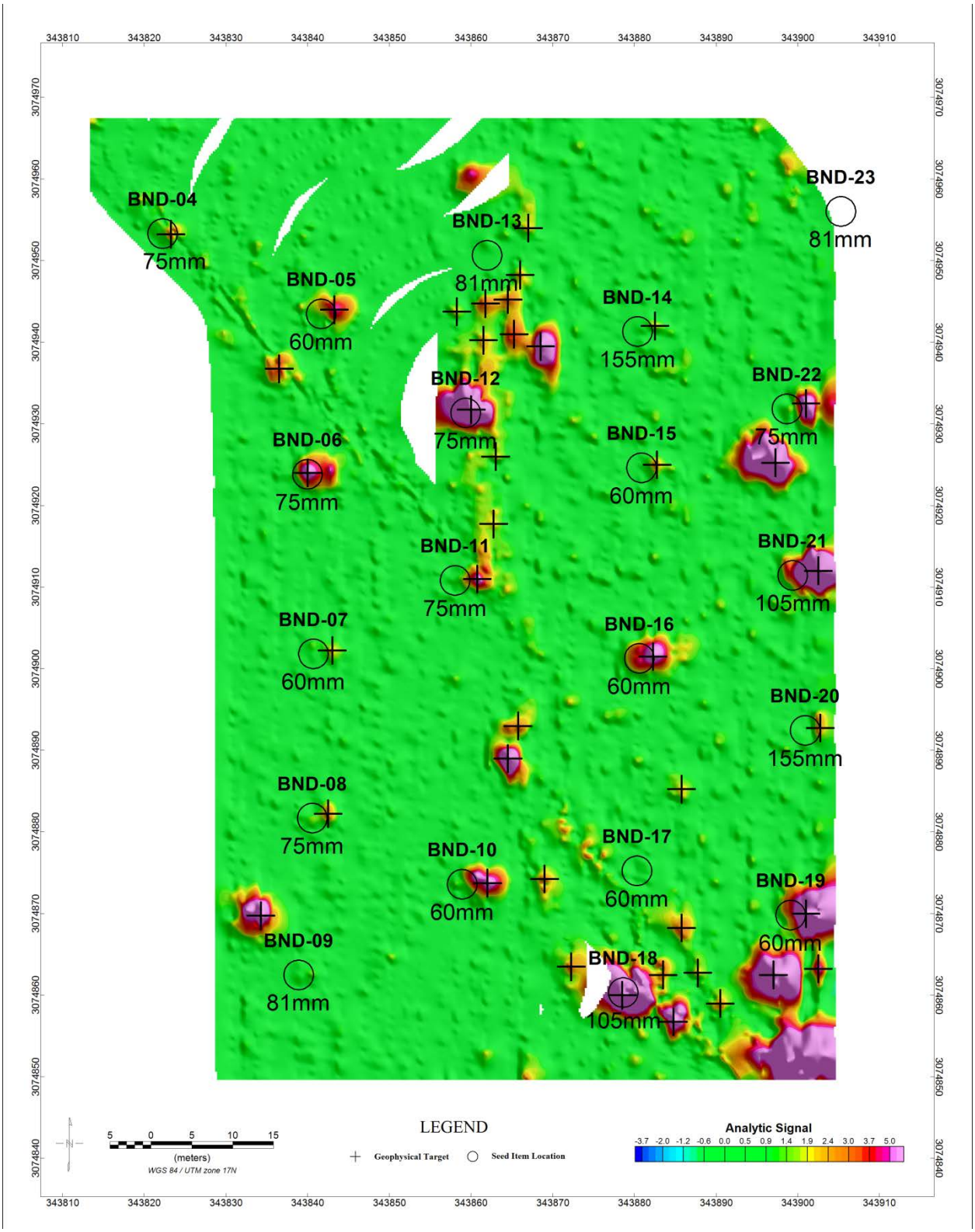


Figure 7-10 Mission 2 Contoured Analytic Signal Data Collected at the Blind Grid Survey Area at an Altitude of 1.5 Meters

Table 7-11 Detection Results for Mission 2 - Blind Grid Survey

Blind Grid - Mission 2 - 1.5-m Altitude									
Seed ID	**Item Type**	**Detect/Non-Detect**	**Offset (m)**	**Response (nT)**	**Altitude (m)**	**ΔN**	**ΔE**	**σN**	**σE**
BND-04	75mm	Detect	1.02	3.67	1.47	0.07	1.02	0.05	0.72
BND-05	60mm	Detect	1.68	5.42	1.30	0.51	1.61	0.36	1.14
BND-06	75mm	Detect	0.16	9.40	1.17	0.16	0.04	0.11	0.03
BND-07	60mm	Detect	2.34	2.17	1.27	0.42	2.30	0.29	1.63
BND-08	75mm	Detect	2.02	2.65	1.37	0.54	1.95	0.38	1.38
BND-09	81mm	Non-Detect							
BND-10	60mm	Non-Detect							
BND-11	75mm	Detect	2.72	6.94	1.48	0.16	2.71	0.12	1.92
BND-12	75mm	Detect	0.78	28.29	1.27	0.39	0.67	0.28	0.47
BND-13	81mm	Non-Detect							
BND-14	155mm	Detect	2.24	2.22	1.20	0.67	2.14	0.47	1.51
BND-15	60mm	Detect	1.93	2.57	1.41	0.36	1.89	0.26	1.34
BND-16	60mm	Detect	1.67	9.27	1.42	0.21	1.66	0.15	1.17
BND-17	60mm	Non-Detect							
BND-18	105mm	Detect	0.36	33.55	1.45	0.34	0.12	0.24	0.09
BND-19	60mm	Detect	1.90	28.45	1.11	0.17	1.89	0.12	1.34
BND-20	155mm	Detect	1.88	2.56	1.30	0.29	1.86	0.20	1.32
BND-21	105mm	Non-Detect							
BND-22	75mm	Detect	2.44	8.58	1.30	0.65	2.35	0.46	1.66
Summary		14/19 Detected	**Mean Values**						
			1.65	n/a	1.32	0.35	1.59	0.25	1.12

Of the 19 items traversed during the survey, 14 were detected within the magnetic data, and of the 14 items, 2 were detected within 0.5 m of the seed location, 1 was detected between 0.5 and 1 m, and 11 were outside 1 m.

7.8.2.3 *Mission 3 – 3-m Altitude*

Figure 7-11 is an analytic signal contour plot of magnetic data collected during Mission 3 over the blind grid survey area. Data were collected at a planned altitude of 3 m using a lawnmower survey pattern. The duration of the 3-m altitude survey was limited due to schedule constraints as well as battery power, which resulted in a limited amount of survey coverage. A total of 4 seed items were traversed during the survey, 2 of which were detected. Detection results for seed items traversed during Mission 3 are detailed in **Table 7-12.**

Figure 7-11 Mission 3 Contoured Analytic Signal Data Collected at the Blind Grid Survey Area at an Altitude of 3 Meters

Table 7-12 Detection Results for Mission 3 - Blind Grid Survey

Blind Grid - Mission 3 – 3-m Altitude									
Seed ID	**Item Type**	**Detect/Non-Detect**	**Offset (m)**	**Response (nT)**	**Altitude (m)**	**ΔN**	**ΔE**	**σN**	**σE**
BND-10	60mm	Detect	2.20	2.00	3.17	0.4	2.2	0.28	1.56
BND-11	75mm	Non-Detect							
BND-12	75mm	Detect	1.40	2.30	3.22	0.1	1.3	0.07	0.92
BND-13	81mm	Non-Detect							
Summary		2/4 Detected	**Mean Values**						
			1.80	n/a	3.2	0.25	1.75	0.18	1.24

Of the 4 seed items traversed during the survey, 2 were detected within the magnetic data, and both were outside the 0.5-m offset metric.

7.8.2.4 *Mission 4 – 2-m Altitude*

Data for Mission 4 were collected at an altitude of 2 m using a sliding box survey pattern. **Figure 7-1**2 is an analytic signal contour plot of magnetic data collected during Mission 4 over the blind grid survey area. A total of 19 seed items were traversed during the survey, 8 of which were detected. Detection results for seed items traversed during Mission 4 are detailed in **Table 7-13**.

During data analysis, a consistent positional offset noted in the data was possibly caused by a poor GPS positional fix obtained prior to the dive. The location of a single seed item was used to determine the positional offset, and a bulk positional shift was applied to the data to correct the positioning.

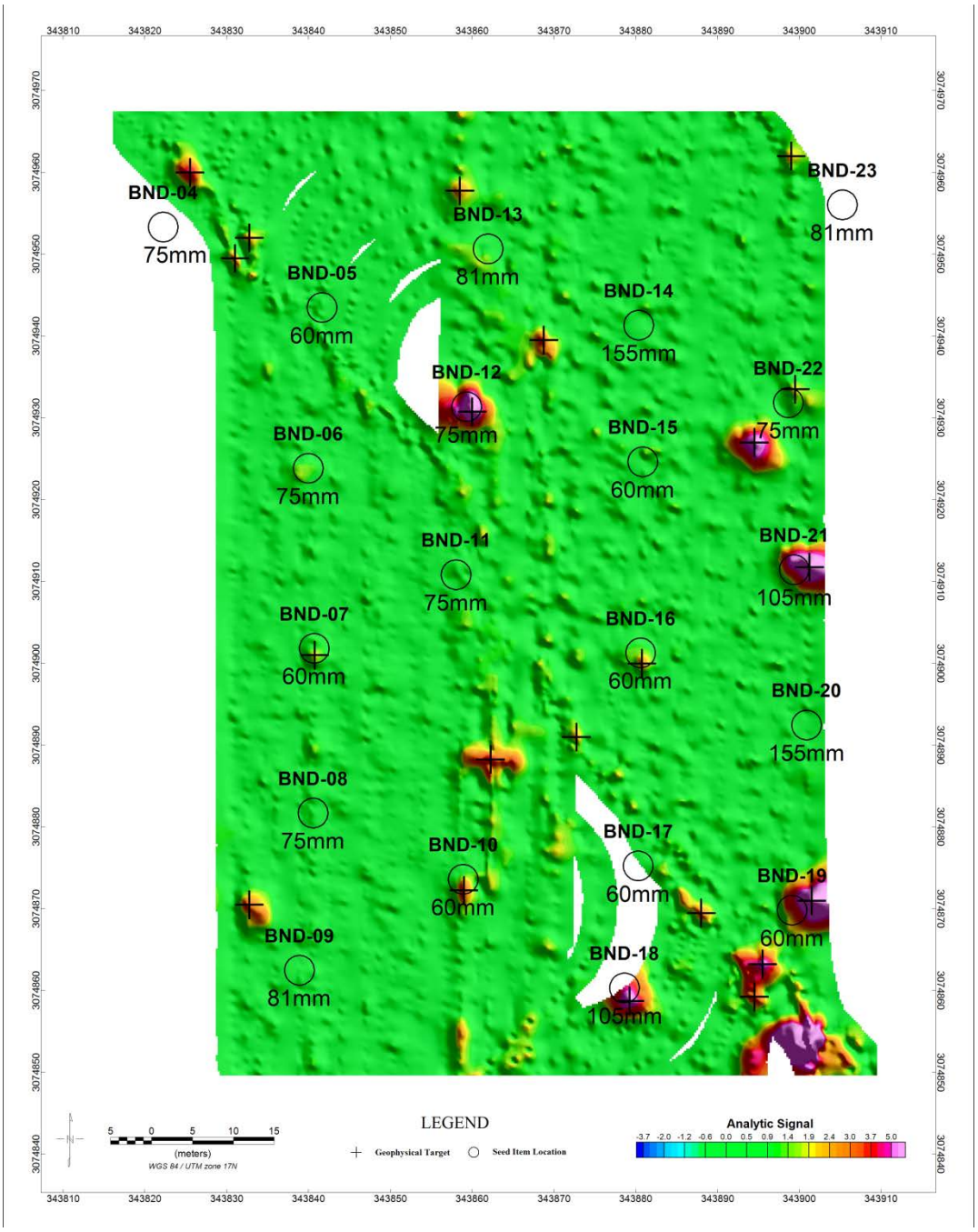


Figure 7-12 Mission 4 Contoured Analytic Signal Data Collected at the Blind Grid Survey Area at an Altitude of 2 Meters

Table 7-13 Detection Results for Mission 4 - Blind Grid Survey

Blind Grid - Mission 4 – 2-m Altitude									
Seed ID	**Item Type**	**Detect/Non-Detect**	**Offset (m)**	**Response (nT)**	**Altitude (m)**	**ΔN**	**ΔE**	**σN**	**σE**
BND-05	60mm	Non-Detect							
BND-06	75mm	Non-Detect							
BND-07	60mm	Detect	0.84	2.16	2.23	0.83	0.05	0.59	0.04
BND-08	75mm	Non-Detect							
BND-09	81mm	Non-Detect							
BND-10	60mm	Detect	1.36	3.45	2.22	1.36	0.10	0.96	0.07
BND-11	75mm	Non-Detect							
BND-12	75mm	Detect	0.91	10.77	2.19	0.61	0.67	0.43	0.47
BND-13	81mm	Non-Detect							
BND-14	155mm	Non-Detect							
BND-15	60mm	Non-Detect							
BND-16	60mm	Detect	1.30	2.52	2.22	1.29	0.16	0.91	0.11
BND-17	60mm	Non-Detect							
BND-18	105mm	Detect	1.71	7.10	2.65	1.59	0.63	1.12	0.44
BND-19	60mm	Detect	2.66	12.15	1.57	1.17	2.39	0.83	1.69
BND-20	155mm	Non-Detect							
BND-21	105mm	Detect	1.91	11.26	2.22	0.30	1.89	0.21	1.33
BND-22	75mm	Detect	1.85	2.01	2.22	1.65	0.85	1.16	0.60
Summary		8/19 Detected	**Mean Values**						
			1.57	n/a	2.19	1.10	0.84	0.78	0.59

Of the 18 items traversed during the survey, 8 were detected within the magnetic data, and of the 8 items detected, 2 were detected within 1 m of the seed location, and 6 were outside 1 m.

7.8.2.5 *Mission 5 – 2-m Altitude*

Mission 5 is a repeat of Mission 4 and used the same mission plan. Data for Mission 5 were collected at an altitude of 2 m using a sliding box survey pattern. **Figure 7-13** shows an analytic signal contour plot of magnetic data collected during Mission 5 over the blind grid survey area. A total of 19 seed items were traversed during the survey, 11 of which were detected. Detection results for seed items traversed during Mission 5 are detailed in **Table 7-14**.

During data analysis, a consistent positional offset noted in the data was possibly caused by a poor GPS positional fix obtained prior to the dive. The location of a single seed item was used to determine the positional offset, and a bulk positional shift was applied to the data to correct the positioning.

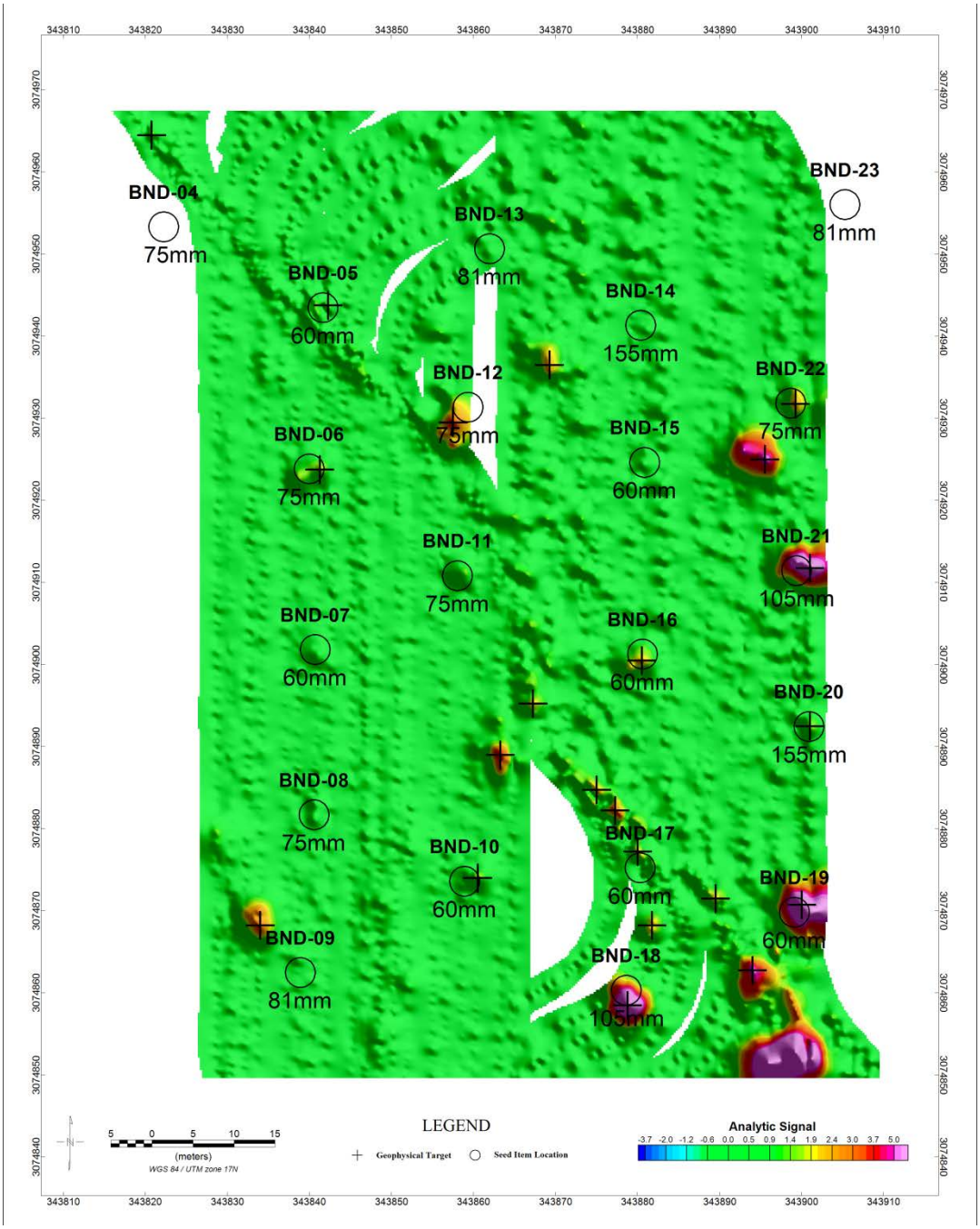


Figure 7-13 Mission 5 Contoured Analytic Signal Data Collected at the Blind Grid Survey Area at an Altitude of 2 Meters

Table 7-14 Detection Results for Mission 5 - Blind Grid Survey

Blind Grid - Mission 5 – 2-m Altitude									
Seed ID	**Item Type**	**Detect/Non-Detect**	**Offset (m)**	**Response (nT)**	**Altitude (m)**	**ΔN**	**ΔE**	**σN**	**σE**
BND-05	60mm	Detect	0.66	1.53	2.24	0.26	0.61	0.18	0.43
BND-06	75mm	Detect	1.29	1.80	2.22	0.09	1.29	0.07	0.91
BND-07	60mm	Non-Detect							
BND-08	75mm	Non-Detect							
BND-09	81mm	Non-Detect							
BND-10	60mm	Detect	1.64	1.77	2.20	0.39	1.60	0.28	1.13
BND-11	75mm	Non-Detect							
BND-12	75mm	Detect	2.61	3.20	2.22	1.86	1.83	1.32	1.29
BND-13	81mm	Non-Detect							
BND-14	155mm	Non-Detect							
BND-15	60mm	Non-Detect							
BND-16	60mm	Detect	0.79	2.38	2.19	0.79	0.09	0.56	0.06
BND-17	60mm	Detect	2.02	2.25	2.19	2.00	0.29	1.41	0.21
BND-18	105mm	Detect	1.84	13.69	2.22	1.84	0.13	1.30	0.09
BND-19	60mm	Detect	1.28	13.46	2.25	0.92	0.89	0.65	0.63
BND-20	155mm	Detect	0.12	1.65	2.18	0.04	0.11	0.03	0.08
BND-21	105mm	Detect	1.66	9.84	2.20	0.30	1.64	0.21	1.16
BND-22	75mm	Detect	0.61	2.39	2.58	0.10	0.60	0.07	0.42
Summary		11/19 Detected	**Mean Values**						
			1.32	n/a	2.24	0.78	0.82	0.55	0.58

Of the 18 items traversed during the survey, 11 were detected within the magnetic data. Of the 11 items detected, 4 were detected within 1 m of the seed location and 7 were outside 1 m.

8. COST ASSESSMENT

8.1 COST MODEL

The cost model for this demonstration is based upon site preparation, mobilization and demobilization, and survey production costs. **Table 8-1** lists the cost elements and the data that were captured during the AUV MEC Detection System demonstration. These elements were used to support the development of a technology cost model.

Table 8-1 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 INSTRUMENT COST

Costs were developed based on the demonstration. Hardware cost estimates were based on actual project costs. Hardware costs include the blank payload module, G-880AUV, fluxgate compass, and associated components. Lessons learned from the system development were used to separate non-recurring engineering costs from effort needed for fabrication. Capital purchases and mechanical and electrical engineering during system integration totaled $300,000.

8.2.1 MOBILIZATION/DEMOBILIZATION

Mobilization and demobilization were directly derived from the demonstration and totaled $13,000. This included costs for a three-person crew to travel to the demonstration site in Florida with the AUV MEC Detection System.

8.2.2 SITE PREPARATION

Site preparation includes the preparation of seed items and the actual deployment of seed items. Labor and materials needed for the seed item preparation were tracked. Seed item deployment costs include vessel support costs, geolocation surveys, and processing and analysis costs totaling $40,000.

8.2.3 INSTRUMENT SETUP COSTS

Instrument setup costs were based on crew size and number of hours required to set up the AUV for deployment. 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).

8.2.4 SURVEY COSTS

Survey costs were evaluated based on effective survey duration, crew size, and coverage rate. Survey duration was based on hours per day spent on the water for survey operations. A crew consisting of three personnel is required for AUV deployment. Coverage was based on the performance requirements (1-m across line spacing and a nominal dynamic speed of 1.5 meters per second). Survey acquisition equated to approximately 1 hectare/3.5 hrs for a total cost of $4,500/hectare.

8.2.5 DETECTION DATA PROCESSING COSTS

Data processing was slightly more complicated than for typical terrestrial surveys. Data processing requirements were monitored based on the steps required to complete the analysis. The data integration, pre-processing, and post-processing steps were tracked by element and number of hours required to complete each dataset. Data processing is approximately $800/hectare of data.

8.3 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. The initial instrumentation costs are substantial; however, these are non-recurring costs that shouldn’t be a factor in the long-term operational cost of the system.

8.4 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 interference (EMI) sensors. The Underwater Simultaneous EMI and Magnetometer System (USEMS) (Siegel, ESTCP Project MR-200733) and Marine Towed Array (MTA) (McDonald, ESTCP Project MR-0324) systems are underwater mapping and detection systems capable of operating in water 3.7-m and approximately 10-m deep, respectively.

The initial investment costs for each system vary widely. 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 possibly 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.

Mobilization costs between the systems also varied. 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, requires heavy equipment 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. 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 most likely end users are commercial munitions response service provider 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.

10. 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.

APPENDIX

APPENDIX A
POINTS OF CONTACT

Appendix A: Points of Contact

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14. ABSTRACT
The objective of this project was to integrate an AUV 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 completed system consists of a high sensitivity Geometrics G-880AUV cesium vapor magnetometer and a Teledyne-Gavia AUV. 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. At constructed underwater test plots, the system showed reliable detection of ≥60mm mortars at 1.5-m altitudes and ≥75mm projectiles at altitudes over 2-m. A 1.3-m average offset between the known and measured locations of seed items was calculated during the missions. Offsets were less than 0.5-m where survey lines crossed seed item locations. Vehicle dynamic performance objectives for bottom keeping, pitch, roll and along-line data density were

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