ESTCP
Cost and Performance Report

(MR-200935)

Shallow Water Marine UXO Detection Survey United States Marine Corps Base, Camp Lejeune, North Carolina

April 2011

ESTCP

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ACRONYMS AND ABBREVIATIONS

3Dg	3Dgeophysics.com
AMEC	AMEC Earth & Environmental, Inc.
Camp Lejeune	U.S. Marine Corps Base Camp Lejeune
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CTT	closed, transferred, and transferring
DGM	digital geophysical mapping
DoD	Department of Defense
EM	electromagnetic
ESTCP	Environmental Security Technology Certification Program
GIS	geographic information system
GPS	Global Positioning System
GSV	geophysical system verification
HDOP	horizontal dilution of precision
ISO	industry standard object
IVS	instrument verification strip
MEC	munitions and explosives of concern
mV	millivolts
OER	Ordnance and Explosives Remediation, Inc.
QA	quality assurance
QC	quality control
RTK	real-time kinematic
TDEM	time-domain electromagnetics
USACE	U.S. Army Corps of Engineers
USMC	U.S. Marine Corps
UTC	Coordinated Universal Time
UUTA	underwater UXO towed array
UXO	unexploded ordnance

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ACKNOWLEDGEMENTS

The demonstration was performed by AMEC Earth & Environmental, Inc. in cooperation with 3Dgeophysics.com and Ordnance and Explosives Remediation, Inc. We would also like to acknowledge the base personnel at Marine Corps Base Camp Lejeune, NC, specifically the Range Development Team, for their support during the demonstration. The following key personnel contributed to the demonstration:

Company	Person	Role in Project
AMEC Earth & Environmental, Inc.	Donna Sharp	Project Manager
	Paula Bond	Principal Investigator
	Raye Lahti	Principal Investigator
	Scott Sigler	Reacquisition Lead
	Stephen Hunt	Reacquisition Survey
3Dgeophysics.com	Brian Herridge	Geophysical Demo Lead
	Erik Kitt	Geophysical Demo
Ordnance and Explosives Remediation, Inc.	Hugh Sease	Dive Validation Lead
	Bud Thrift	Dive Validation
	Thomas Ligon	Dive Validation
Camp Lejeune Marine Corps Base	David Lynch	Range Control

A complete list of Points of Contact is provided in Appendix A.

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1.0 EXECUTIVE SUMMARY

1.1 TECHNOLOGY DESCRIPTION

The underwater unexploded ordnance (UXO) towed array (UUTA) electromagnetic system designed by 3Dgeophysics.com (3Dg) utilizes modified and improved Geonics, Ltd. electromagnetic (EM)61 metal detection technology. The UUTA system includes a 2.0 m (6.56 ft) wide (two receiver coil) non-contact bottom-skimming sensor platform, a down rigging tow bar, and a hydrofoil control surface mounted on a 6.7 m (22 ft) ThunderJet® boat. The system was designed to be used with a 6 to 7 m (20 to 23 ft) long boat in water depths ranging from 1 to 10 m (3.28 to 32.8 ft). It was determined during the demonstration that the maximum wave height in which data collection could be conducted was 1 m (3 ft). The towing system, hydrofoil, and tiller were not designed to withstand greater sea state height, and minor repairs to the UUTA were required after work in higher seas was attempted.

The UUTA demonstration was conducted at a former range, which provided a perfect setting for a representative study area. The overall demonstration area was a 180-acre area located adjacent to U.S. Marine Corps Base Camp Lejeune (Camp Lejeune), NC's, BT-3/N-1 impact area, a former bombing and artillery range near Browns Island, a public recreational, boating and fishing area. The survey area, exposed to the open Atlantic Ocean, was subject to rapidly changing weather conditions, rip currents, offshore winds, wave action, and tidal variations.

1.2 OBJECTIVES OF THE DEMONSTRATION

In the United States, the total area of underwater UXO impacted land associated with former ranges inaccessible to standard UXO search technologies is estimated to exceed a million acres (Environmental Security Technology Certification Program [ESTCP] Project MM-200324, 2008). The characterization of Department of Defense (DoD) UXO underwater sites has been challenging with the available sensor deployment platforms in existence today. Weather conditions and sea state also play a role in presenting challenges for deployment of detection systems. The problem for modern underwater UXO detection systems has been their limited effectiveness in detection of UXO at depths greater than one meter as well as the inability to accurately record survey positions. Achieving accurate position control is difficult for many technologies that employ flexible tethers to tow sensor "fish" or bottom dragging sleds. The objective was to test and validate the UUTA's accurate horizontal and vertical (height above sea floor) position control for UXO detection and mapping in a dynamic marine environment. UUTA was tested successfully and does improve detection and location accuracy over former underwater UXO mapping technologies.

UUTA will provide DoD and its contractors an accurate (up to within 1 m or 3.28 ft) method for surveying/relocating underwater munitions and explosives of concern (MEC) anomalies. Benefits of this research include the development of a UUTA that enables high accuracy geolocation of anomalies at a cost equivalent to that of any other multisensor system currently available. The capability to accurately determine underwater sensor position will not only enable high resolution mapping of underwater sites but will also provide information for improved characterization of underwater targets.

1.3 DEMONSTRATION RESULTS

The UUTA demonstrated from May 17 to July 6, 2010, at Camp Lejeune was performed in a dynamic marine environment, and showed the accurate horizontal and vertical (height above sea floor) position control of the UXO detection and mapping instrument package. The demonstration was led by AMEC Earth & Environmental, Inc. (AMEC) and performed by 3Dg and Ordnance and Explosives Remediation, Inc. (OER) for the Navy and DoD's ESTCP.

A total of 97 acres was surveyed during the demonstration. A production rate of 8.1 acres/day was achieved during the demonstration. Fifty-three targets, in addition to the instrument verification strip (IVS) seed items, were reacquired by the OER dive team. A high percentage (96.8%) of all recovered targets and IVS seed items were verified within 2.0 m (6.56 ft) of mapped positions (mean distance 0.87 m or 2.85 ft); 68.3% were mapped within 1.0 m (3.28 ft); and 95.4% of the data points were acquired with a sensor platform height less than 1.0 m (3.28 ft) above the sea floor.

Performance Objective Results Table

Performance Objective	Metric	Data Required	Success Criteria	Results
Positional accuracy	Number of items reacquired within 1 m of detected position	• Target list with position coordinates • Validation data for selected targets	95% of all recovered and IVS items reacquired within 1 m of detected position	68.3% reacquired within 1 m 95.4% reacquired within 2 m
Production rate	Number of acres of data collection per day	• Distance platform has traveled and width of transect	5 acres/day	96.9 acres in 12 days (8.1 acres/day average)
Probability of detection	Number of IVS items found	• Number of total items within surveyed area • Number of items found	95% of all items detected	Undetermined; only 12 of the 28 available targets were surveyed
Sensor proximity	Number of EM sensor readings recorded within 1 m of the sea floor	• Sensor array depth • Bottom depth	90% of all EM readings recorded with the sensor array height ≤ 1 m above the sea floor	95.4% of the 4,382,130 sensor readings were ≤ 1 m above the sea floor

1.4 IMPLEMENTATION ISSUES

UUTA has a limited working depth range of 1 to 10 m (3.28 to 32.8 ft). In addition, the rigid design of UUTA limits the maneuverability of the system. The system was designed to perform large radius turns and straight survey lines. Weather conditions may also limit the ability to deploy UUTA. UUTA can work in seas with a maximum wave height of 1 m (3.28 ft). Other environmental conditions that affected the performance of the UUTA system included high winds, excessive rain, lightning, sea state, and strong currents.

2.0 INTRODUCTION

This report provides a summary of demonstration details of a marine underwater UXO detection survey authorized by DoD and ESTCP. The work was performed by AMEC as the managing contractor in partnership with 3Dg as the geophysical consultant and OER as the UXO reacquisition team. The objective of the work was to demonstrate the highly accurate horizontal and vertical (height above sea floor) position control for underwater UXO detection and mapping surveys in a dynamic marine environment. The demonstration was performed using an underwater, non-contact towed sensor array platform newly designed by 3Dg. The new platform, named UUTA, utilizes commercially available geophysical instruments and global positioning systems (GPS), including proven Geonics, Ltd. EM61 time-domain EM metal detection sensors. UUTA differs from most current multisensor underwater platforms used for MEC digital geophysical mapping (DGM) surveys. It was designed to place the sensor platform in a fixed position relative to the centerline of the tow vessel, to allow real-time monitoring of sensor height above the sea floor, and to provide precise height above sea floor control of the sensor platform. These design features increase the accuracy of sensor position determinations and improve data collection rates.

The demonstration was conducted within a portion of an approximate 250-acre shallow water area located within the boundaries of Camp Lejeune. This study area is part of the coastal near shore zone of the Atlantic Ocean within one of the bombing targets and training sites of Camp Lejeune.

This cost and performance report is described in the following pages with nine report sections including this introduction, the technology, performance objectives, site description, test design, data analysis and products, performance assessment, cost assessment, and implementation issues.

2.1 BACKGROUND

In the United States, between 10 and 20 million acres of UXO impacted land are associated with closed, transferred, and transferring (CTT) ranges. The size of the area, which is underwater and inaccessible to standard UXO search technologies, is poorly defined; however, it is estimated to exceed a million acres (ESTCP Project MM-200324, 2008). The characterization of DoD UXO underwater sites has been challenging with the available sensor deployment platforms in existence today. Weather conditions and sea state provide major challenges for deployment of these detection systems. Sites that have potential UXO at depths greater than 1 m have been difficult to assess. Until recently, geophysical sensors applied to these environments have had limited success in detection and accurate location determination of potential MEC items. This is primarily the result of the distance between the sensor and the UXO (i.e., height of the sensor above the bottom of the water body) as well as the inability to accurately determine the position of recorded measurements.

Figure 1. Site location.

Most of the demonstrated instrumented systems have employed either carts or sleds, which are dragged across the bottom of the water body being investigated, or sensor fish that are towed behind a boat using a flexible tether. The deployment of sensors using these technologies creates several problems, including 1) disturbance of benthic environments (including wildlife), 2) resuspension of sediments that degrade water quality and could contain toxic constituents, 3) damaging or losing equipment caused by physical contact with bottom debris or UXO, 4) poor navigational and sensor position control, and 5) inaccurate determination of anomaly locations.

At this time the detection and remediation of underwater MEC is several times more expensive than performing the same work on land. It is often the case in munitions response characterization and remediation projects that shallow water areas are eliminated from the scope of work because of the logistical difficulties and the expense of collecting geophysical data in these challenging environments.

UUTA was designed to improve detection and location accuracy over former underwater UXO mapping technologies. Achieving accurate position control is difficult for many technologies that employ flexible tethers to tow sensor "fish" or bottom dragging sleds. The UUTA system utilizes modified and improved Geonics, Ltd. EM61 metal detection technology. The UUTA system includes a 2.0 m (6.56 ft) wide (two receiver coil) non-contact bottom-skimming sensor platform, a down rigging tow bar, and a hydrofoil control surface mounted on a 6.7 m (22 ft) ThunderJet® boat. The system was designed to be used with a 6 to 7 m (20 to 23 ft) long boat in water depths ranging from 1 to 10 m (3.28 to 32.8 ft). It was determined during the demonstration that the maximum wave height in which data collection could be conducted was 1 m (3 ft).

2.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the demonstration was to test and validate a newly designed shallow water time-domain electromagnetic towed array for the detection of MEC. The primary emphasis was to demonstrate UUTA's highly accurate horizontal and vertical (height above sea floor) position control for UXO detection and accurate mapping of potential UXO target anomalies in a dynamic marine environment. The four evaluated performance objectives include positional accuracy, production rate, sensor proximity, and probability of detection. Positional accuracy success metric included the reacquisition of 95% of recovered and IVS items within 1 m of the detected position. The probability of detection metric was locating 95% of items within the surveyed area.

2.3 REGULATORY DRIVERS

There are no specific regulatory drivers that influenced this technology demonstration. Activities related to UXO are generally conducted under authority of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). Regardless of the lack of specific regulatory drivers, many DoD agencies are actively pursuing innovative technologies employable in shallow water to address a variety of issues associated with sites containing MEC.

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3.0 TECHNOLOGY

UUTA is a 3Dg designed underwater UXO mapping towed array. It has been designed to interface with suitable commercial grade boats (6 to 7 m long) (20 to 23 ft); with off-the-shelf detection systems; and associated mechanical, positional, navigational and control components. UUTA is designed to map MEC in water depths from 1 to 10 m (3.28 to 32.8 ft), and its components and use are described in more detail below.

3.1 TECHNOLOGY DESCRIPTION

UUTA, shown schematically in Figure 2, is based on Geonics, Ltd. EM61 metal detection technologies. The UUTA system includes an underwater EM61 sensor platform, a downrigging tow bar, and an elevator control surface, commonly referred to as a hydrofoil, to adjust the EM61 sensor height above the sea floor. During the demonstration the system was mounted on a 6.7 m (22 ft). ThunderJet® boat. Photos of UUTA in production are shown in Figure 3.

3.1.1 EM61 System and Sensors

The EM61 is a high-resolution time-domain EM metal detector that is capable of detecting both ferrous and nonferrous metallic objects. The EM61 consists of air-cored transmitter and receiver coils, a digital data recorder, batteries, and acquisition electronics. The EM61 was modified by Geonics, Ltd. for use with UUTA. The EM61 on UUTA uses flexible, underwater EM coils attached to a fiberglass sensor platform. The EM coils include two 1 m × 0.5 m (3.28 to 1.64 ft) receiver coils and a single grand 2 m × 0.5 m (6.56 to 1.64 ft) transmitter loop that surrounds the receiver coils. The EM61 drives alternating square waveform current through the grand transmitter loop during data collection. The transmitted current generates a pulsed primary magnetic field that induces eddy currents in nearby metallic objects. These eddy current voltages are sensed by the receiver coils and then measured and recorded as sharp peaks in millivolts (mV).

The modifications completed by Geonics for the UUTA EM61 system include 300-watt transmit power, stacked and averaged received voltage measurements, and 150-hertz frequency. The advantages of these modifications along with the increased transmitter loop size include an increase of the transmitter's effective moment from approximately 150 to 1200 amperes/m^2. These improvements increase the signal-to-noise ratio of the received voltage, thus increasing the signal from any given target and the depth of sea floor penetration.

3.1.2 Towing System

The towing system consists of the following components:

- A 6.7 m (22 ft) ThunderJet® boat houses the operators and all system components.
- The sensor platform housing the EM61 coils is towed by a stainless steel and fiberglass twin truss system (downrigger) attached to the boat. An inclinometer measures the deployment angle of the downrigger. The downrigger wireless

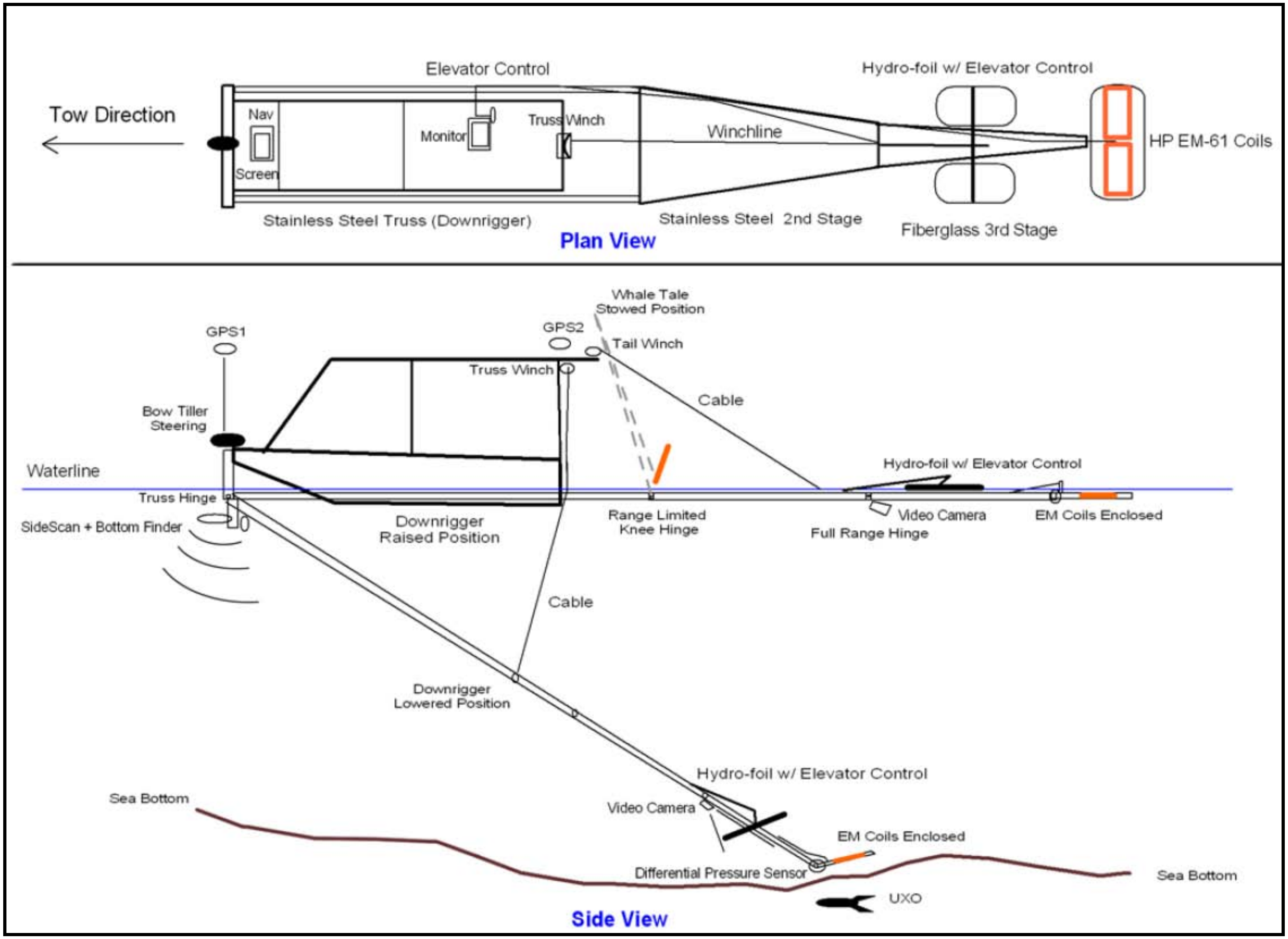

Figure 2. Underwater UXO towed array design.

Figure 3a. UUTA in parking lot

Figure 3b. Collecting geophysical data

Figure 3c. Rear of boat with tail submerged

Figure 3. Deploying the tail

Figure 3. Photos of UUTA in production.

controlled winches provide the primary stage of depth control over the towed bar and sensor platform and also pull the entire UUTA system above the water line to facilitate travel to and from the study area. The hydrofoil (also referred to as an elevator) is an active control surface that produces upward and downward lift on the sensor platform and secondary depth control as it is being towed through the water. A technician is tasked with keeping the sensor platform within close proximity of the sea floor.

- A calibrated pressure transducer is mounted near the sensor platform. The pressure transducer provides the system control software with sensor depth below water surface.
- A sonar unit is mounted near the bow of the boat. The bottom depth data are used in conjunction with the pressure transducer data by the system control software to calculate the location of the sensor platform with respect to sea floor.
- A tiller controlled by a linear actuator is used at the bow of the survey boat to steer when the downrigger is deployed.

Once deployed, the downrigger tow bar renders the normal steering mechanism of the boat (stern thrusting jet drive) ineffective. To overcome this limitation, a tiller is used at the bow of the survey boat to steer left or right, with the jet drive being used only for propulsion when the downrigger is deployed. The tiller is driven by a linear actuator controlled remotely by the boat captain. Based on feedback from the boat's navigation system, the captain uses the tiller control to steer UUTA along data collection grid lines.

3.1.3 Navigation, Positioning, and Data Collection

UUTA uses two Trimble real-time kinematic (RTK) GPS receivers mounted on fixed or gimbaled staffs along the centerline of the boat. The bow and stern-mounted GPS receivers provide an accurate system to measure position, speed, and heading of the vessel. The downrigger is designed to provide only one degree of freedom (up and down) and is configured to keep the EM61 sensors in line with the GPS receivers and the keel of the boat. Since the exact length of the downrigger is known, recording the inclination angle of the downrigger and the depth of the hydrofoil (with a pressure transducer) allows the exact distance of the sensor array behind the trailing GPS receiver to be calculated. The exact position of the EM sensors is known to within a few inches using the geometry of the rigid tow structure and the depth sensor.

A Trimble FmX navigation system provides real-time graphical guidance along virtual grid lines that are established over survey areas. The boat captain uses the FmX display to systematically drive UUTA across the survey area according to the pre-planned survey geometry. The FmX navigation system is integrated with the Trimble RTK GPS receivers. The survey geometry (survey line spacing and boundaries) is designed prior to deployment of the field team using geographic information system (GIS) software and uploaded to the FmX navigation system. During data collection the FmX navigation system graphically displays the current position of UUTA, virtual grid lines, previously travelled survey lines, and data gaps.

During field operations data are collected using a ruggedized personal computer (PC) housed in the tow vessel. All measured parameters are collected and managed by software developed by Geomar, Inc., including all data from the UUTA positioning sensors (inclinometer, bottom sonar, and pressure transducer), GPS receivers and EM61. The software also performs all calculations required for determining the sensor position within the water column.

3.2 DEVELOPMENT CHRONOLOGY

The UXO detection capabilities of UUTA are based on the tested and proven EM61 metal detection system. ESTCP has funded a number of studies utilizing this technology. The EM61-MK2 continues to be the instrument of choice for the majority of UXO/MEC DGM surveys performed.

In September 2006, AMEC and 3Dg performed a technology demonstration at the U.S. Army Aberdeen Test Center Shallow Water Test Site located at Aberdeen Proving Ground, MD (DTC Project No. 8-CO-160-UXO-016). The technology demonstration involved testing of an underwater sensor platform at the site, which provided a controlled environment containing varying water depths, multiple types of ordnance and clutter items, as well as navigational and detection challenges. As a result of the lessons learned during the demonstration, 3Dg began to refine the design for the UUTA system.

In August 2009, 3Dg began construction of the current UUTA system. All components of UUTA were acquired and assembled by 3Dg without funding from ESTCP, including testing prior to the Camp Lejeune demonstration. The current contract to perform the current project detailed in this report was awarded on September 15, 2009.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Two challenges of collecting useful underwater UXO detection data are measuring the exact position (both horizontally and vertically) of the EM sensors and controlling the vertical position of the sensor platform. Many tested and deployed UXO mapping systems employ either a sensor fish or a bottom dragging sensor sled on the end of a flexible tow wire. These systems measure the position of the tow boat and then try to extrapolate the position of the detector based on cable length and GPS heading. In most cases, the position of the fish or sled cannot be accurately known due to environmental conditions affecting the systems (i.e. currents, wind, tidal forces and bottom topography). Georeferencing data with these systems is typically less accurate than is considered acceptable for terrestrial UXO surveys. In addition, both types of systems are hard to control (horizontally and vertically) with flexible tow wires that can have a wide range of movement. Bottom draggers typically drag along sinusoidal tracks making gap-free coverage time consuming, expensive, and, in challenging environments, logistically impossible. The UUTA system minimizes many of the aforementioned limitations, thereby increasing the efficiency and reducing the costs of performing underwater UXO surveys in water depths of up to 10 m (32.8 ft).

3.3.1 Advantages

UUTA provides advantages over other available underwater UXO mapping systems and overcomes positioning and sensor control challenges. UUTA is one of the few marine systems that can measure the X,Y position of the sensors with better than 1 m accuracy. In addition it can accurately measure and control the vertical position (Z or depth) of the sensor platform above the ocean or lake bottom. Without these two critical features, the efficiency of underwater UXO survey systems is diminished.

Since UUTA is designed to be towed above the ocean or lake bottom, physical contact and disruption with the sea or lake bottom does not occur. The benefits of such systems include the reduction of impacts to benthic ecosystems, to water quality through the resuspension of sediments (which may contain toxic constituents), as well as the minimization of impacts to submerged obstacles and potential UXO strikes. Many states have regulations for maintaining water clarity in surface water bodies and thus would favor this technology. Bottom dragging systems are also susceptible to creating geophysical anomalies not associated with UXO. Sudden impacts of the sensor platform with submerged obstructions, or the bottom itself, create erroneous anomalies ("false positives") that can mistakenly be interpreted as UXO.

Another advantage of the UUTA system is that it employs the latest modifications to the Geonics EM61 metal detector. Modifications include higher transmitter power and frequency, faster sampling rates, and flexible underwater transmitter and receiver coils. These modifications improve the signal-to-noise ratio of the system, the maximum depth of penetration, the speed of data collection, and the field survivability and ruggedness of the sensors.

UUTA was designed to integrate with commercially available towing vessels. As such, it can be easily transported to the site on commercially available trailers and rapidly deployed using available public or private boat ramps. Other current marine surveying technologies require custom shipping solutions for mobilization and specialized heavy lifting equipment, such as cranes, for deployment.

3.3.2 Limitations

One limitation of the UUTA system is the working depths in which the system can be used. The system was designed to collect data in water depths between 1 – 10 m. Because of its rigid design to improve sensor positioning accuracy, the UUTA system has limited maneuverability when the tow bar is deployed. It was designed to perform DGM along large radius turns or straight survey lines. Tight radius turning by the tow boat is limited with UUTA fully deployed for data collection. Other system limitations were the result of weather, currents, or sea conditions. Excessively windy, rainy, strong currents, or strong tidal conditions and thunder storms negatively affected the UUTA system production. It was determined during the demonstration the maximum wave height in which data collection could be conducted was 1 m (3.28 ft). The towing system, hydrofoil, and tiller were not designed to withstand higher wave heights.

4.0 PERFORMANCE OBJECTIVES

The objective of the demonstration was to test and validate UUTA in shallow water (1 to 10 m) (3.28 to 32.80 ft) for the accurate detection and location of MEC. The primary emphasis was to demonstrate accurate horizontal and vertical (height above sea floor) position control for an underwater UXO detection array and mapping system in a dynamic marine environment. This survey demonstrated the system performance while providing data that are of benefit to the U.S. Marine Corps (USMC) at Camp Lejeune in assessing the MEC contamination in the survey area. The field demonstration included the acquisition of EM data within portions of the designated 101-hectare (250-acre) survey area and specifically within a zone with measured water depths ranging from 1.5 – 7 m (mean 4.0 m).

The four evaluated performance objectives include positional accuracy, production rate, sensor proximity, and probability of detection. Table 1 presents the performance objectives and results for the field demonstration.

Table 1. Performance objectives.

Performance Objective	Metric	Data Required	Success Criteria	Results
Positional accuracy	Number of items reacquired within 1 m of detected position	• Target list with position coordinates • Validation data for selected targets	95% of all recovered and IVS items reacquired within 1 m of detected position	68.3% reacquired within 1 m 95.4% reacquired within 2 m
Production rate	Number of acres of data collection per day	• Distance platform has traveled and width of transect	5 acres/day	96.9 acres in 12 days (8.1 acres/day average)
Probability of detection	Number of IVS items found	• Number of total items within surveyed area • Number of items found	95% of all items detected	Undetermined; only 12 of the 28 available targets were surveyed
Sensor proximity	Number of EM sensor readings recorded within 1 m of the sea floor	• Sensor array depth • Bottom depth	90% of all EM readings recorded with the sensor array height ≤ 1 m above the sea floor	95.4% of the 4,382,130 sensor readings were ≤ 1 m above the sea floor

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5.0 SITE DESCRIPTION

The geophysical demonstration site was located at Camp Lejeune. The technology demonstration included a DGM survey for UXO/MEC detection within a portion of an approximate 250-acre shallow water area within Onslow Bay adjacent to Browns Island along the near shore zone within the Camp Lejeune boundary (Figure 4). The site extends from the low water mark to a depth of approximately 7.5 m (24.60 ft) and parallels the shoreline beach.

5.1 SITE LOCATION AND HISTORY

Established in May 1941, Camp Lejeune provides specialized training to prepare troops for amphibious and land combat operations. Today Camp Lejeune occupies 153,000 acres with a diverse array of ecosystems composed of wildlands, urban areas, and surface water resources. Over 100,000 acres of land are in forests and other wildlands. Water resources include approximately 11 miles of beach on the Atlantic Ocean and 26,000 acres of estuaries containing the New River, Intracoastal Waterway, and associated streams and marshes. The population of the base includes 144,000 marines, sailors, and their families. The base houses six major Marine Corps commands and two Navy commands.

5.2 SITE GEOLOGY

Camp Lejeune is located within the North Carolina Coastal Plain belt that covers a large portion of the state. The geology of the study area consists primarily of marine sediments with dominant sand, silt, and clay. The wave and tidal action in the study area alters the beach and near shore sediments on a regular basis. The Coastal Plain Region of North Carolina consists of a wedge of Cretaceous and Tertiary sedimentary strata thickening toward the coast as well as dipping toward the southeast. Outcropping strata away from the study area are younger near the coast. The sedimentary rocks of the Coastal Plain partly consist of sediment eroded from the Piedmont and Valley and Ridge and partly of limestone generated by marine organisms and processes. The North Carolina Coastal Plain belt covers a large portion of the state. The most common sediment types are sand and clay, although a significant amount of limestone occurs in the southern portion.

5.3 MUNITIONS CONTAMINATION

The coastal beach area was a former bombing and artillery range at Camp Lejeune from the 1940s through the 1980s. The area is located within impact area BT-3/N-1, between Onslow Beach and Hammocks Beach State Park. UXO ranging from 40 mm grenades to 2000 lb bombs may be located throughout the beach and coastal region. The Navy and Marines occasionally sweep the area and remove any items discovered on the beach. A UXO sweep of the beach area in January and February of 2009 discovered items including Mk23 (3 lb) practice bomb, 100 lb GP bomb, Mk 81 bomb, Mk 82 bomb, 5-inch Naval Round HE, 106 m HEAT, 155 mm HE, 90 mm HE, 2.75-inch rocket HE, 500 lb GP bomb and 250 lb GP bomb.

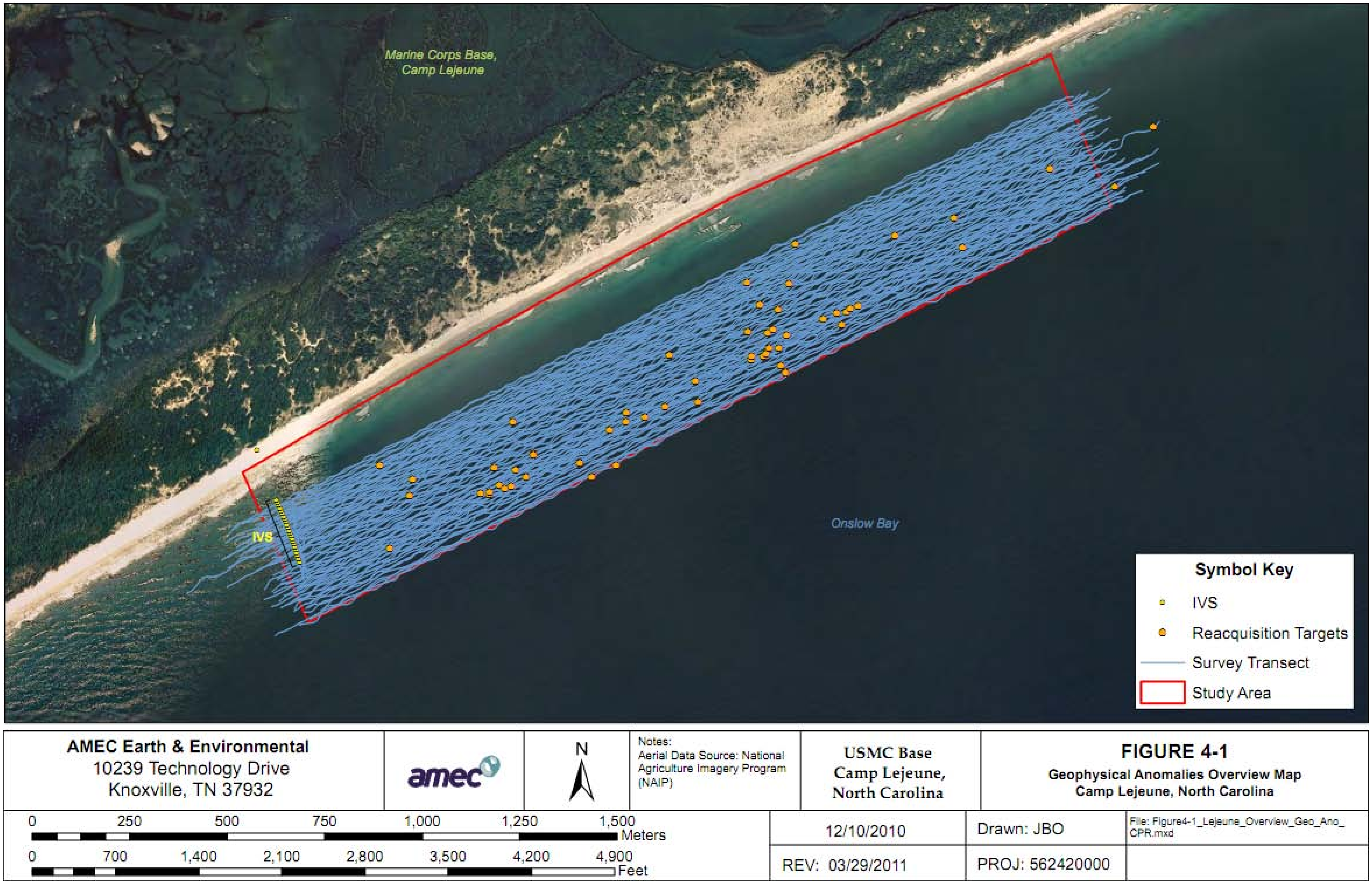

Figure 4. Geophysical anomalies overview.

6.0 TEST DESIGN

The objective of the demonstration was to test and validate UUTA in shallow water (1 to 10 m) (3.28 to 32.80 ft) for the accurate detection and location of MEC. The primary emphasis was to demonstrate accurate horizontal and vertical (height above sea floor) position control for an underwater UXO detection array and mapping system in a dynamic marine environment. This survey demonstrated the system performance while providing data that are of benefit to the USMC at Camp Lejeune in assessing the MEC contamination in the survey area. The field demonstration included the acquisition of EM data within portions of the designated 101-hectare (250-acre) survey area and specifically within a zone with measured water depths ranging from 1.5 – 7 m (mean 4.0 m).

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

The UUTA system demonstration was performed on the Atlantic Ocean side of Browns Island. The demonstration site contained MEC over an area of approximately 250 acres. The data collected from the DGM transects would be used to evaluate the performance objectives of UUTA (i.e., positional accuracy, production rate, sensor proximity, and probability of detection). The demonstration transects would include traversing the IVS and validating target anomalies through the reacquisition and visual inspection of targets by divers. The demonstration would also provide information regarding the effect of environmental conditions on the UUTA system (i.e., weather conditions, currents, and sea state). The duration of the demonstration was approximately 7.5 weeks (May 17 to July 6, 2010).

6.2 SITE PREPARATION

The USMC provided all necessary permits for work to be conducted in the survey area. The primary preparatory work required for the site was the fabrication and deployment of the chained IVS. The intent of the chained IVS was to provide a viable, cost effective tool to test the EM detection response and positional accuracy of the UUTA system in a shallow water environment.

The chained IVS consisted of 1000 ft (304.8 m) of 3/16-inch (4.76 mm) stainless steel cable attached at one end by a heavy-duty spade-type marine boat anchor, and at the other end by a 5 ft (1.524 m) steel winch anchor point. The IVS employed a modification of the geophysical system verification (GSV) concept with standard seed items. Both industry standard object (ISO) and ISO surrogates were used in the creation of the IVS. Steel discs were preferred as the primary seed item because of the logistics of deploying the IVS, and the belief that the flattened discs would scour into the sea bottom and remain stationary throughout the demonstration. Twenty-eight seed items were affixed to the steel cable at 25 ft (7.62 m) intervals beginning at the 300 ft (91.44 m) mark and continuing to the end of the cable.

6.3 SYSTEM SPECIFICATION

The components and specifications of the UUTA sensor platform and positioning and data acquisition systems are summarized in Tables 2 and 3.

Table 2. UUTA primary systems components.

Component / Function	Instrument / Equipment
Time-domain electromagnetics (TDEM) metal detection sensor array	Geonics, Ltd. EM61-Flex4
Sensor array positioning	Trimble 5700 RTK DGPS
Sensor array navigation & guidance	Trimble AgGPS FmX Navigation System
Sensor array depth transducer	Campbell Scientific, Inc. CS455 vented pressure transducer
Bottom depth transducer	Hummingbird 997c SI combo depth/side imaging sonar
Data acquisition system	Panasonic Toughbook PC with proprietary data acquisition software

Table 3. TDEM sensor array specifications.

Parameter	Value
Instrument	Geonics EM61-Flex3
Power mode	High (24 volt)
EM sensors	2
Coil type	Flexible, submersible
Receiver (Rx) coil geometry	2 per sensor, symmetrical, inline ("Figure 8")
Rx coil dimensions	1.0 × 0.2 m
Transmitter (Tx) coil dimensions	2.0 × 0.5 m
TDEM recording window	3rd time gate
Sampling interval (per sensor)	18 samples/sec

6.4 DATA COLLECTION

The UUTA system was used to perform DGM for the detection of MEC within the 250-acre survey area (Figure 4). The field test was performed in water depths ranging from 1.5 to 7 m (4.92 to 22.97 ft) (average depth 4.0 m or 13.12 ft). Data collection occurred across approximately 1.5-mile (2.41 km) long transects that functioned as virtual grid lines. These grid lines were approximately parallel to the shoreline and were spaced 2 m (6.56 ft) apart. The UUTA system contains two EM sensors that record data at the coil center of each coil resulting in data paths spaced 1 m (3.28 ft) apart. Data were collected at a rate of 18 measurements/sec/sensor. The average boat speed during data collection was 3.6 mph (1.6 m/sec). A total of 392 km (243.6 linear miles) of ocean bottom were surveyed during the demonstration (Figure 4). The total area surveyed was calculated to be 96.9 acres (39.2 hectares), based on the 1 m (3.28 ft) individual sensor width. During the demonstration the UUTA system surveyed an average of 8.1 acres per day.

To establish confidence in the geophysical mapping, data reliability tests for the UUTA system were conducted in a systematic manner throughout the duration of the technology demonstration. Quality control (QC) consisted of daily instrument tests and the collection of data over the chained IVS.

6.5 VALIDATION

Validation of data produced during the field test was integral to the success of the technology demonstration. The UUTA system results were validated through the use of divers reacquiring the locations of target anomalies, and by including the IVS in the survey transects (Figure 5). During the demonstration, 68% of the target anomalies were reacquired within 1 m (3.28 ft), and 95% were reacquired within 2 m (6.56 ft) of the original survey position. Due to time constraints of the demonstration schedule, the dive team was able to validate only 57 of the 120 target anomalies.

Boats after placing GPS receiver

Diver moving GPS receiver over a target

Dive boat with gear and personnel

Figure 5. Boats with their teams in operation at the site.

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7.0 DATA ANALYSIS AND PRODUCTS

The following sections summarize the analysis steps that were used to produce the final data products that were used to calculate the performance objectives (i.e., positional accuracy, production rate, probability of detection, and sensor proximity).

7.1 PREPROCESSING

A data conversion program from Geomar, Inc. was initially used to convert the binary DGM data files (field files) generated by the UUTA data acquisition software into the Geosoft file format. The converted data files included the following data fields: X position, Y position, EM amplitude (per sensor), sensor depth, bottom depth, sensor height above bottom, GPS fix status, GPS quality (horizontal dilution of precision [HDOP]), and Coordinated Universal Time (UTC) time.

Geosoft Oasis Montaj software was used for all geophysical data processing; graphical representations of the daily QC tests, as well as track plots of the UUTA sensor positions across the survey area, were created. Data processing routines developed by the U.S. Army Corps of Engineers (USACE) and available in the UX-Process module of the Oasis Montaj software were used to preprocess the EM data.

Oasis Montaj was also used to preprocess the DGM data, contour the EM data, and identify potential UXO targets. The program identified peak amplitude responses within the contoured (gridded) EM sensor dataset. The processing of the UUTA data included leveling, latency and lag correction, filtering, sensor height calculation, gridding of sensor data and preparation of geophysical and target maps.

7.2 TARGET SELECTION FOR DETECTION

Upon completion of the data preprocessing, the geophysical data were gridded to produce an anomaly map. The UXO Detect module of Oasis was used to develop a target database of anomalies within the gridded EM dataset that exceeded the target picking threshold. AMEC and 3Dg prioritized the selected target database and determined a subset of the targets to be used to validate the data. OER conducted UXO diving on the subset of targets to validate the positional accuracy of the mapped anomalies. The target database was also correlated with calculated positions of the IVS seed items. The positions of seed items located within the collected data coverage area were used to validate the probability of detection for the UUTA system. The daily data coverage maps and distance traveled data were used to calculate the production rate for the UUTA system. Any EM anomalies (peak amplitudes) within the data grid that exceeded the target detection threshold were selected as potential targets. Potential targets within a 1 m (3.28 ft) distance of each other were treated as a single target.

The primary emphasis of the project was to demonstrate the positional accuracy of the UUTA system. To accomplish this goal, a statistically relevant subset of targets required validation. The target locations were selected directly from the anomaly peak amplitudes from the gridded data set. The reacquisition team was limited by budgeted time, weather conditions, and the logistics of the reacquisition procedures as to the number of the targets that could be reacquired. It was believed that higher amplitude anomalies would probably represent targets that were either proud of the bottom or buried at a very shallow depth.

Classification of anomalies was not the focus of this demonstration. Targets were selected purely based on amplitude to allow for dive teams to easily validate a subset of the targets.

7.3 DATA PRODUCTS

The outputs of the field test data analysis were annotated geophysical anomaly maps of the survey area, data coverage map of the survey area, and a spreadsheet of selected targets (Target List).

The geophysical anomaly maps are plan-view color-contour plots of the gridded EM sensor measurements. The anomaly maps are presented in different map scales to show all portions of the survey area in detail. The anomaly maps are annotated with the locations of selected targets (EM anomalies) and the positions of the seeded IVS items.

The data coverage map is a plan-view plot of the survey area showing the traveled path of the UUTA sensor array during the field test based on recorded GPS coordinates.

The Target List is a spreadsheet containing the following data fields: target number, X position, Y position, EM value (peak amplitude in mV), bottom depth (ft), and data analysts comments. The Target List was provided to the reacquisition team after data processing was completed. The Target List was supplemented with the results of the target reacquisition upon the completion of dive operations. The reacquired target ID, measured X position, measured Y position, reacquisition date, and position difference was subsequently added to the Target List. The Target List was divided into two classifications: primary and secondary. The primary list included EM anomalies with amplitudes greater than 100 mV. The secondary list included anomalies with amplitudes between 75 and 100 mV.

8.0 PERFORMANCE ASSESSMENT

The performance objectives of the UUTA system was evaluated by assessing four criteria: positional accuracy, production rate, probability of detection, and sensor proximity. The following sections discuss the results of the performance objectives evaluation. The performance objectives and results have been summarized in Table 4.

Table 4. Performance objective and results.

Performance Objective	Metric	Data Required	Success Criteria	Results	Metric Met?
Positional accuracy	Number of items reacquired within 1 m of detected position	• Target list with position coordinates • Validation data for selected targets	95% of all recovered and IVS items reacquired within 1 m of detected position	68.3% reacquired within 1 m 95.4% reacquired within 2 m	No
Production rate	Number of acres of data collection per day	• Distance platform has traveled and width of transect	5 acres/day	96.9 acres in 12 days (8.1 acres/day [3.8 hectares/day] average)	Yes
Probability of detection	Number of IVS items found	• Number of total items within surveyed area • Number of items found	95% of all items detected	Undetermined; only 12 of the 28 available targets were surveyed	No*
Sensor proximity	Number of EM sensor readings recorded within 1 m of the sea floor	• Sensor array depth • Bottom depth	90% of all EM readings recorded with the sensor array height ≤ 1 m above the sea floor	95.4% of the 4,382,130 sensor readings were ≤ 1 m above the sea floor	Yes

*Undetermined, insufficient number of samples to accurately assess the probability of detection.

8.1 POSITIONAL ACCURACY

The effectiveness of the UUTA system to detect MEC is a function of the system's ability to accurately record the horizontal (X,Y) georeferenced position of mapped EM anomalies. The performance objectives of the demonstration state that the success criteria would be met if the measured GPS positions of more than 95% of the validated targets and IVS items were located within 1 m (3.28 ft) of the original survey GPS positions (Figure 6).

This success criteria was not met, but it is unlikely that all positional accuracy errors can be attributed to the UUTA system (as further discussed below). A total of 63 dive targets were validated for positional accuracy (53 target anomalies and 10 IVS items). A total of 43 of the 63 targets (68.3%) were located within 1 m of the geophysically mapped positions; while 61 of the 63 targets (96.8%) were located within 2 m of the mapped positions. The mean difference between the validated and mapped target positions was 0.87 m (2.85 ft).

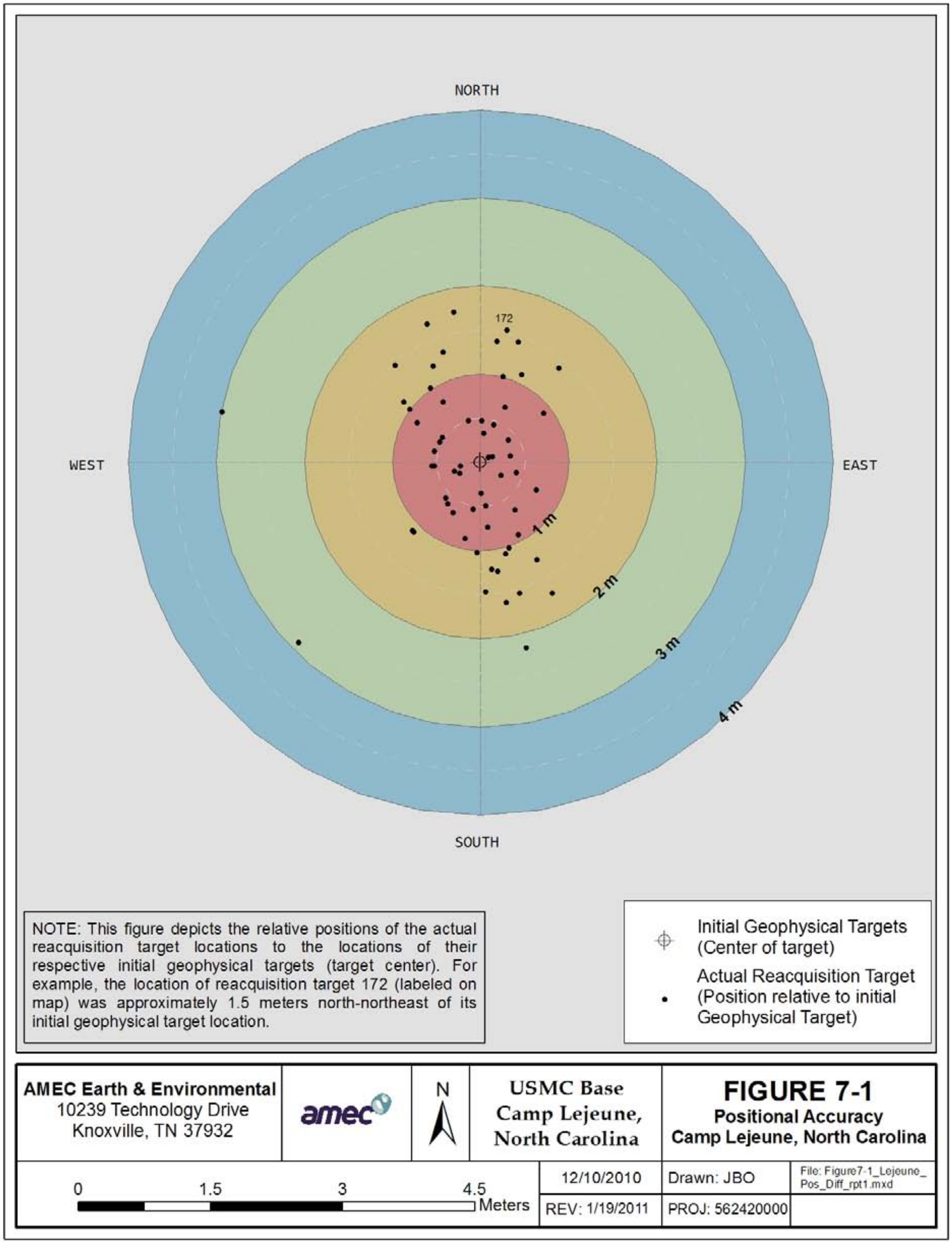

Figure 6. Positional accuracy.

A definitive assessment of the positional accuracy of the UUTA system could not be determined because the error associated with the reacquisition process could not be measured. Although errors attributed to reacquisition measurements are negligible for terrestrial surveys, this error can be significant in a dynamic marine environment. At the onset of reacquisition activities the AMEC UXO QC/Safety Officer qualitatively observed that measured positional accuracy of the validated targets decreased as sea state conditions intensified. After this determination the project team ceased reacquisition activities until new reacquisition procedures were formulated. Although the OER dive team exercised extreme care during the target validation, there is a non-negligible component of the overall positional error that must be considered during the analysis of these data. Unfortunately there were limited data acquired during the demonstration for the purpose of a quantitative analysis of reacquisition error. It was however determined that the mean difference between reacquired and mapped target positions was 0.55 m (1.8 ft) for IVS seed item targets, compared to a difference of 1.07 m (3.5 ft) for all other targets. The IVS seed items were all located in less than 4 m of water, and the positions of these seed items were collected on calm days. All of the currently available qualitative and quantitative data suggest that a significant percentage, perhaps 50% or more, of the reported positional error during the demonstration may be attributable to reacquisition error.

8.2 PRODUCTION RATE

The effectiveness of UUTA system for DGM is a function of the system's ability to rapidly collect data over large survey areas. The performance objectives of the demonstration state that the success criteria will be met if the calculated production rate of the system exceeds 5 acres per day during the demonstration.

The success criteria were met. A total of 243.6 linear miles of data were collected during the demonstration. Based on the 1 m (3.28 ft) sensor width, a calculated total area of 96.9 acres was surveyed. Validated data were collected on 12 days during the demonstration. The calculated production rate for the demonstration was 8.1 acres/day. Data were collected during the demonstration using wide area assessment surveying techniques. It is believed that the calculated production rate can be maintained, and even improved, in similarly scoped future projects. However, an accurate estimate of production rates for full coverage surveying, including data gap management, cannot be assessed at this time.

8.3 PROBABILITY OF DETECTION

The effectiveness of the UUTA system for the detection of MEC is a function of the system's ability to record EM anomalies (detected targets) over a high percentage of seeded target items. The performance objective of the demonstration states that the success criteria would be met if more than 95% of the validated IVS seed items were detected during the DGM.

The success criteria were undetermined. The chained IVS consisted of 28 seeded target items. However, DGM data were only collected within 0.5 m (1.64 ft) of 12 of the 28 targets. Target responses were observed over 10 of the 12 mapped seed items (83.3%).

Almost 30% (8 of 28) of the IVS seed items were inaccessible during the DGM because they were located too close to the shore and within the surf zone. As a result of the lack of targets identified in the DGM data during the early stages of the demonstration, the data acquisition methodology was changed from attempting 100% volumetric coverage to wide area assessment (transect) surveying. The sensor platform only encountered 12 of the 28 seed items due to this change. During data collection over the two seed items, which did not produce EM targets in the dataset, the sensor platform height was not within optimum data recording specifications (the platform was greater than 1 m [3.28 ft] above sea floor). A total of 12 seed items did not represent a statistically significant sampling dataset to calculate the probability of detection for the system.

8.4 SENSOR PROXIMITY

The effectiveness of the UUTA system for the detection of MEC is a function of the system's ability to control and record the vertical position of the sensor platform. The performance objectives of the demonstration state the success criteria will be met if the calculated sensor height above the sea floor is less than or equal to 1 m (3.28 ft) for more than 90% of the EM sensor readings. The sensor height above the sea floor calculation was made by subtracting the measured platform depth from the measured bottom depth at every EM sample position.

The success criteria were met. A total of 4,382,130 unique data points were collected during the DGM, and 4,180,552 points had a calculated sensor platform height above the sea floor of 1.0 m (3.28 ft) or less (95.4%). The remainder of the data points exceeded the 1.0 m (3.28 ft) performance metric. The mean sensor platform height above the sea floor was 0.61 m (2 ft).

9.0 COST ASSESSMENT

This type of marine geophysical survey in an open sea setting has rarely been performed. The cost of the survey depends on a number of factors, including:

- Deployment vessel transportation to the site, fuel costs, and survey area access
- Total size of the proposed area to be surveyed and length of the proposed survey lines
- Extent of weather, currents, tides, and sea state that can influence data collection productivity
- Location of the site, which can influence the cost of logistics
- Travel distance between vessel launch location and the survey area
- Scouting, creating, and maintaining a suitable GPS base station location
- Survey objectives and density of coverage, specifically high density for individual ordnance detection (100% coverage) versus transects for target/impact area delineation and footprint reduction (wide area assessment)
- Safety requirements, specifically the need for a companion safety boat.

The costs for underwater UXO surveys in an oceanic environment lie largely in logistics. Much time is used for activities other than data collection. Some of these activities include performing on-land quality assurance (QA)/QC procedures, launching the vessel, transecting the vessel to and from the survey area, and stand-by time due to unacceptable weather conditions or sea state. For this demonstration launching the UUTA system and transecting the approximately 3-mile path through the intercoastal waterway to the study area was a challenging and time-consuming task.

Data coverage requirements also greatly affect survey costs. It is obvious that 100% data coverage surveys require greater time and resources than wide area assessment surveying. As currently configured the UUTA system acquires data along a 2 m (6.56 ft) wide array path. For the purposes of this demonstration and cost assessment, only the wide area assessment approach was evaluated.

9.1 COST MODEL

Cost information associated with the demonstration of the UUTA marine EM metal detection system was tracked and recorded from the onset of the contract through the testing phase, the field demonstration, the validation (reacquisition), data processing, and preparation of the demonstration report. These costs provided the data necessary to prepare the cost model. Table 5 summarizes the various cost elements that were recorded for the project. However, not all project costs are reflected in the table. Project management, oversight, additional ESTCP reporting, and other incidentals are not included in Table 5.

Table 5. Cost summary.

Cost Element	Data Tracked During Demonstration	Estimated Costs ($K)
Geophysical equipment testing	Initial geophysical equipment testing—travel, equipment integration, reconfiguration, software development*	176
Mobilization and demobilization	Cost to mobilize and demobilize to site	12
Site preparation	Evaluation trip IVS assembly and installation Work plan and logistics	17 6 35
Survey costs	Item costs: Rental vehicles Safety boat rental—truck, trailer, boat, and fuel Unit costs: UUTA (boat and equipment) rental - $2990/day Daily labor support (3 men w/per diem) Safety diver support (2 men with per diem) <u>Total Survey Cost (7 Weeks)</u> <u>Cost per acre</u> Number of personnel on survey team 3 on survey boat 2 on safety boat	 3.2 21.6 134.6 172.6 55.3 <u>387.3</u> 3.87
Reacquisition	Item costs: Rental vehicles Survey equipment (included in the labor cost) Unit costs: Dive boat rentals (2)—truck, trailer, boat, equipment, and fuel—$1600/day Daily dive support (5 men w/per diem) Survey support (1 man w/per diem) <u>Total reacquisition cost (4 weeks)</u> Number of personnel on reacquisition team 5 divers, 1 surveyor on 2 dive boats	 1.2 28.8 86 15 <u>131</u>
Survey products	Data processing Survey and reacquisition report	28.1 45

Note: Costs summarized in this table do not reflect the total cost of the project. Some of the costs not captured include project management, oversight, additional ESTCP reporting, and other incidentals.
*The equipment testing was a single event to test the system on the boat used on the project. It was a one-time event that will not factor into future surveys.

9.2 COST DRIVERS

The major cost drivers for a marine UXO detection survey are the costs associated with accessing the site, the number of hours that can safely be utilized for data collection, and the data processing and analysis associated with the acquired data. In terms of tasks, these constitute the majority of the field-related survey costs (i.e. mobilization, data acquisition, and demobilization costs). The in-field survey costs represent the largest cost item for a marine UXO detection survey.

The data collection platform (the entire UUTA system, including the tow vessel) is a significant component of the costs associated with the demonstration. This cost element is included in the mobilization, data acquisition, and demobilization tasks. The costs include mobilization, accessing the site, fuel, field crew, maintenance of systems, and per diem and travel for the survey and safety teams. Depending on the survey location (distance from home base), mobilization and demobilization costs can be significant when compared to the overall data acquisition cost. Additionally, the type of survey, weather conditions, length of the survey day, weather, and sea state stand-by time all affect the data collection costs of the project.

Data processing and analysis functions constitute the majority of the remaining costs associated with the field demonstration.

The variability of the cost drivers may be modeled under several different project differences. Survey time and equipment cost is typically on a daily basis. The size of the site to be surveyed can vary. The amount of time spent mobilizing to and from the site will vary, as will the amount of time required for the survey vessel to transect from the launch point to the survey area. The speed at which data can safely and accurately be collected will also vary based on site conditions. The other major cost drivers mentioned above include equipment and personnel, mobilization/demobilization and data processing. These costs are a function of project size and transportation distance, respectively.

9.3 COST BENEFIT

The cost benefit of the UUTA system cannot be compared with conventional geophysical surveys, such as land based EM61 or airborne geophysical surveys, because they may not be used in the conditions (depths up to 7 m or 22.97 ft in near shore environments) encountered during this demonstration. However, Table 5 provides information for comparison with future underwater surveys using this system.

The UUTA system has the ability to produce high quality DGM survey data, including accurate target anomalies position data with low environmental impacts. The system is versatile and can perform 100% coverage or transect grid surveys depending on the project requirements.

Because the UUTA system is designed to be towed 1 m (3.28 ft) above the sea floor, impacts to the benthic environment are minimal, and there are no impacts to water quality caused by the resuspension of sediment, which may contain toxic constituents. In addition, the design of the sensor platform, which allows the operator to maintain the platform height of 1 m above the sea floor, reduces the occurrences of Type 1 errors (false positives) associated with sensor impacts with the sea floor. The system design also reduces downtime associated with impacts with the sea floor or submerged objects such as UXO, which could damage other towed arrays.

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10.0 IMPLEMENTATION ISSUES

The following sections address potential implementation issues and lessons learned from the technology demonstration.

10.1 REGULATORY ISSUES

Licensing of the towing vessel and permits from the state or country of deployment are required. It will be necessary prior to deployment to identify potential regulations that may apply to use of the towing vessel in certain lakes, estuaries, or coastal waters. In large part to its non-bottom contact design, no environmental regulations are anticipated to restrict the implementation of the technology.

10.2 END-USER CONCERNS

The assembly and construction of the downrigging and towing system and the deployment may require skilled personnel and machinery. The towing vessel and safety boats require skilled operators. Safety as with any water activity, especially in a dynamic marine environment, is a concern. However, with the proper personnel and training, the operation as demonstrated can be conducted without incident.

10.3 PROCUREMENT AND AVAILABILITY

The UUTA system is a combination of geophysical instrumentation, navigation and positioning sensors, and a deployment vessel that are all commercially available. The acquisition software (Geomar, Inc.) that manages and stores the incoming data and the processing software (Geosoft, Inc.) are all commercially available products. The cables, winches, and materials used to fabricate the downrigging and towing platform are products readily available from commercial vendors. Some components may require long lead times.

10.4 SPECIALIZED TRAINING

Assembly and operation of the UUTA system, and quality control, processing, and interpretation of the collected data require experienced and skilled personnel. Validation requires qualified UXO technicians with dive certificates.

10.5 LESSONS LEARNED

The accuracy of the verification of anomalies depends on the depth of water and the current sea state in which this process is conducted. Reacquisition position accuracy diminishes beyond 3 m (10 ft) water depths, or in wave heights greater than 0.6 m (2.0 ft). It is possible that 50% or more of the positional errors of the EM anomalies validated during the demonstration may be attributable to the implemented reacquisition procedures, especially in deeper water or high seas. The UUTA system cannot be deployed in sea states with consistent wave heights greater than 1 m (3.0 ft).

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11.0 REFERENCES

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APPENDIX A

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