

Vieques Underwater UXO Demonstration Projects VIEQUES ISLAND, PUERTO RICO

November 2006 & June 2007
FINAL REPORT



Joint Projects Between -
NOAA's Ocean Service
US Naval Facilities Engineering Command Atlantic Munitions Response Program

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Vieques Island, Puerto Rico

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LIST OF ACRONYMS

AFWTF – Atlantic Fleet Weapons Training Facility

AUV – Autonomous Underwater Vehicle

CO-OPS – Center for Operational Oceanographic Products and Services

DOI – Department of the Interior

ECA – Eastern Conservation Area

EMA – Eastern Maneuver Area

EOD – Explosive Ordnance Disposal

EPA – Environmental Protection Agency

GIS – Geographic Information System

GMI – Geo-Marine, Inc.

LIA – Live Impact Area

MBES – Multibeam Echo Sounder

NASD – Naval Ammunition Storage Detachment

NAVFAC Lant – Naval Facilities Engineering Command Atlantic Munitions Response Program

NOAA – National Oceanic and Atmospheric Administration

NPL – National Priority List

OCS – Office of Coast Survey

ORR – Office of Response and Restoration

ROV – Remotely Operated Vehicle

SIA – Surface Impact Area

UNH – University of New Hampshire’s Joint Hydrographic Center

UXO – Unexploded Ordnance

VNTR – Vieques Naval Training Range

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EXECUTIVE SUMMARY

This report discusses three underwater unexploded ordnance (UXO) demonstration projects led by the National Oceanic and Atmospheric Administration (NOAA). The field components of the projects occurred during November 2006 and June 2007 off the eastern coast of Vieques Island, Puerto Rico. Throughout this report, discussion of the three projects is differentiated by dates and locations where the projects were conducted.

The November 2006 field activities included a limited hydrographic survey of an area with known underwater ordnance located in Bahía Salina del Sur off the southeastern coast of Vieques Island. The survey included participants from NOAA's Office of Coast Survey (OCS), NOAA's Office of Response and Restoration (ORR), University of New Hampshire's Joint Hydrographic Center (UNH), Naval Facilities Engineering Command Atlantic Munitions Response Program (NAVFAC Lant), and Geo-Marine, Inc. The November 2006 project represented an interdisciplinary approach to determine the feasibility of using modern seafloor mapping, detection and discrimination technologies as an effective and efficient way to evaluate underwater UXO and munitions debris. UXO and related debris detected by sonar equipment aboard a NOAA survey vessel were verified by real-time video and Self Contained Underwater Breathing Apparatus (SCUBA) divers trained in explosive ordnance disposal (EOD). Geo-Marine, Inc. conducted an assessment of munitions, munitions related debris and non-munitions items at Vieques Island in conjunction with NOAA.

Also in November 2006, NOAA conducted a second demonstration project using an Autonomous Underwater Vehicle (AUV) with sidescan sonar to detect UXO and related debris in Bahía Icacos, a bay off the northeastern coast of the island. This project included participants from NOAA's OCS, ORR and NAVFAC Lant.

The third demonstration project was conducted in June 2007 using an AUV equipped with sidescan sonar to detect UXO and related munitions debris and a Remotely Operated Vehicle (ROV) to groundtruth objects detected by sonar in the waters adjacent to Bahía Salinas and Bahía Icacos off the northeastern coast of Vieques Island. The survey included participants from NOAA's OCS, ORR and NAVFAC Lant.

Instruments and techniques used in all three projects represented an appropriate selection of modern hydrographic mapping equipment. The resulting data from all tools were utilized to complete project objectives. Some survey tools worked better than others for detecting and classifying UXO and related debris exposed on the seafloor.

Areas containing UXO appear in the multibeam sonar as depth anomalies; identification of these items was simplified when an associated grazing halo surrounded the object. Sidescan sonar, both ship-based and AUV-based, provided clear images of UXO items when the sonar contact was free of biological clutter, such as coral outcroppings, but UXO were difficult to detect in the sonar in areas of rough bathymetry or coral encrustation. The magnetometry

dataset was of little value in Bahía Salina del Sur as the omni-directional single sensor was floated at the water surface and only detected background magnetic signatures. Diver and ROV video groundtruthing provided project participants photographic evidence as to the nature of the sonar contact, but improved diver and ROV positioning equipment was noted and recommended. Many contacts selected from the sidescan dataset were confirmed by divers to be coral outcroppings that had the appearance of potential UXO items. NOAA hydrographers gained experience in differentiating coral and other benthic features from UXO and developed a sonar contact classification scheme. The AUV-based sidescan sonar record, and subsequent ROV video groundtruthing, proved to be the safest, most cost-effective and efficient collection of tools used to detect munitions and related debris on the seafloor. NOAA has recommended the use of an AUV system with both sonar and video image capabilities to further enhance operational safety and efficiencies.

NOAA has produced survey coverage maps, mosaic images of sidescan and multibeam sonar data, still and video images with positions of UXO contacts, and a Geographic Information System (GIS) with all the associated data layers collected during the survey efforts.

1.0 INTRODUCTION

1.1 Site History and Description

Vieques is an island located seven miles southeast of mainland Puerto Rico. A portion of the island was formerly used by the United States Navy in the early 1940s for naval gunfire support and air-to-ground ordnance training. The Naval Ammunition Storage Detachment (NASD) occupied about 8,000 acres on the western end of the island, while the eastern end of the island was used for the Eastern Maneuver Area (EMA - 11,000 acres) and the Atlantic Fleet Weapons Training Facility (AFWTF - 3600 acres), which included the Live Impact Area (LIA - 900 acres). Beginning in 2001, the Navy turned over land on the western end of Vieques to the Municipality of Vieques, the U.S. Department of the Interior (DOI), and the Puerto Rico Conservation Trust. In early 2003, the Navy ceased all operations and finalized transfer of all real property on the eastern end to DOI for use as a wildlife refuge, with the former LIA to be managed as a wilderness area closed to the public.

The Navy is now investigating areas it previously occupied to determine the extent of any potential contamination. The Atlantic Fleet Weapons Training Area - Vieques was officially listed on the U.S. Environmental Protection Agency's (EPA) National Priority List on February 11, 2005. Areas required to be investigated by the Navy as part of this listing include the EMA (including Camp Garcia), the former Surface Impact Area (SIA), the Live Impact Area (LIA), and the Eastern Conservation Area (ECA) on the east end of Vieques. Within the Naval Ammunition Support Detachment (NASD) on the western end of Vieques, areas include, but are not limited to, eight areas for which the Navy considers the ongoing investigations and remediation to be incomplete. It also includes any additional areas that may be discovered to be impacted by Department of Defense activities during the course of investigations of the areas. The waters surrounding all these areas are largely uncharacterized; identified areas of concern include waters impacted by target practice on eastern Vieques, ship anchoring areas north of Vieques, and waters near western Vieques, including Mosquito Pier.



Figure 1. Project areas overlaid on Google Earth™ satellite imagery (images collected 2006).

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1.2 Areas Surveyed

The spatial extent of the Vieques Underwater Unexploded Ordnance Demonstration Projects includes the waters located to the north and the south of the former U.S. Navy Vieques Naval Training Range (VNTR) on the eastern end of the island, now designated as the Vieques National Wildlife Refuge (Figure 1). The land adjacent to the project waters was used for many years as military training grounds. A variety of training exercises occurred throughout the region and many types of munitions were used and are known to have landed in the bay. Portions of the refuge are open to the public; however the majority of the area remains closed due to the presence of UXO.

The primary focus area for the November 2006 UXO survey demonstration project was in Bahía Salina del Sur, located on the southern shore near the eastern tip of Vieques Island. The bay area is approximately $\frac{3}{4}$ by $\frac{1}{2}$ nautical miles. Depths range from the shoreline to approximately 14 meters deep. As shown on the NOAA navigational chart 25650, this area is defined by a variable bottom with numerous rock outcrops and flatter regions of sediment (Figure 2). These seafloor features tend to follow the geological structure seen along the coastline.

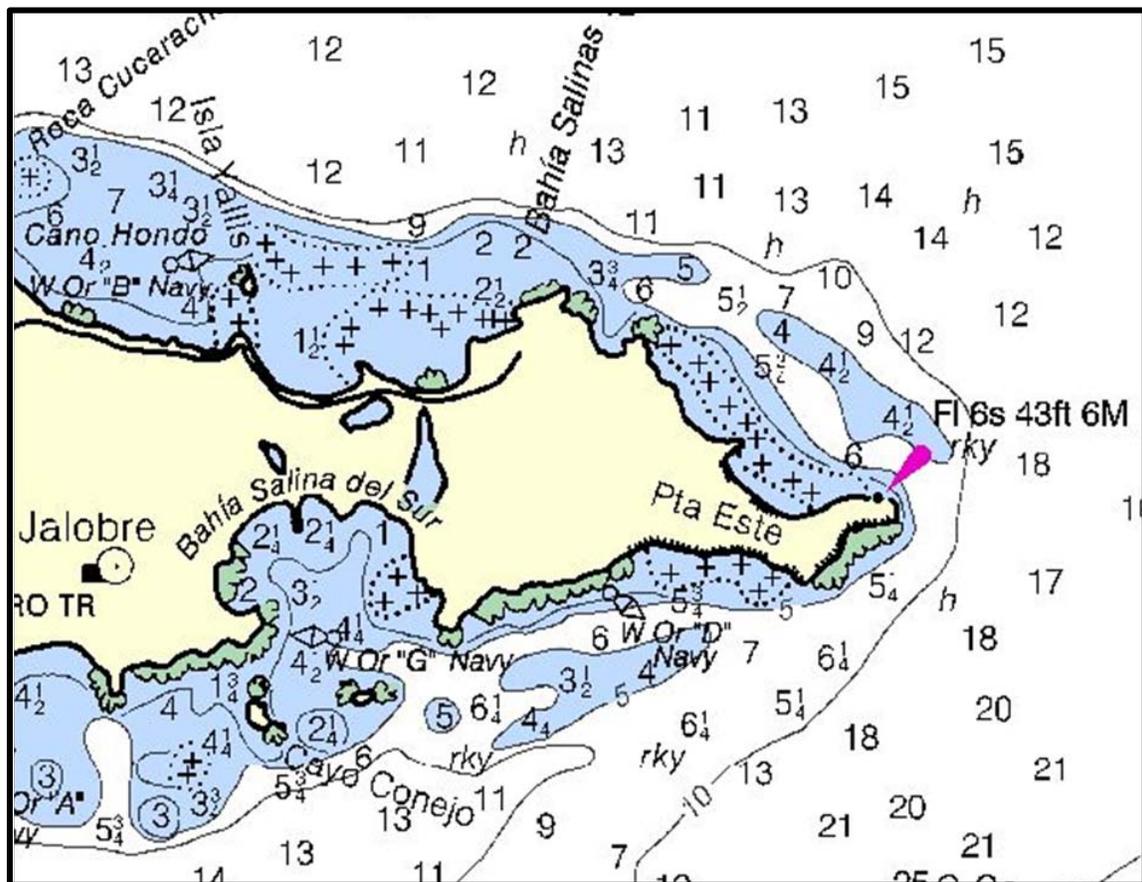


Figure 2. Cropped portion of NOAA chart 25650 (34th edition, April 2004, Soundings in fathoms) depicting hydrography in project areas. Note: + symbols on nautical charts indicate coral outcroppings or rocks, not UXO.

Centrally located in the area is the wreckage of the USS *Killen*, a US Navy retired battleship used for bombing practice. The ship was intentionally sunk in 1963 as part of a series training exercises, and provides well defined features that were used for the sonar patch test. The patch test consists of a number of set survey lines run over a known bottom feature. These lines are used to determine misalignments between the sonar and the positioning, orientation and attitude sensors. The misalignment values are entered into the acquisition and processing software so that each sounding and sidescan sonar point acquired can be correctly geo-referenced for sidescan mosaics and bathymetric maps.

On the northeastern side of the island, NOAA conducted two Autonomous Underwater Vehicle (AUV) sonar surveys, one in November 2006 and a second survey in June 2007 in the waters of Bahiá Salinas and Bahiá Icacos. These bays are located on the northern shore near the eastern tip of the island. The survey area was approximately 30 linear nautical miles. Project depths range from 3 meters to approximately 15 meters. The spatial extent of the project areas are depicted in Figure 1.

Access to all survey areas was restricted and was coordinated with the on-site Navy representative and ordnance disposal contractors. The project teams were provided with shortwave radios and were required to contact on-site safety prior to moving locations within the restricted area. In an effort to maintain a good working relationship with the on-site personnel, NOAA survey schedules were modified so that project teams could arrive and depart the restricted areas with the contractor work crews and not require special escorts.

1.3 Project Objectives and Goals

The Vieques Underwater UXO Demonstration Project's (November 2006 in Bahiá Salina del Sur) primary objective was to evaluate the use of an interdisciplinary approach to locate UXO and related debris in a shallow bay known to contain UXO. The tool suite included sidescan and multibeam sonar, a magnetometer, underwater photography and videography.

The two AUV Underwater UXO Investigation Projects' (November 2006 and June 2007) primary objectives were to conduct follow-on surveys using an AUV equipped with high resolution sidescan sonar to detect and locate UXO and an ROV equipped with a video camera to visually identify UXO in areas previously un-surveyed by acoustic sensors. The use of an AUV is particularly beneficial due to the flexible mobilization, reduced logistical requirements, and ability to deploy from the shore to survey the shallow bays to the north of the LIA. In both AUV projects (Nov 2006 and June 2007), the AUV project team deployed the AUV from beaches within the LIA to map potential UXO contacts. In June 2007, NOAA used an ROV operated from a charter fishing vessel to investigate the sonar contacts.

The overall objectives of all three demonstration projects were to:

- Support NAVFAC Lant's evaluation of the public safety hazard posed by UXO and munitions by determining, where practicable, the quantity, types and distribution of munitions and other objects present on the surface of the seafloor in the project areas;
- Describe the habitat associated with individual objects in the survey area by using high resolution sidescan and multibeam sonar, magnetometer, remotely operated vehicle and SCUBA divers;
- Record the habitat associated with individual objects in the survey area by using high resolution sidescan sonar and remotely operated vehicle-based video;
- Demonstrate the feasibility of using an AUV to detect UXO;
- Compare AUV to ship based sonar technologies in small object detection;
- Provide near-real time data products to a wide audience base; and
- Demonstrate the effectiveness of various hydrographic mapping technologies to help guide planning and technology choices for future underwater surveys.

2.0 METHODOLOGY

2.1 Field Activities

Underwater surveys for UXO and munitions related debris were conducted off the eastern end of Vieques Island, in the vicinity of former shoreline military contacts located within the LIA. The field components of the projects occurred during November 2006 and June 2007.

During the November 2006 effort, individual surveys were carried out to identify locations of possible UXO. These surveys were: 1) a high resolution bathymetric survey using a multibeam sonar system; 2) a high resolution sidescan sonar survey; 3) a magnetometer survey and; 4) a groundtruth survey performed by a remotely operated vehicle with video imaging and divers with still image cameras. Positioning for all the shipboard surveys was performed using Real time Kinematic (RTK) GPS whereas the diver positioning was performed using WAAS enabled GIS. Diver support was provided by Geo-Marine, Inc. (GMI) scientists and UXO technicians (former U.S. Navy Explosive Ordnance Disposal personnel). GMI conducted the groundtruthing of underwater sidescan, multibeam and magnetic contacts generated by NOAA. This involved completion of underwater visual survey of munitions-related items and non-munitions debris at Bahía Saliná del Sur. NOAA provided GMI the geographical coordinates of 109 anomalies that were acquired from the hydrographic surveying equipment. Results of the GMI efforts can be found in Appendix C.

Also during the November 2006 effort, a series of sidescan sonar surveys were conducted from NOAA's AUV platform to identify locations of possible UXO in the bays on the north side of the LIA. The purpose of conducting these surveys was to test the feasibility of launching and recovering NOAA's small AUV from a beach and to compare sidescan sonar images collected from an AUV platform to sidescan sonar images collected from the hydrographic equipment used on the NOAA boat.

During the June 2007 effort, a series of sidescan sonar surveys were conducted from NOAA's AUV platform to identify locations of possible UXO. A follow-up groundtruth survey was performed by using NOAA's ROV with video imaging to verify anomalies identified from the sidescan sonar imagery.

2.2 Equipment

The vessels and equipment for these demonstration projects were selected based on the following criteria: Depth of areas to be surveyed, bottom topography of the area, environmental conditions anticipated, and resolution required for identification of UXO and munitions debris. The top priority for all partners involved in these projects was personnel safety; the final criteria for vessel and equipment selection was made to ensure there would be absolutely no contact with UXO.

2.2.1 NOAA Navigation Response Team (NRT)Vessel

The survey vessel used was the NOAA NRT Vessel NRT-7. Details regarding the vessel are included in Table 1 below.

TABLE 1: NRT- 7 Vessel Specifications

| | NRT-7 |
|----------------------------------|--|
| Official Number | S-3004 |
| USCG | Designated Research Vessel, subchapter "C" |
| Length Overall | 30 feet |
| Beam | 9 feet |
| Draft, Maximum | 3 feet |
| Maximum Speed | 28 knots |
| Attitude & Positioning Equipment | PosMV V3 |
| Type of operations | Navigation response vessel |



Figure 3. NRT 7 boat with pole-mounted sidescan sonar fish and magnetometer on aft deck.

2.2.2 Sonar Equipment

Reson 8125 Multibeam Echosounder (MBES)

The NRT-7 was fitted with a Reson 8125 focused Multibeam Echosounder used to collect both bathymetry and backscatter data (Figure 4). The Reson 8125 is a shallow water MBES with a nominal frequency of 455 KHz. The 8125 transducers are capable of creating 240 dynamically focused beams. Coverage is up to 3.5 times water depth and the operating range is from 1-120m of the transducer face. Depth resolution is quoted as 6mm and -3dB beam opening angles are 1° along track and 0.5° across track (at nadir). The system is capable of meeting the special order accuracy requirement as defined by the International Hydrographic Office.



Figure 4. Reson 8125 MBES sensor head and processor unit.

Klein System 5000 Sonar

The NRT-7 also came equipped with a pole-mounted Klein 5000 sidescan sonar. The system is what Klein refers to as a multibeam system, not to be confused with MBES systems as described elsewhere in this document. Multibeam here refers to the 10 simultaneous sidescan beams (5 on each side, see Figure 5). The Nominal frequency of the system is 455 KHz, identical to the Reson 8125 MBES, precluding concurrent operation. Therefore the NRT-7 uses the same mounting pole for both systems. Along track resolution is 20 cm to the 75 m range, increasing to 36 cm at the 150 m maximum range scale – operations in Bahía Salina del Sur used the 50 m range scale setting. Across track resolution is determined by pulse length and in this case is 3 cm. The output data are provided as 12bit digital numbers allowing for a high dynamic range.

The rationale for using a pole mounted towfish was to optimize the mobility in a highly constrained work area, and perhaps more importantly, to minimize the risk of the towfish accidentally coming into contact with UXO.



Figure 5. Klein System 5000 sidescan sonar fish.

2.2.3 Marine Magnetics SeaSpy Magnetometer

The NRT-7 was equipped with the entirely omni-directional Marine Magnetics SeaSPY magnetometer (Figure 6). The system has a claimed absolute accuracy of 0.2 nano Tesla and a repeatability at better than 0.01 nT. The system uses Nuclear Magnetic Resonance technology applied to the hydrogen nuclei.

The omni-directionality of the system provided both benefits and limitations for this project. The benefits are primarily that the sensor is independent of heading and that target intensity is only a function of distance and not azimuth. The limitations are also tied in to the omni-directionality of the instrument since it is not possible to tell in which direction contacts are observed. Also the background signature of the local geology was much stronger than the UXO contacts that were being sought.

Note that prior to the survey, there was concern about the cable possibly entangling with UXO in the area. This concern quickly abated when it became clear that the magnetometer cable remained completely at the water surface.



Figure 6. Marine Magnetics SeaSpy magnetometer.

2.2.4 Benthos Stingray Remotely Operated Vehicle (ROV)

The Teledyne Benthos Stingray ROV (Figure 7) was equipped with a video camera and lights to facilitate small or large object identification. Images of the habitat in and around the area were also captured during the ROV operations. Target areas were identified for ROV inspection based on the abundance of suspect munitions present and/or any unusual sonar returns. Close examination and imaging of individual munitions helped facilitate identification and assisted in classifying benthic habitats adjacent to sonar contacts.

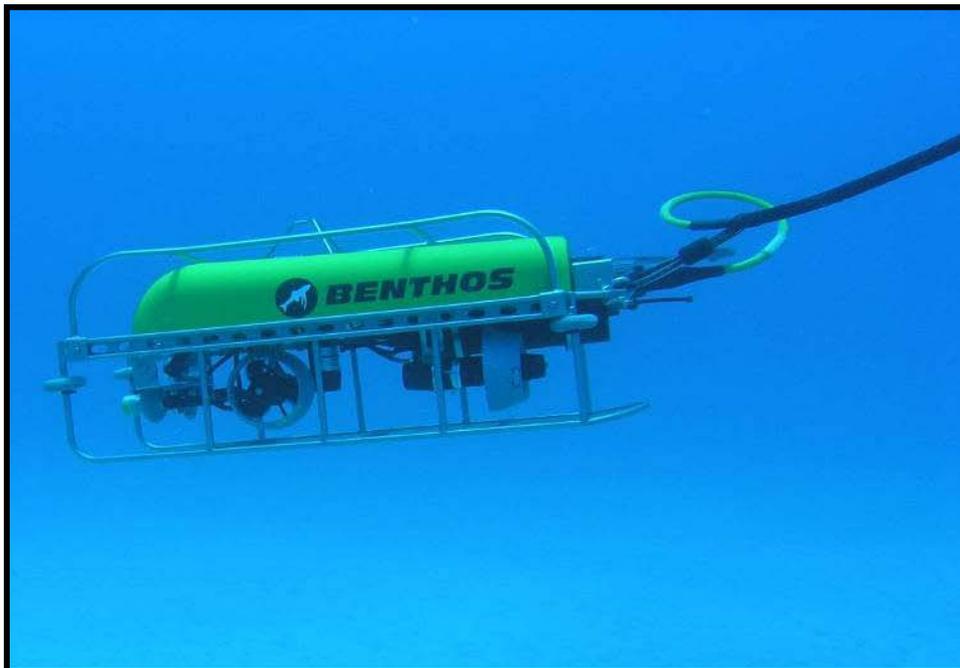


Figure 7. Teledyne Benthos Stingray ROV.

Specifications of Stingray ROV:

- Auto heading and depth/altitude
- High-resolution color 12X zoom camera
- 3 camera capable, 2 live simultaneous, 1 switchable
- Camera tilt home feature
- Full 180°, multi-use tilt bar (holds up to 4-lights and 3-cameras)
- Heading, rate gyro, pressure, and pitch and roll sensors
- 2 Built-in slide rails
- Rugged one-piece stainless steel chassis
- 4 powerful, reliable, magnetically coupled DC brushless thrusters
- Maneuverability: 3-axis translation and yaw rotation
- Horizontal speed: Greater than 3 knots on surface with a short tether deployed
- Vertical speed: 0.75-1 knot up or down
- Lateral speed: 0.75-1 knot left or right
- Operating depth: 350 m (1150 ft) of seawater
- Stability: Gravity stabilized in roll and pitch to maintain ± 5 degrees maximum inclination
- Payload: 2.5 kg (5.5 lb) in-water weight with removal of all ballast; additional buoyancy modules are available for an almost unlimited payload capability

2.2.5 Autonomous Underwater Vehicle (AUV) Platform

NOAA’s OCS staff used a REMUS 100 AUV (Figure 8) with 300 KHz sidescan sonar to detect UXO and related munitions debris in the waters adjacent to Bahía Salinas and Bahía Icacos. The REMUS 100 is a compact, light-weight, autonomous underwater vehicle designed for operation in coastal environments up to 100 meters in depth (Table 2). The REMUS 100 is man-portable and can be launched from the beach or a small boat to run a preprogrammed survey mission.

Table 2. Specifications of NOAA’s Hydroid REMUS 100 AUV

| | |
|----------------------|---|
| Maximum Diameter: | 19 cm (7.5 in) |
| Maximum Length: | 160 cm (63 in) |
| Weight In Air: | 37 kg (< 80 lbs) |
| Trim Weight: | 1 kg |
| Max Operating Depth: | 100 m (328 ft) |
| Energy: | 1 kw-hr internally rechargeable Lithium ion |
| Endurance: | 10 hrs at optimum speed of 1.5 m/s (3 knots) >8 hrs at 2.6 m/s (5 knots) |
| Propulsion: | Direct drive DC brushless motor to open 3-bladed propeller |
| Velocity Range: | Up to 2.3 m/s (4.5 knots), variable over range |
| Control: | 2 coupled yaw and pitch fins |
| External Hook-Up: | 2-pin combined Ethernet, vehicle power and battery charging; 4-pin serial connector |
| Navigation: | Long baseline (LBL); Ultra short baseline (USBL); and Doppler-assisted dead reckoning |
| Transponders: | 20–30 kHz operating frequency range |
| Tracking: | Emergency transponder, mission abort, and in-mission tracking capabilities |
| Standard Sensors: | Acoustic Doppler Current Profiler (ADCP) / Doppler Velocity Log |
| | 300 KHz Side Scan Sonar |
| | GPS aided Inertial Navigation System (INS) |
| | Navigation data including: Long baseline (LBL) |
| | Conductivity & Temperature |
| | Pressure |
| Software: | GUI-based: programming, post-mission analysis, documentation, maintenance |
| Shipping: | 2 reusable cases for all equipment, each less than 150 lbs |



Figure 8. Hydroid REMUS 100 AUV.

2.2.6 Horizontal and Vertical Control Equipment

Real Time Kinematic GPS Base Station

A Trimble GPS 5700 24 channel Dual Frequency code and carrier phase capable receiver was used as a Real Time Kinematic (RTK) GPS base station (Figure 9). CMR+ phase differential correctors were broadcast using a Trimble TrimMark III radio modem operating in the 450-470 MHz frequency range. Clearance with Vieques range control was first obtained in order to ensure that the broadcast would not inadvertently detonate live ammunition in the area. A significant challenge was posed by the extremely remote location of the base station, making it difficult to ensure continuous power supply and thus operation.

A second TrimMark III radio modem was used on the NRT-7 to receive the CMR corrections and export them to the Applanix Pos MV V3 system. 5700 RTK, combined with Trimble Trim Mark III S/N 4526152517.



Figure 9. Project lead calibrating RTK GPS base station.

Water Level Gauge

NOAA Tide gauge 9752695 installed at the government pier in Esperanza, Vieques Island, PR was used for water level information. Tide data were retrieved through the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) Tides and Currents web page. Vertical control of gauge 9752695 was reestablished by CO-OPS in the summer of 2006. Tidal zoning was requested from CO-OPS and the entirety of Bahía Salina del Sur was covered by a single zone with a delay of zero minutes and range scalar of 1.8.

2.2.7 Positioning, Heading, and Attitude Equipment

The NRT-7 was equipped with an Applanix Positioning and Orientation System for Marine Vehicles (PosMV) model MV V3 Inertial Motion sensing Unit (IMU) with tightly coupled internal GPS receivers. The PosMV calculates position, heading, attitude, and vertical displacement (heave) of a vessel. It consisted of a rack mounted version 2.12 POS Computer System (PCS), a strap down IMU-200 (Inertial Measurement Unit), and two Trimble GPS antennas corresponding to GPS receivers in the PCS. The port side antenna was designated as the primary receiver, and the starboard side antenna was the secondary receiver.

The PosMV uses data from both its accelerometers as well as the internal GPS receivers to create all data products. Very high update rates are achievable due to the accelerometers whereas long term drifts are avoided through tightly coupling the Inertial and GPS data using Kalman filtering.

The overall absolute accuracy of the data is strongly affected by the quality of the GPS data and improves by an order of magnitude by going from a C/A solution to Differential GPS and another order of magnitude by going to RTK GPS positioning. During the entire survey, RTK differential correctors were available and all positions were calculated using fixed RTK solutions. The positioning accuracies were consistently on the order of centimeters throughout the project, although some long term heave artifacts were observed on some of the more southern survey lines, due to the heavy sea state.

2.2.8 Sound Speed Equipment

A Seabird Electronics SBE 19plus SEACAT profiler was used to obtain water column sound speed data. NRT-7 was equipped with a SV Plus Applied Microsystems sound velocity profiler used to acquire sound speed data in the water column. Its field accuracy is 0.05 m/s with precision of 0.03 m/s and a sampling rate of 25Hz.

2.2.9 Data Acquisition Software

HYPACK®

HyPack 4.3a Gold from HYPACK Inc. was used for line planning and vessel navigation. Lines were planned in parallel offsets from a set of baselines.

ISIS

Triton Imaging Inc Isis was used for the acquisition of both MBES and sidescan data. Both types were logged in the non proprietary XTF format. This is the default Isis output format developed by Triton and is commonly accepted as an input data format by post processing software. Note that sound speed corrections were not applied in Isis, but rather in post processing.

2.2.10 Data Processing Software

CARIS

CARIS HIPS & SIPS™ 6.0 Service Pack 2 (Hydrographic Information Processing System) was used to integrate all multibeam data with ancillary data, including sound speed profiles; HIPS was used for quality control and to edit and filter data as necessary. CARIS HIPS was also used to calculate the Total Propagated Error (TPE) associated with the resulting bathymetry models. A set of CARIS BASE surfaces at varying resolutions is one of the main deliverables for interpretation of the results.

GeoCoder

GeoCoder Version 2.8.1 Level 2 was used to process all Klein 5000 data. This software allows for the removal of angular dependent and other systematic features as well as providing various mosaicing options.

Fledermaus

Interactive Visualization Systems Fledermaus V 6.3.0 Build 323 was used to visualize the various geo-referenced data sets in a 3 dimensional environment. The associated dMagic software was used to prepare the data for visualization as well as for the evaluation of simple data queries. Finally the cross check tool was used for the evaluation of the consistency of the MBES bathymetry data.

3.0 RESULTS

3.1 Results from November 2006 Demonstration Survey Conducted on NRT-7 Boat in Bahiá Salina del Sur

The NOAA NRT-7 boat worked exclusively in Bahiá Salina del Sur for 6 days performing demonstration surveys using a variety of hydrographic technology. The total area covered by the demonstration surveys was 667,909.750 square meters x 4 (2 perpendicular passes with multibeam and 2 perpendicular passes with sidescan) and is shown in Figure 10.

There were 58.6 total linear nautical miles (108.6 lineal kilometers) covered for Bahiá Salina del Sur.

26.6 – Lineal kilometers MBES East West coverage

25.8 – Lineal kilometers of MBES North South coverage

28.4 – Lineal kilometers of sidescan East West coverage

27.8 – Lineal kilometers of sidescan North South coverage



Figure 10. Survey coverage performed by NRT 7 boat in Bahiá Salina del Sur.

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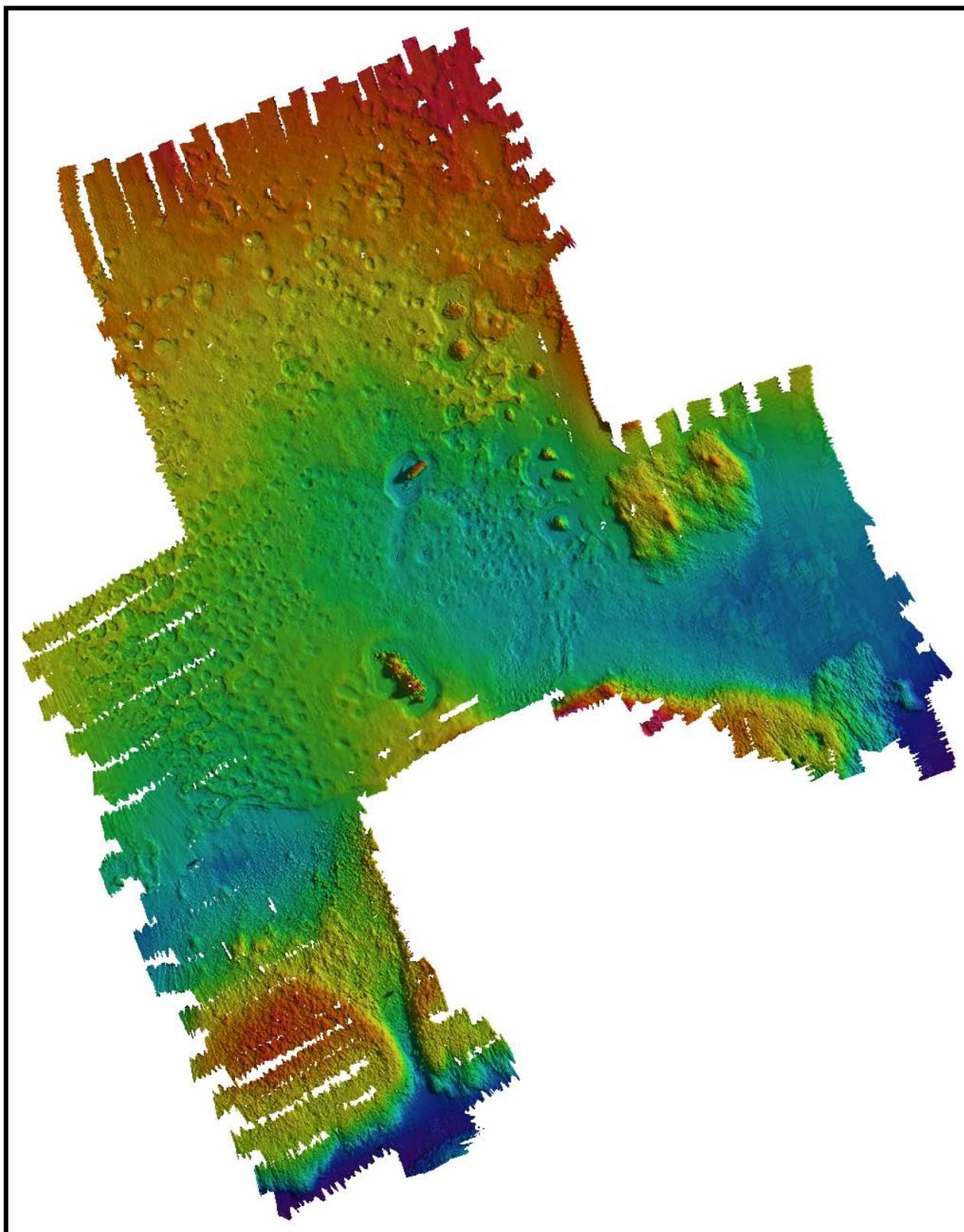


Figure 11. 1 meter resolution bathymetry of Bahiá Salina del Sur.

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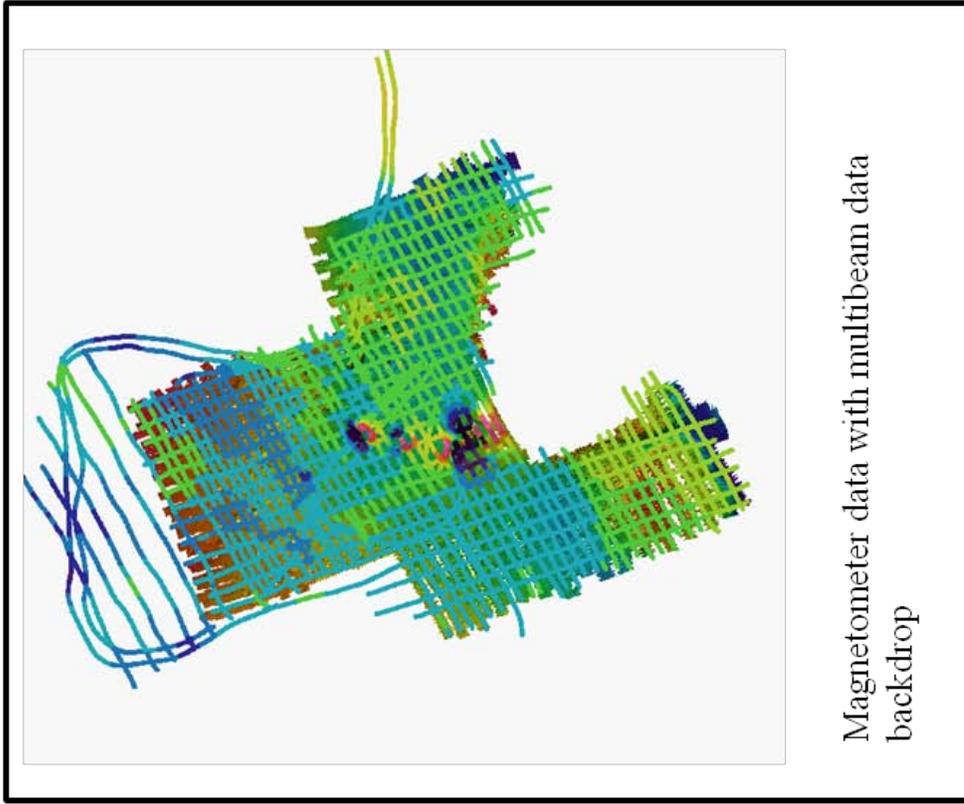
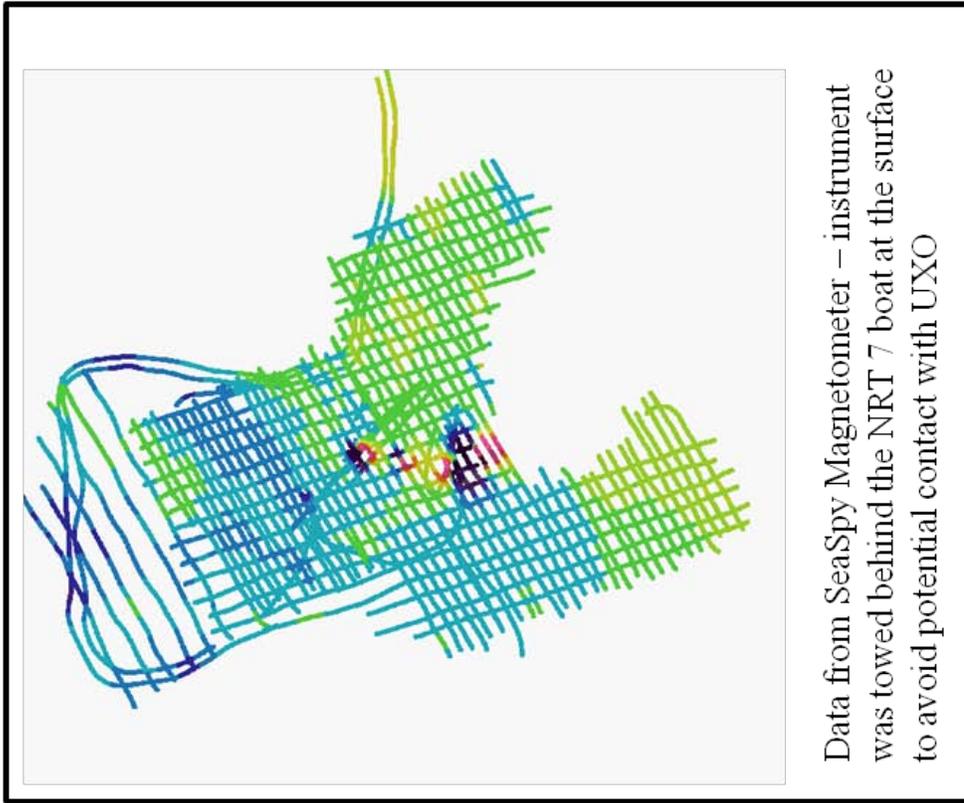


Figure 12. Fluctuations in the observed magnetic data are primarily driven by the bathymetry and do not identify UXO targets. The large anomalies located near the center are created by the wreck of the USS *Killen* and its associated debris field.

After conducting multibeam, sidescan and magnetometer survey lines (see figure 12 for magnetometer data), NOAA hydrographers selected 109 contacts from those data sets.

Of these 109 contacts (see figure 13), 13 were investigated by ROV with video camera and 42 were investigated by divers equipped with metal detectors and underwater still cameras.

All of the diver investigated contacts were photographed from multiple view angles. In each photo, the view direction as well as the target name was indicated.

42 contacts were evaluated by SCUBA divers during two days of diver groundtruthing. Former Navy EOD, contract and NOAA divers classified the 42 contacts into the following categories:

- 9 Munitions debris
- 6 Munitions items
- 4 Non-munitions debris
- 7 Natural (Reef Rock, Carbonate Nodules, Patch reef)
- 11 Unknown (Not visible to diver but a magnetic response present)
- 5 Not Found

See Appendix C - Geo-Marine Inc. Report to see all diver photographs, UXO classifications, field methods and discussion of other groundtruthing operations.

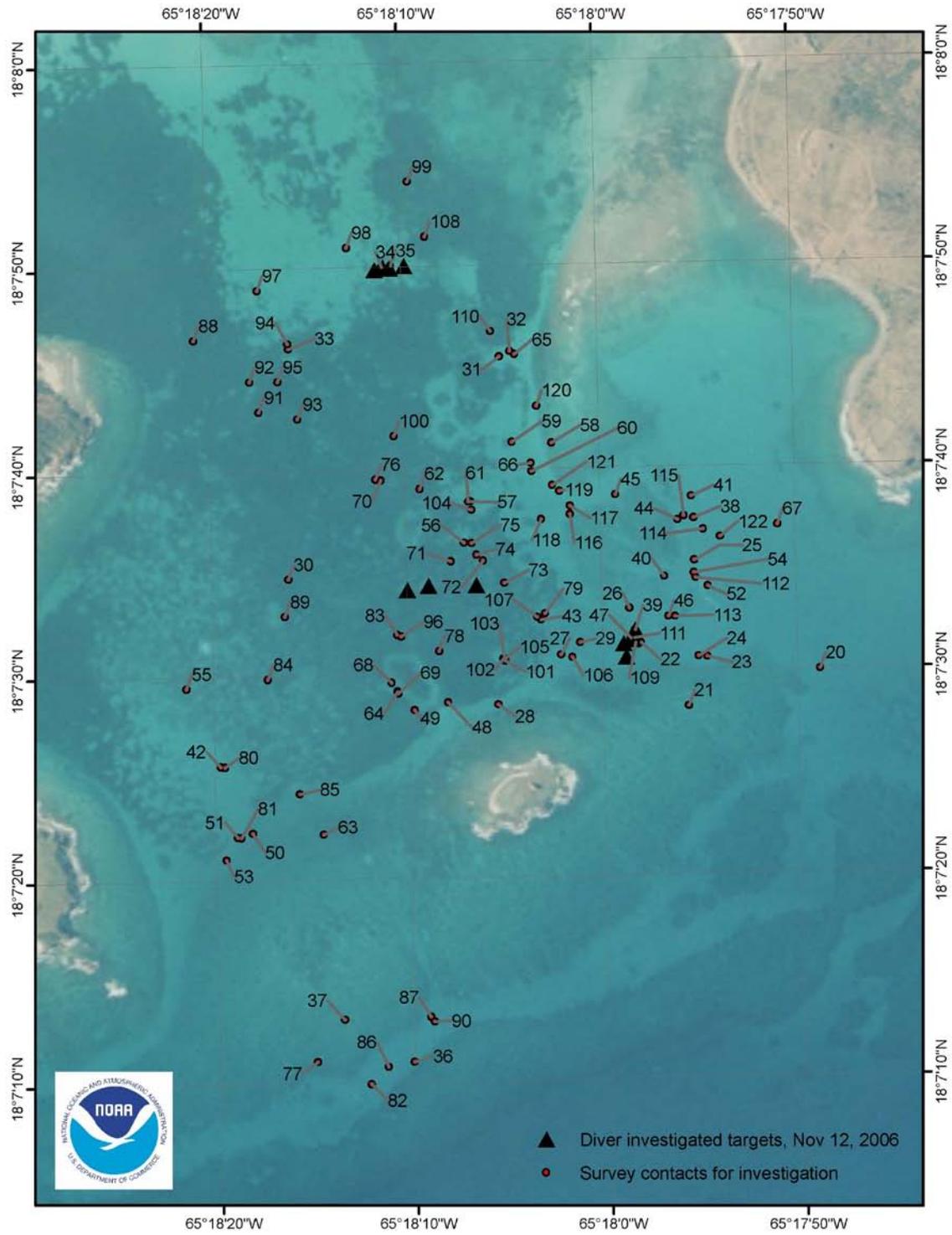


Figure 13. 109 sonar contacts selected by NOAA hydrographers

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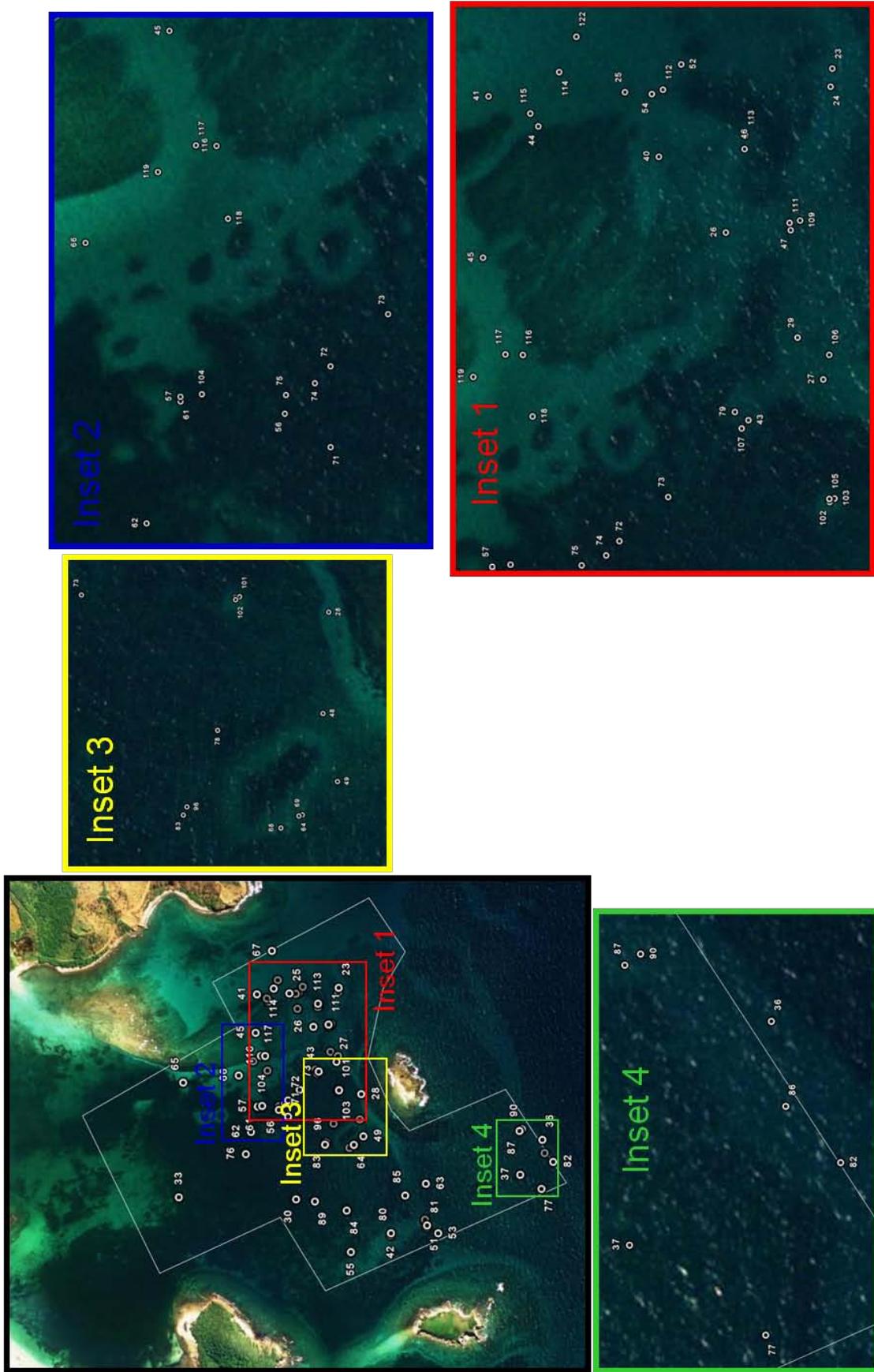


Figure 14. Non-groundtruthed contacts from 2006 NOAA NRT-7 boat survey work.

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3.2 Results from November 2006 AUV demonstration Survey Conducted in Bahía Icacos

NOAA used a Hydroid REMUS-100 AUV equipped with 300 KHz sidescan sonar to identify potential UXO. All sonar contacts were classified according to image characteristics and bottom type. The purpose of the survey was to demonstrate the capabilities of unmanned systems for identifying potential UXO.

Initial missions in Bahía Icacos were run with the AUV operating at or near the surface to acquire coarse bathymetry data to determine the possible extent of the sidescan survey; the AUV requires a minimum water depth of 3 meters to obtain sonar images of the bottom.

Water depths of up to 7 meters were recorded in the bay (Figure 15), which allowed the AUV to be run at a higher altitude than expected (3 meters with a sidescan sonar range of 30 meters).

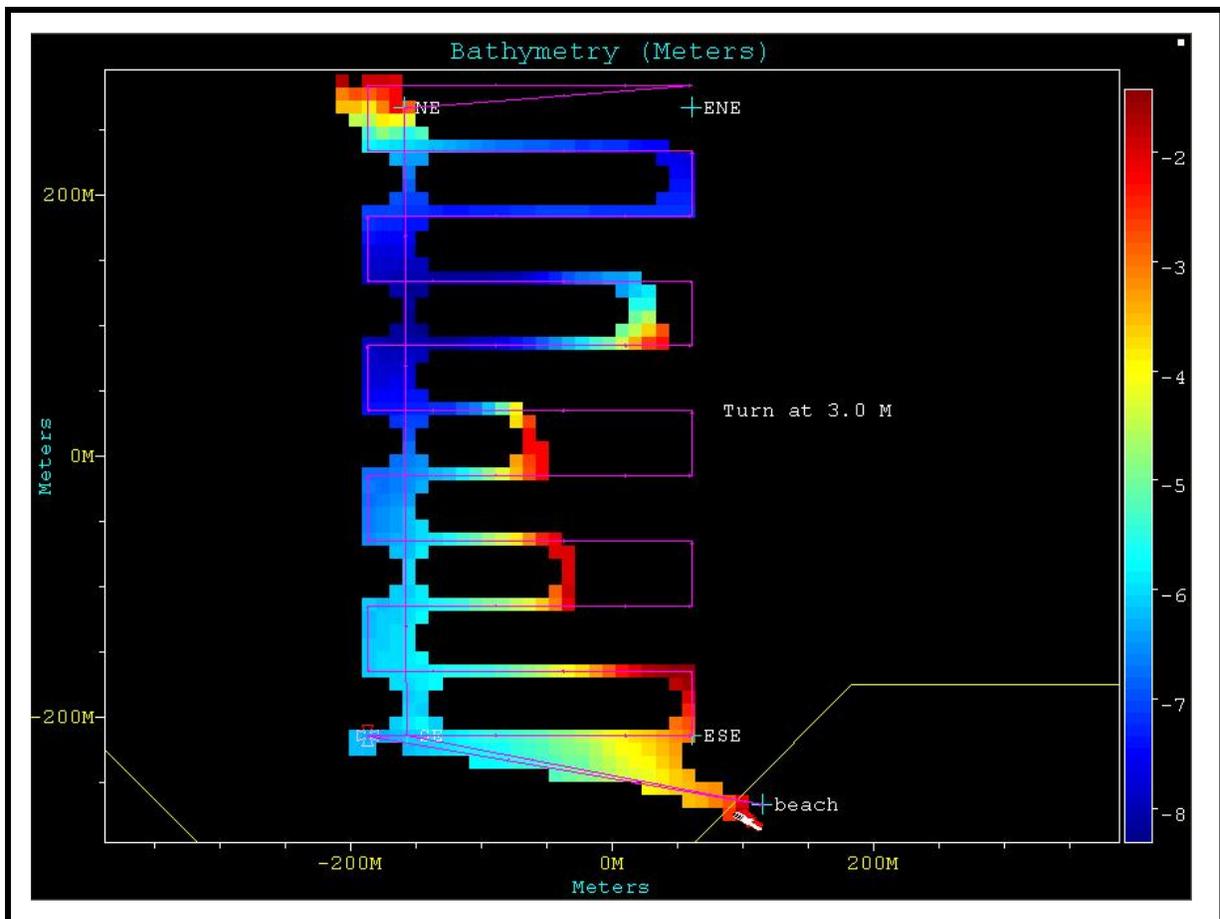


Figure 15. Course bathymetry map from AUV sonar of Eastern Portion of Bahía Icacos

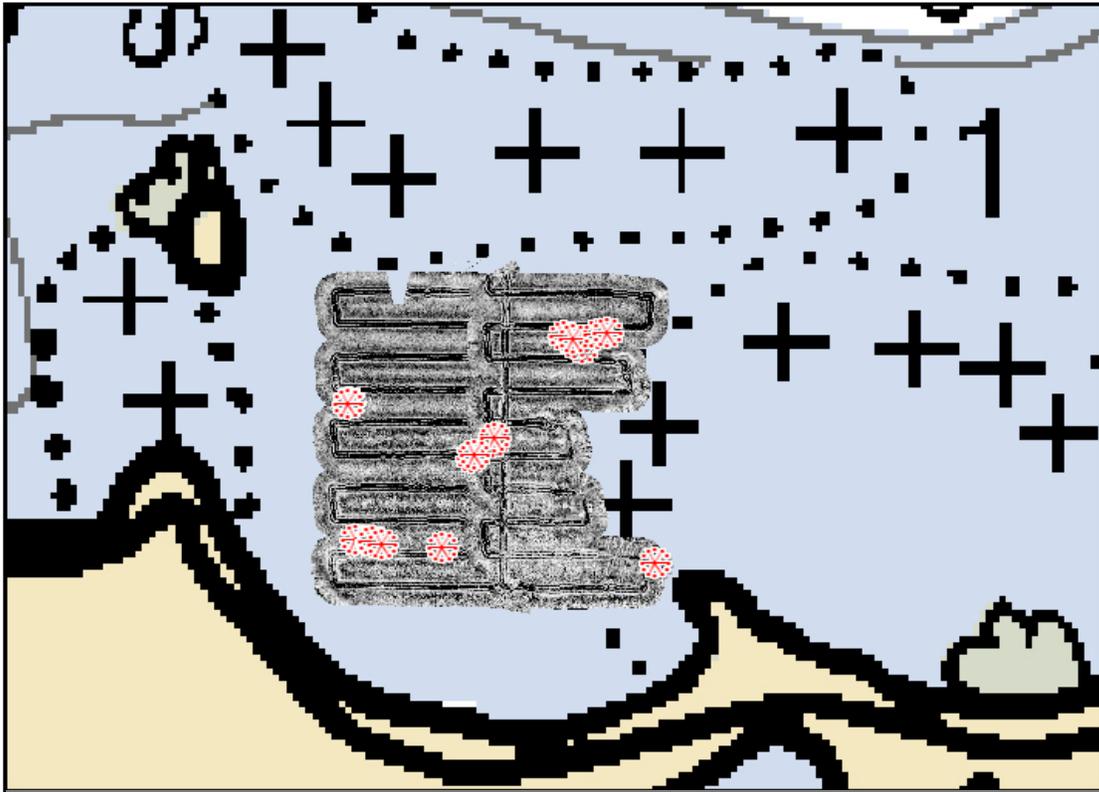


Figure 16. AUV 300KHz sonar mosaic and contacts in Bahía Icacos overlaid on NOAA Chart 25650.

AUV Sidescan Sonar Imagery

Many of the contacts that were identified in the sidescan sonar records are actually clusters that are not clearly distinguishable as ordnance, coral, or rock without additional investigation with an ROV or EOD-trained SCUBA diver (Figure 17). However, the success of the AUV survey is that the results can be used to direct manned resources to areas where some anomaly exists. The contacts identified with the AUV are comparable to the contacts identified by NRT7 using a pole-mounted Klein 5000 sonar (Figure 18).

3.2 Results from November 2006 AUV demonstration Survey Conducted in Bahía Icacos

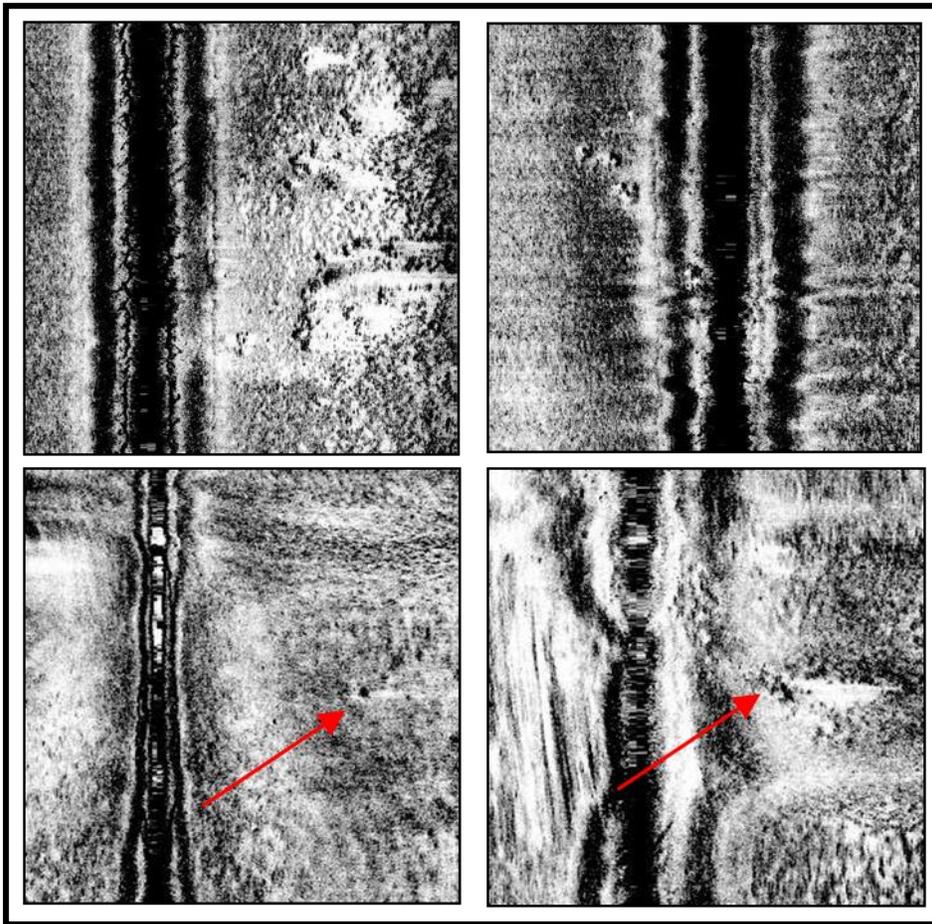


Figure 17. Examples of discrete contacts that were identified in the AUV sonar data.

There was no groundtruthing done on AUV sonar contacts, but video images of NRT-7 sidescan sonar contacts similar in size and shape to AUV sonar contacts possessed the same sonar image properties as diver and video confirmed UXO found in Bahía Salina del Sur. Both contacts in Figure 18 are approximately 1 meter proud of the seafloor.

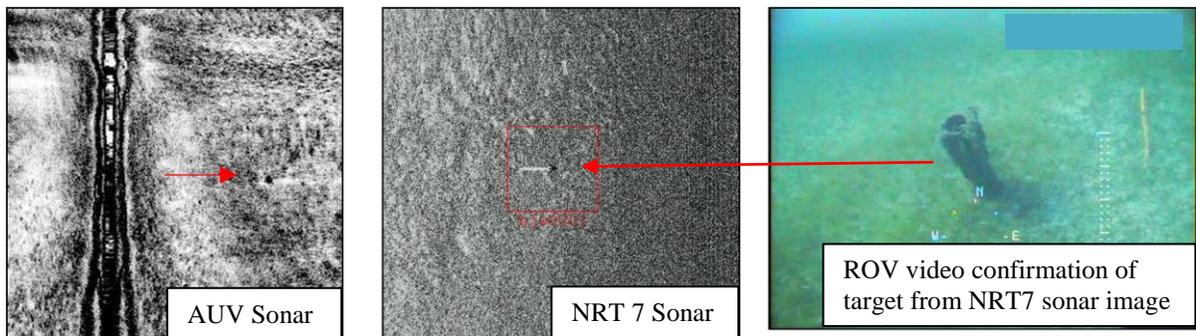


Figure 18. Comparison of AUV Sonar (left image) with NRT 7 Sonar (center image) and ROV video confirmation of NRT 7 target (right image).

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3.3 Results from June 2007 AUV Survey Conducted in Bahiá Icacos and Bahiá Salinas

In June of 2007, NOAA returned to the northeastern bays of Vieques and used its Hydroid REMUS-100 AUV equipped with 300 KHz sidescan sonar to identify potential UXO proud of the seafloor. NOAA hired a local dive vessel and captain to act as lookout for the AUV should the AUV suffer a navigation malfunction and not return to the AUV operators on the beach. The dive vessel also provided a platform from which to operate the NOAA ROV with video to groundtruth AUV sonar contacts.

The purpose of the survey was to demonstrate the capabilities of unmanned systems for identifying potential UXO. The AUV team used lessons learned from the November 2006 project to set the AUV up for maximum survey efficiency. The AUV was programmed to operate in water depths greater than 3 meters with the sonar range scale set to 30 meters.

After each day of survey operations, hydrographers studied imagery and selected sonar contacts that were expected to be munitions or related debris. All sonar contacts were classified according to image characteristics and bottom type and representative contacts from each classification category were investigated with ROV equipped with a video camera.

NOAA conducted 4 AUV survey missions over 3 days. For each mission, the AUV was launched and recovered from the beaches adjacent to Bahiá Salinas and Bahiá Icacos.

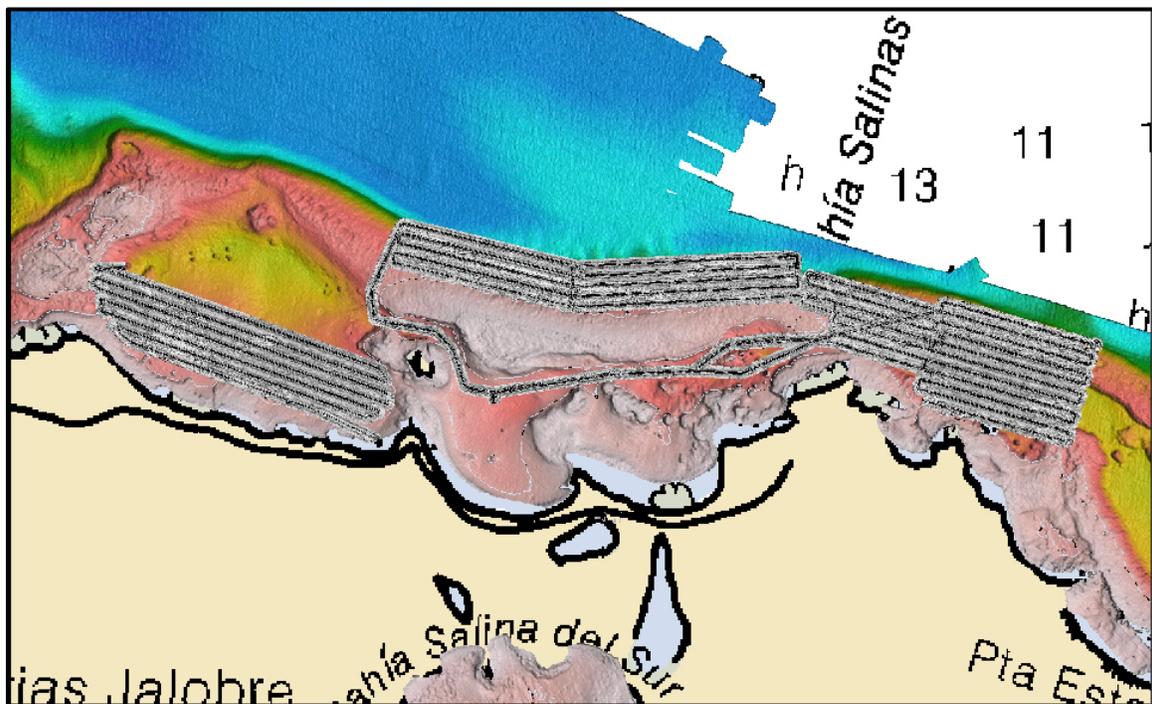


Figure 19. Sidescan sonar coverage map of Bahiá Salinas and Bahiá Icacos (shallow water bathymetry and sonar mosaic overlaid on NOAA nautical chart).

The NOAA AUV collected sidescan sonar data totaling approximately 28 linear nautical miles (0.6 square nautical miles). See Figure 19.

The NOAA hydrographers selected 215 contacts from the sidescan sonar imagery. The number of contacts included multiple passes over the same contacts from reciprocal lines and some likely geologic features. The sonar contacts were classified into categories describing bottom type (rough or smooth) and contact type (linear, point, or uncertain). Multiple types of each contact were chosen for investigation with the ROV to correlate sonar contact types with video.

Despite challenging winds and strong ocean currents during both days of ROV operations combined with the dive vessel's handling characteristics (single engine), the NOAA team was able to establish a positive correlation between video and sonar contacts of each type.

22 sonar contacts were selected to represent 6 classification categories (Figure 20) based on bottom texture and apparent contact shape:

Smooth Bottom - Point feature, Linear feature or Uncertain

Rough Bottom - Point feature, Linear feature or Uncertain

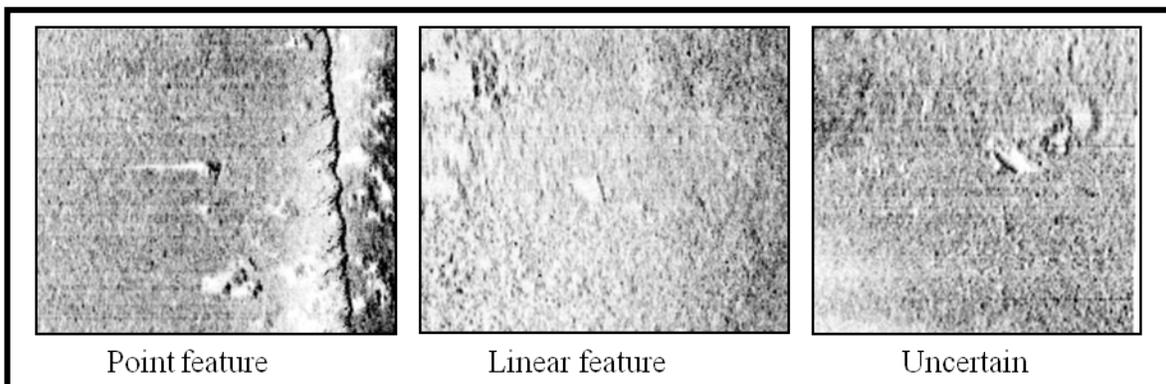


Figure 20. Sidescan sonar coverage images of Point, Linear or Uncertain contacts on a smooth bottom texture.

See Appendix B that provides a representative sample of sonar images with correlating video still images.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions and Recommendations from NRT 7-based Survey Operations in Bahía Salina del Sur, November 2006

The chosen approach that utilized modern mapping technologies and software is appropriate for rapid evaluation of UXO exposed on the seafloor. Many of the contacts identified in the sonar records correlate well to those located in the underwater photography. Many of the UXO found were characterized by the presence of a grazing halo. The cause of the halo is likely fish and macro-invertebrates living in or near the artificial habitat created by the UXO's structure.

The multibeam sonar bathymetry resolution set at 5cm grids proved to be the most conclusive of the various data sets. The UXO and munitions debris appear in bathymetry as depth anomalies. These contacts were often surrounded by a grazing halo. Grazing halos are a good proxy for detecting UXO using bathymetry data. See Figure 21.

The sidescan data set enabled the detection of more and similar UXO, but also led the hydrograpers to select a larger number of non-munitions contacts. The distinguishing feature for most munitions identified by sidescan sonar is a sharp edge with a well defined acoustic shadow.

Due to the omni-directional nature of the SeaSpy magnetometer, inability to guide the magnetometer near the sea floor and strong magnetic signature of local geology, only very large contacts such as USS *Killen* debris could easily be identified. A detailed gradiometer survey of the area that was overlaid with sonar graphics would yield a high correlation of iron-bearing anomalies to contacts identified in sonar records.

ROV videos and divers provided human eyes and experience to distinguish UXO from coral outcroppings, but in an exposed body of water such as Bahía Salina del Sur, an AUV equipped with precise navigation and positioning and a geo-registered video camera would be a preferable vehicle to an ROV due to the AUV's greater independence of sea-state.

The underwater photography taken by SCUBA divers provided many positive correlations to the selected contacts. However, the analysis of underwater photography would greatly benefit from more diver-verified contacts using higher accuracy underwater positioning.

Many of the munitions are located in very shallow waters that are difficult or dangerous to access using a surface vessel. An Unmanned Surface Vehicle that employs both sonar and video imagery may be useful in shallow water. Airborne LIDAR may also provide good coverage of shallow surf zone areas.

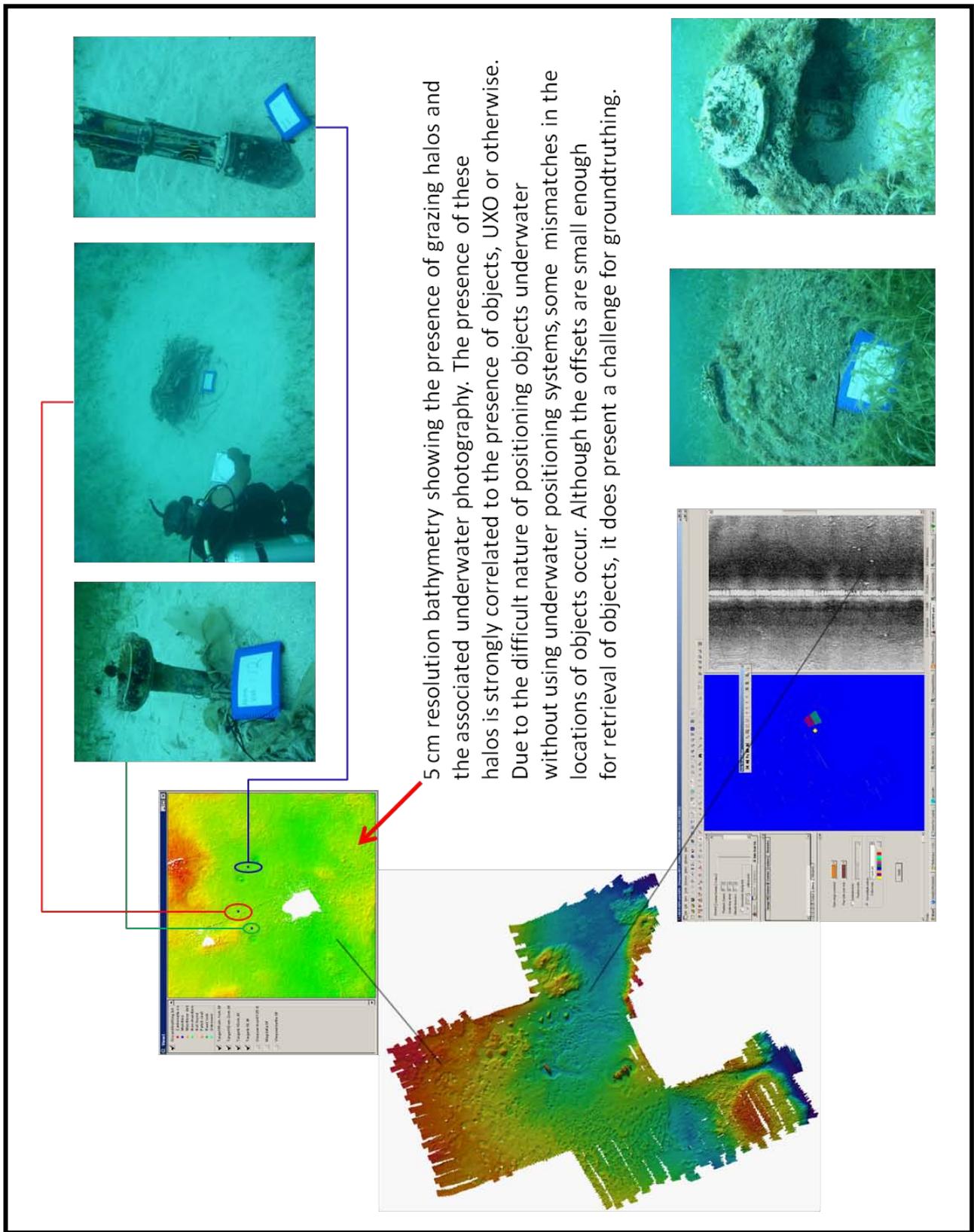


Figure 21. 1 meter resolution bathymetry overview with 5cm resolution inset and corresponding diver photographs of UXO and debris.

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4.2 Conclusions and Recommendations from AUV-based Survey Operations in Bahiá Icacos and Bahiá Salinas, November 2006 and June 2007

The NOAA AUV team demonstrated the capabilities and limitations of unmanned systems for identifying potential UXO. Once appropriate bathymetry and shoreline boundaries were programmed, the AUV provided an efficient data collection system over a large geographic area in waters deeper than 3 meters.

Deployment and recovery of the REMUS-100 AUV from a sandy beach is easily accomplished (Figure 22). The vehicle recovery position for each mission was programmed to be approximately 15 meters off the beach and the vehicle's momentum practically swam the vehicle into the team's hands.



Figure 22. AUV team launching REMUS 100 and verifying acoustic modem signal.

Additional survey collection in Bahiá Icacos and Bahiá Salinas could have been accomplished if more accurate bathymetry data of the area were programmed into the navigation software. The existing NOAA chart depicts only one sounding (1.5 fathoms) and grossly inaccurate shoreline (up to 120 meters error determined by handheld GPS) in the project areas. The coarse and inaccurate data are artifacts of the area's historic use as a military practice facility and the fact that if NOAA had collected and published new nautical charting

information, those data may have encouraged pleasure boaters to enter the area because of perceived safe waters.

The shallow bays in Vieques are excellent candidates for airborne LIDAR bathymetry as the water clarity is excellent and the bottom appears to be sandy, soft coral, or covered with low grass.

A motorized AUV recovery vessel increased the team's confidence in operating the AUV near the shoal areas at the northern limits of Bahía Icacos. Rather than requiring the team and equipment to travel to the project site by truck over the roads in the LIA, a dedicated small boat that could perform longer distance transit operations would allow for better access to the site and more time on station.

Some munitions present in the area are of a dimension smaller than the resolution of the sonar systems used. An AUV equipped with higher frequency (600-900 KHz) sidescan sonar may detect smaller munitions and be more effective in the shallow water.

ROV operations were limited by weather, sea state, currents, and other vessels and required many positioning and navigation calibrations and offsets. Live boating, or holding a position on the water without use of an anchor, increased the challenge of accurately determining the position of the ROV. NOAA suggests an ROV is of limited use and could be eliminated from munitions groundtruthing operations. This would reduce the total number of science team members on site and limit the required equipment. NOAA recommends the use of an AUV equipped with precise navigation and positioning as well as high resolution sonar and geo-referenced video photography capabilities.

Many of the munitions in the project areas were encrusted by corals, making it challenging to distinguish munitions from naturally occurring features. The hard shadows created by UXO lying proud on their sides on the seafloor are easily recognized in sidescan images. But many of the munitions found in Vieques waters have been in place for many years, which allows a great deal of time for bio-growth and ultimately obscures their hard sonar signature. An AUV with good positioning and video allows for grid pattern search missions that completely cover a given area and allow for the AUV to return to contacts to get multiple view angles. Ruling out obvious coral outcrops from the list of contacts allows more time for EOD-trained divers to distinguish the coral-encrusted munitions from simple coral outcroppings.

4.3 Comprehensive NOAA Recommendations for Detecting and Classifying Proud Munitions in Vieques Waters

Many shallow water sites (less than 130') that contain military munitions also contain large amounts of submerged debris, clutter, and obstructions that pose significant safety and navigation hazards to vessels and divers whose mission it is to characterize a specific site. Added to those safety risks are complicating environmental conditions such as the presence

of rock outcroppings, coral reefs, and shifting sands, all of which contribute to the challenge of discriminating munitions from the surrounding benthic environment. Compared to deep munitions disposal sites, shallow water sites are more quickly affected by coastal storms and wave action, therefore munitions in shallow environments are more likely to move over time. When the US Navy determines a timeline for underwater munitions assessment and clean up for Vieques, whether munitions are removed or blown in place, response efforts will require up to date detailed survey data to ensure efficient reacquisition of previously surveyed munitions as well as detection and classification of munitions recently moved into the area of interest by storms or wave action.

The current approach to munitions detection in shallow waters often involves coordinating multiple small vessels using traditional survey techniques such as towed sidescan sonar and fixed beam-forming bathymetric sonars. Small surface vessels are inherently susceptible to wave action and winds, which may reduce their effective survey time. These vessels also require complex integration of multiple sensors to achieve high levels of data quality. Required survey techniques can vary from vessel to vessel depending on sensor configuration, which requires a wider range of expertise to integrate the disparate data sources during acquisition and processing. Current methodologies for groundtruthing sonar contacts require an ROV or EOD-trained SCUBA diver to visually classify contacts, which introduces greater uncertainty for accurately positioning objects of interest. Using surface survey vessels also introduces many logistic problems such as: availability of an appropriate survey vessel, availability of qualified boat operators and properly trained survey personnel, transportation of vessel and equipment to survey site, access to marinas and associated services, and physical security of vessel and equipment.

NOAA recommends that an AUV with high resolution sidescan sonar and geo-referenced video imagery to detect, classify, and identify proud munitions would be the most efficient, cost effective and safe method to detect and discriminate munitions exposed on the surface of the seafloor in the complex underwater environments surrounding Vieques.

NOAA recommends that the AUV be equipped with a precision navigation system consisting of a GPS-aided Inertial Navigation System. NOAA operational experience with these systems has demonstrated navigational and target reacquisition accuracy to be equal to, or better than traditional surface vessel towed sonar systems. NOAA suggests the use of dual-frequency high-resolution imaging sonar (sidescan sonar) for target detection and classification. Dual-frequency imaging sonar allows a broad swath, high-resolution search for target detection at a lower frequency and target reacquisition for classification or identification at a higher frequency. Additionally, geo-referenced video imagery should be used to aid in target classification and identification.

NOAA suggests using survey planning and initiation procedures established by its nautical charting program. These procedures include delineating survey areas using available data, including nautical charts, satellite imagery, and existing bathymetry. The AUV survey mission should be defined to provide complete coverage of the survey area seafloor with

the AUV parameters, including altitude, speed, and sonar range, configured to balance survey efficiency with object detection.

NOAA recommends the use of two identically configured AUVs in order to maximize the efficient use of survey personnel's time on scene and ensure equipment redundancy. Based on NOAA's successful procedures developed while conducting surveys in the Florida Keys, one AUV should be used to conduct broad area object detection surveys, while the second AUV should be used to reacquire previously detected objects with the sonar set for higher resolution and video. This approach allows for the most rapid and efficient identification of objects detected.

Typically, broad area surveys are conducted with the lower frequency sonar (600 KHz) with range set to 40-50 meters, which results in up to a 100 meter swath. Reacquisition surveys are typically conducted with the higher frequency sonar (1200 KHz) and with range set to 20-30 meters and concurrent video image recording. The combination of high resolution imagery and co-registered video greatly aid in object identification. NOAA's experience using similar methodology combining an AUV and ROV is that proud objects as small as 50 centimeters can be detected and their positions determined and reacquired within 3 meters.

There are several technical risks associated with AUVs. Due to the independent operation of an AUV, there is a risk of vehicle loss due to equipment failure, collision, or fouling in an underwater obstruction. The risk is mitigated by routine and emergency communication methods, including acoustic modem, radio modem, and satellite telephone. In response to system failures, AUVs are programmed to respond with expected behavior including reversing propulsion to extract the vehicle from an obstruction, automatically surfacing, and increasing the frequency of status and position transmissions. Additionally, the risk can be mitigated procedurally through monitoring, mission programming to minimize exposure to hazards, and communication with other vessel traffic.

Benefits to the US Navy using this approach include:

- Improved operational safety because AUV operators are physically distant from munitions;
- AUVs provide efficient platform with reduced logistical constraints as compared to survey boats;
- Life cycle costs associated with AUV operations are expected to be considerably less than those costs associated with owning or leasing, maintaining, and operating small survey vessels;
- Conservative estimates of 2.5 – 3 square kilometers surveyed per day using an AUV;
- Equipment and techniques applicable to many shallow water sites;
- A small launch and recovery vessel and small team of hydrographers are all that are required to conduct a detailed survey;
- No towfish tether to foul on objects whether they are munitions or biological/geological features;

- Precise navigation and collision mitigation procedures in AUVs;
- AUVs may be able to operate on more days in sea state conditions unsuitable to a small survey boat;
- Geo-referenced video groundtruthing to better distinguish natural features in the benthic environment from munitions;
- Habitat characterization from the backscatter sonar data used to derive three dimensional representation of the sea floor; and
- New hydrographic and bathymetric data could be compared with AUV and boat-based sonar data from prior NOAA 2006-07 projects included with this report, which could provide historical data and context in change detection or munitions mobility models.

Appendix A: Geo-Marine Inc.



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