INTERIM REPORT

Unexploded Ordnance Characterization and Detection In Muddy Estuarine Environments

SERDP Project MR-2730

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14. ABSTRACT

A significant proportion of military testing ranges with potential UXO have been linked to characteristically muddy environments. This study is working to address this data gap. Using a shallow estuarine site in the Delaware Bay, this study is 1) monitoring the mobility and behavior of sensor-integrated surrogate munitions in cohesive sediments using a high-accuracy acoustic positioning system, 2) comparing surrogate munition response to hydrodynamic forcing through instrumented bottom frame time-lapse hydrodynamic data and sonar imagery, and 3) monitoring site changes and testing an autonomous underwater vehicle-borne magnetometer through repetitive site surveying. Surrogate UXO, modified with acoustic tracking devices and inertial motion units, were deployed at an estuarine site with cohesive sediment. The surrogates were monitored for changes in mobility and burial using the VEMCO positioning system, an off-the-shelf acoustic positioning system that is capable of tracking the position of multiple acoustic tags with accuracies down to 10 cm.

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1. Abstract

SERDP has recognized a need for better quantitative understanding of the impact of coastal environments on UXO behavior (MRSON-17-01). While current studies are addressing the mobility and detection of UXO in sandy coastal areas (e.g. Calantoni SERDP MR-2320, Traykovski MR-2319, Puleo MR-2503), a significant data gap has been identified regarding UXO in shallow, muddy environments (SERDP Munitions Mobility and Modeling Workshop, Dec. 8-9, 2015). A significant proportion of military testing ranges with potential UXO have been linked to characteristically muddy environments (SERDP Munitions Mobility and Modeling Workshop, Dec. 8-9, 2015). This study is working to address this data gap. Using a shallow estuarine site in the Delaware Bay, this study is 1) monitoring the mobility and behavior of sensor-integrated surrogate munitions in cohesive sediments using a high-accuracy acoustic positioning system, 2) comparing surrogate munition response to hydrodynamic forcing through instrumented bottom frame time-lapse hydrodynamic data and sonar imagery, and 3) monitoring site changes and testing an autonomous underwater vehicle-borne magnetometer through repetitive site surveying. Surrogate UXO, modified with acoustic tracking devices and inertial motion units (IMU), were deployed at an estuarine site with cohesive sediment. The surrogates were monitored for changes in mobility and burial using the VEMCO positioning system (VPS), an off-the-shelf acoustic positioning system that is capable of tracking the position of multiple acoustic tags with accuracies down to 10 cm. Concurrently, time-series acoustic imagery and hydrodynamic sensors were deployed to characterize UXO response to varied hydrodynamic conditions and compared to site-wide surrogate behavior. A series of repetitive surveys were conducted using a magnetometer specifically designed for UXO detection on an autonomous underwater vehicle (AUV). Survey results are also being compared to long-term acoustic positioning of the surrogate UXO to determine the effectiveness of the magnetometer for efficiently and effectively locating UXO in shallow, muddy environments. This study will help inform parameters for UXO mobility and behavior in storms and muddy environments, and the anticipated data will be made available for integration into the existing expert system modeling of UXO burial and mobility (e.g. Underwater Munitions Expert System "UnMES", Rennie MR-2227, SERDP Munitions Mobility and Modeling Workshop, Dec. 8-9, 2015). Additionally, the proposed study will provide important data regarding the ideal design for test beds to evaluate sensor capabilities in muddy environments (MRSON-17-02), including the use of AUV magnetometry for UXO Wide-Area Assessments in muddy environments (MRSON-17-01).

2. Objective

Unexploded ordnance (UXO) in the shallow coastal regions has increasingly become a topic of concern. There remains a recognized need for better quantitative understanding of the impact of coastal environments on UXO behavior and enhanced sensor capabilities to detect UXO (MRSON-17-01). While current studies are addressing the mobility and detection of UXO in sandy coastal areas (e.g. Calantoni SERDP MR-2320, Traykovski MR-2319, Puleo MR-2503), a significant data gap has been identified regarding UXO in shallow, muddy environments (SERDP Munitions Mobility and Modeling Workshop, Dec. 8-9, 2015). A significant proportion of military testing ranges with potential UXO have been linked to characteristically muddy environments: 139 formally used defense sites have been identified in tidal environments with cohesive sediments (USACE 2007 FUDS). This study is working to address a number of key issues and priorities identified by MRSON-17-01 and previous SERDP reports. In particular, this study is observing and working to characterize UXO behavior in muddy environments, focusing on burial or mobility in normal versus episodic high-energy events. In doing so, this study will help inform parameters for UXO behavior in storms and muddy environments for integration into the existing expert system modeling of UXO burial and mobility (e.g. Underwater Munitions Expert System, Rennie MR-2227, SERDP Munitions Mobility and Modeling Workshop, Dec. 8-9, 2015). Additionally, this study will provide important data regarding the ideal design for test beds to evaluate sensor capabilities in muddy environments (MRSON-17-02), including the use of Autonomous Underwater Vehicle (AUV) magnetometry for UXO Wide-Area Assessments (WAA) in muddy environments (MRSON-17-01).

In summation, the goal of this study is to test and characterize munition mobility, behavior, and detection in shallow, muddy environments. Using a shallow estuarine site in the Delaware Bay, this study initially proposed to:

1) Monitor the mobility and behavior of sensor-integrated surrogate munitions in muddy environments using a high-accuracy acoustic positioning system, long-baseline (LBL) network
2) Observe and compare surrogate munition response to hydrodynamic forcing through instrumented bottom frame time-lapse hydrodynamic data and sonar imagery
3) Monitor site changes and test an AUV-borne magnetometer through repetitive site surveying.

Thus far, this study has deployed surrogate munitions, modified with acoustic tracking devices and instrumented with inertial motion units (IMU) at a previously characterized site, and monitored for changes in mobility and burial. Time-series acoustic imagery and hydrodynamic sensors were also deployed to characterize UXO response to varied hydrodynamic conditions. A series of repetitive surveys were conducted using a magnetometer developed specifically for an AUV. Survey results are being compared to long-term acoustic positioning of the surrogate UXO to determine the effectiveness of the magnetometer for efficiently and effectively locating UXO in shallow, muddy environments, and, as will be shown, served as an additional tracking mechanism for buried surrogate UXO.

3. Technical Approach

3.1. Background

Hydrodynamic and morphological conditions typical in shallow, muddy environments pose problems for predicting UXO behavior and detection. While the behavior of small, man-made objects in non-cohesive, sandy substrates has been studied (e.g. Traykovski MR-2319, Catano-Lopera et al, 2007; Mayer et al. 2007; Trembanis et al., 2007) and remains under consideration (e.g. Traykovski MR-2729, Calantoni SERDP MR-2320, Puleo MR-2503), the fundamental differences in sediment dynamics between cohesive and non-cohesive sediments suggest little of this data will be applicable to UXO behavior in muddy environments. In non-cohesive sediments, the interaction between objects and the seabed often occurs in predictable manners (e.g. Trembanis et al., 2007). In certain sediment transport regimes, scour occurs around seabed objects, eventually resulting in scour infill and burial of the object, with episodic exposure in high-energy events; this behavior was thoroughly characterized and modeled in recent mine burial studies (Traykovski et al., 2007; Trembanis et al., 2007; Catano-Lopera and Garcia, 2006) The question of when UXO mobility occurs, instead of scour and burial, is less understood. Recent studies focusing on UXO have attempted to parameterize when incipient motion of UXO may be expected (e.g. Friedrichs MR-2224 & MR-2647, Garcia MR-2410). In non-cohesive sediments, incipient UXO motion has been related to critical threshold for object motion versus the ratio of the diameter of the UXO (D) to the relative roughness of the seabed (k); incipient motion is expected when critical threshold exceeds D/k, although mobility was found to drop drastically in sediment transport regimes where scour dominated (Friedrichs, MR-2224). However, cohesive sediments, under significant shear stresses, conform to different transport regimes than non-cohesive particles; transport may occur as flocculate particles, which both aggregate and dissipate with particle interaction (Letter and Mehta, 2011), or may even travel as fluidized mobile mud beds (Inman and Jenkins, 2002). Further, wave-seabed interactions are significantly different. With muddy seabeds, the coupling between flow and sediment motion is stronger than that of sandy environments, with waves experiencing significant dampening (Sheremet et al., 2005; Jain and Mehta, 2009).

The strongly contrasting characteristics of cohesive sediments beds likely leads to significant impacts on UXO behavior and detection. Under increasing wave height, fluid mud layer thickness has been shown to increase (Soltanpour et al., 2009), thereby potentially burying or obscuring objects. It has even been suggested that during storm events, both muddy sediment layers and objects may move as a unit (Inman and Jenkins, 2002). In areas of strong tidal influence, such as estuaries and shallow coastal regions, fluidized mud has been shown to fill in scour pits around seabed mines, resulting in transient burial and exposure (Inman and Jenkins, 2002; Traykovski et al., 2007). In a recent study by Baeye et al., (2012), transient mine burial was linked to high-concentrated mud suspension in high-turbidity areas; nearly complete mine burial was found to occur during slack tides in spring tidal cycles. The resulting high probability that mines would be missed during tracking surveys in similar environments led the authors to conclude further experiments were necessary to characterize mine burial with mud suspensions of various thickness and stability (Baeye et al., 2012). Due to varying stability, cohesive sediments can differ considerably, and thus UXO may also behave differently. In contrast to fluid mud seabeds, mines in stiff muds were found to only undergo slight scour and partial burial (Inman and Jenkins, 2002). There, impact burial was observed to be the largest contributor to mine burial, not subsequent hydrodynamics.

The different behavior of cohesive sediments and therefore, UXO contained within, will have strong influence on UXO detection methods. Acoustic systems, such as side-scan sonar, while capable of greater ranges, may have difficulty locating UXO that is obscured or buried in dynamic bed states (Traykovski et al., 2007). Previous work has been conducted using a low frequency synthetic-aperture sonar (SAS) to detect buried or partially buried UXO in mud (Hunter et al., 2013). However, this required a large, sophisticated sonar and complex processing chain. Work was conducted in water depths greater than 8m and the results, while promising, indicated the system was largely unable to distinguish between bottom clutter and UXO contacts (Hunter et al., 2013). For depths less than 8m, smaller, more mobile systems, such as autonomous vehicles, will be required. These systems are typically fitted with both acoustic (i.e. side-scan and multi-beam) and non-acoustic systems, such as optical sensors and magnetometers. The characteristically turbid environments in muddy systems renders optical sensors impractical. However, magnetometry can differentiate ferrous from non-ferrous objects that may be otherwise indistinguishable in traditional acoustic or optical surveys, as well as detect objects that are buried or obscured.

Despite its potential, magnetometry is not without complications that have limited its effectiveness as a tool for UXO detection in the past. Magnetometry requires careful control of both diurnal and environmental signal removal (Wald and Cooper, 1989) that can obscure small anomalies generated by UXO. Further, the ability of a magnetometer to detect an object drops as a cube of the distance between the sensor and target object (Breiner, 1999). To maximize sensor effectiveness, the sensor must remain consistently near the seafloor, an effort that is difficult to achieve with traditional towed or pole-mounted arrays. A recent ESTCP study (Steigerwalt et al., 2014) turned to mounting a cesium-vapor magnetometer (Geometrics G880) on an autonomous underwater vehicle (AUV), which then conducted precise, near-seafloor surveys maintaining altitude following within 10 cm of a set-point of 1.5 m above the seabed otherwise unachievable by towed or pole-mounted array. This study utilizes this same AUV mounted magnetometer to survey instrumented surrogate munitions in a muddy estuarine environment in conjunction with acoustic tracking methods.

3.2. Approach

3.2.1. Task 1 – Tracking and Motion Sensor Technology Design

Task 1 includes the preparation and deployment of surrogate munitions in an acoustic Long-Baseline (LBL) network for tracking munition behavior and mobility. The nature of this study requires the design and manufacturing of “smart” munitions with integrated motion tracking sensors (IMU’s) for high temporal and spatial resolution. For gross movements, an acoustic LBL network must be capable of detecting multiple surrogates over a larger spatial and temporal scales.

3.2.1.1. Surrogate UXO Development

The question of how to appropriately design and equip smart munitions to allow for high precision motion tracking, while retaining similar characteristics to actual munitions was the topic of recent discussion at a SERDP Munitions Mobility and Modeling Workshop (Dec. 8-9, 2015). Drawings illustrating basic munitions geometry are available from military manuals, but specific characteristics inherently relevant to munitions mobility (e.g. density, center of gravity, etc.) have not been made readily available until recently (Calantoni MR-2320 has catalogued numerous practice and inert munitions and generated estimated density distributions for common UXO types). Past SERDP studies have instead experimented with varying surrogate UXO density (Traykovski MR-2319; Calantoni MR-2320) to determine thresholds for mobility vs. scour/burial in non-cohesive sediments. Traykovski (MR-2319) found that only UXO surrogates with low object to water density ratios were mobile ($\rho_{uxo}/\rho_w < \sim 2$), while denser UXO ($\rho_{uxo}/\rho_w > \sim 2.75$) were more likely to bury *in situ,* unless under extreme forcing events. Although parameterizing the relationship as UXO density to sediment grain density ($S_m = \rho_m/\rho_g$), Calantoni (MR- 2320) had similar results, finding that surrogates with S_m>1 would always bury after intense transport regimes in regions of stable bathymetry. Subsequently, in the latest SERDP Munitions Mobility and Modeling Workshop (June 20-21, 2017), the consensus was to focus on densities within Calantoni's estimated distributions of actual munitions (>2800 kg/m^3), given that the majority of anticipated UXO would fall within that parameter space.

Surrogate payload sensors were also discussed for tracking motion and mobility. Inertial Motion Units (IMU) are a primary sensor for recording object motion, and are available in small form factors. Current SERDP funded studies (Traykovski MR-2319, Calantoni MR-2320, Puleo MR-2503) utilize the X-io IMU, which is capable of recording both orientation and movement up to 512 Hz. The small form factor of this unit (57x38x21mm) and relatively low cost make this unit ideal for surrogates that may potentially be lost or destroyed. It was also suggested that surrogates may be fitted with acoustic "pinger" tags in order to minimize loss. These tags emit sound at specific frequencies, allowing surface mounted or diver-held units to navigate to the tags location through signal strength detection and directional receivers. A more robust version of this concept utilizes Ultra-Short Baseline (USBL), which derives position estimates of surrogates. Traykovski (MR-2319) developed USBL transponders for periodic tracking of surrogates. This method requires a larger acoustic transponder fitted to the surrogates, and requires direct line of site for accurate position estimates (i.e. not buried). The latter issue was solved by attaching the USBL transponders to floats and connecting them to the surrogates via short cable. However, there is question over the influence of this design on surrogate munition behavior. Further, this method requires repetitive surveys to the field site via surface vessel or autonomous craft to log surrogate positions, which are often limited by surface conditions. Thus, major mobility or burial events, driven by strong hydrodynamic forcing, are often missed and gross movements are only recorded after the fact. Other sensors that can be fitted include SLAM sticks, which record acceleration at very high sampling rates, and are thus ideal for capturing mobility in high energy environments (e.g. surf zone studies; see Puleo MR-2503). On board optical sensors can also be included, determining orientation and burial based on ambient light detection. Visual markers, such as bright paint or flashing LED's for camera detection have also been proposed, but require clear visual conditions and nearby cameras.

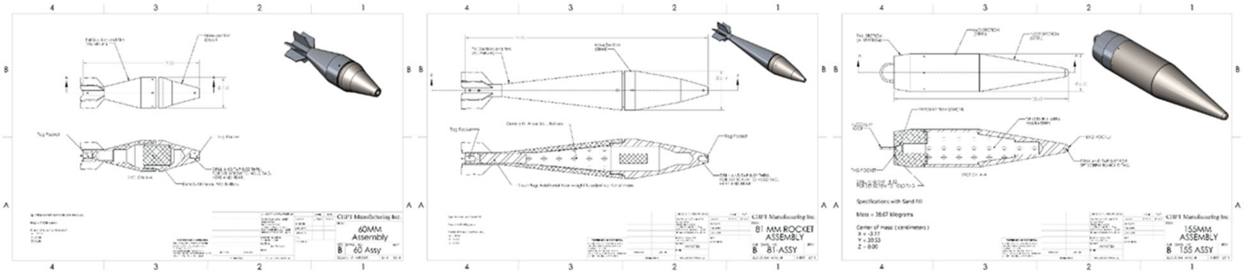

Figure 1: Surrogate UXO design plans for 60mm mortar, 81mm mortar, and 155mm artillery shell.

The discussions from the SERDP Munitions Mobility and Modeling Workshops led to the selection of three munition types for this study, each of which were identified as munitions of interest (MOI) by the USACE. These were 60 mm and 81 mm mortars, and 155 mm artillery shells (figure 1). The surrogates were designed to meet best known characteristics of the respective UXO type, including a minimum density within the estimated density distribution of measured UXO (from Calantoni MR-2320). The surrogates were designed with open internal cavities, allowing for customization and variation of density within the UXO density parameter space through variable fills. The open cavities would also accommodate x-io IMU's and additional batteries to extend deployment duration. The 155mm were also designed to house a water-level pressure sensor and data logger, both used also by Puleo (MR-2503). Externally, each surrogate was designed with cavities at either end to fit VEMCO acoustic locater tags, which would serve as the primary surrogate tracking method during field deployments (see 3.2.1.2). Optical sensors and visual markers were not to be fitted to the surrogate munitions; the depth and turbidity characteristic of the proposed field site would render these methods ineffective.

3.2.1.2. Vemco Positioning System Grid Design and Testing

Long-Baseline systems have been used for the past several decades to locate and track submerged vehicles, particularly in deep water conditions typical to the oil and deep mineral industries. A proven technology, these systems are composed of a grid of acoustic transponders that use active acoustics to track underwater movement of a target receiver. Each LBL transponder is surveyed to a precisely known position, and use the difference in signal arrive time from an acoustic pulse generated by the tracked object to calculate position. Positional accuracy of the LBL transponders are paramount, as well as the physical conditions of the site that may affect sound speed within the grid (e.g. thermoclines, salinoclines, etc.). Positional error can be constrained by using precise time synchronization techniques and high-resolution GPS. Typically, LBL technologies are large, expensive systems that require considerable time and effort to set up and run effectively. Deployment duration is often limited to a few days or weeks, and require constant monitoring via wireless or satellite communications. More modest systems have been developed for smaller AUV or ROV tracking, but these systems still require larger transponders, have limited endurance (hours to days), and are designed to be constantly monitored. As such, traditional LBL systems are not ideal for a long-term munitions tracking study.

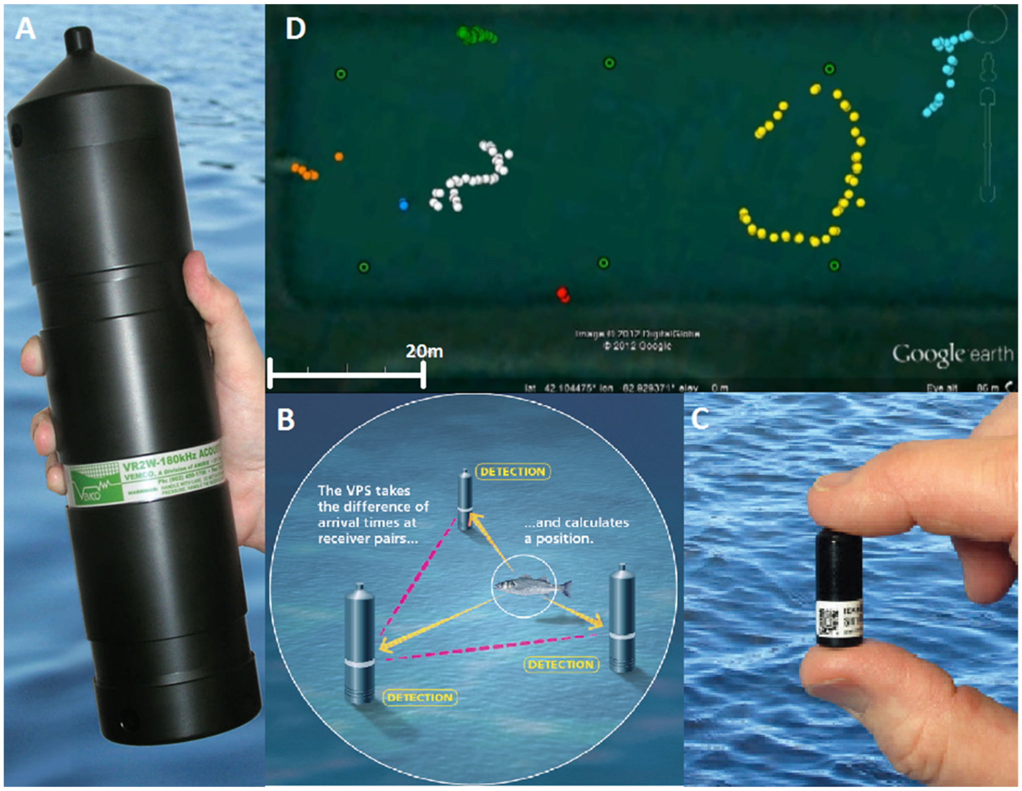

Figure 2: Vemco Position System. HR2 Acoustic Receivers (A) are placed in a network (B) that records the difference in arrival times of small acoustic tags (C). Multiple tags can be tracked over time (D) with position accuracies down to 10cm (Courtesy of Vemco).

While traditional LBL systems were excluded from use in this study, modified acoustic positioning systems, such as those developed for fisheries studies, were identified as potential candidates. Although fisheries studies typically cover large areas (> 1 sq. km), recent systems have been modified for precision tracking over smaller study sites. The Vemco Positioning System (VPS) was originally developed for tracking acoustically tagged biology with meter level positional resolution. The system is capable of simultaneous positioning of multiple tags within an acoustic receiver network (figure 2). The VPS is based off of previously developed and proven Vemco VR2W (69 kHz) acoustic receivers, which greatly reduces overall expense. These systems can be deployed for 6 months and used in freshwater, estuarine, coastal or even open continental shelf environments. Several recent biological tracking studies (Piraino and Szedlmayer, 2014; Roegner and Fields, 2014; Yoshida et al., 2014) have used this system with high degrees of success; one study by Piraino and Szedlmayer (2014) was able to capture fine-scale movements of red snapper with ~1-m accuracy using the previous VR2Tx configuration. The updated VPS HR2 (180 kHz) receivers are now capable of positional accuracies down to 10 cm. Since the acoustic tags are designed to be surgically placed within biota, the tags come in small form factors ideal for placement on the surrogate munitions. Each tag measures as 9 mm x 25.5 mm in size and have extended battery life (~220 days), and can be turned on and off to extend shelf life. The combination of battery life, form factor, customization, and relative low-cost to typical LBL systems led to the selection of the VPS for use in this study.

VPS data processing is handled by Vemco, who provide precision positioning for each acoustic tag. Vemco has over 6 years of experience processing VPS data and have developed a robust workflow for calculating positioning from the acoustic tags. This includes data products useful to this study, such as horizontal positioning error (HPE), which will allow the team to refine the results and establish positional accuracy error and confidence. Additionally, the Vemco receivers record all of the raw detection data with millisecond time resolution, which is made available in ASCII readable text files. This will allow the science team to verify the Vemco processing is valid, and will further allow any interested party, to complete the ranging analyses separately.

3.2.2. Interim Milestone 1: Task 2 Go / No-Go Decision

Performance Objective	Metric	Data Required	Success Criteria
Development of Instrumented Surrogate UXO	• IMU and acoustic tag integration and data collection	• IMU motion data and VEMCO VPS acoustic positioning	• Collection of IMU motion data verified by acoustic positioning
Surrogate Tracking Positional Accuracy	• Horizontal Positional Error (HPE)	• Surrogate Positions calculated from VEMCO VPS Receivers	• Average HPE < 1m for 50% of field deployment duration
Site Hydrodynamic Characterization	• In-situ characterization of hydrodynamics during field deployments	• Wave and current measurements from ADCP • Near-bed velocities, turbulence, shear stress estimates from PC-ADCP	• Measurements of in-situ hydrodynamics throughout field deployment period
Geophysical and Geotechnical Site Characterization	• Complete acoustic bathymetric and backscatter coverage • Background magnetics • Ground control sediment classification	• Bathymetric and side-scan sonar • Magnetometry • Surface sediment sampling • Push core or Box core	• 100% bathymetry and acoustic backscatter coverage at <1 m gridded resolution • Complete interpolated magnetometry surface at <2 m gridded resolution • 20 surface sediment samples • 5 push cores
Instrument Verification Strip	• Deployment and repetitive survey of IVS	• AUV sonar and magnetics	• Complete IVS characterization before and after every magnetometer survey

Table 1: Data collection and Quantitative Performance Metrics

In preparation for the field effort task (Task 2), a number of quantitative performance metrics were identified to establish data collection objectives and determine final performance of this study. These metrics (table 1) address the development and testing of the surrogate UXO and Vemco VPS as part of Task 1, and field data collection metrics, including site geophysical, geotechnical, and hydrodynamic characterization, as outlined in Task 2 (see section 3.2.3). Further, these metrics will serve to test the performance of the Vemco VPS system surrogate tracking capabilities during the two proposed field tests. A Go / No-Go decision would be rendered after the completion of Task 1.

3.2.3. Task 2 – Field Implementation

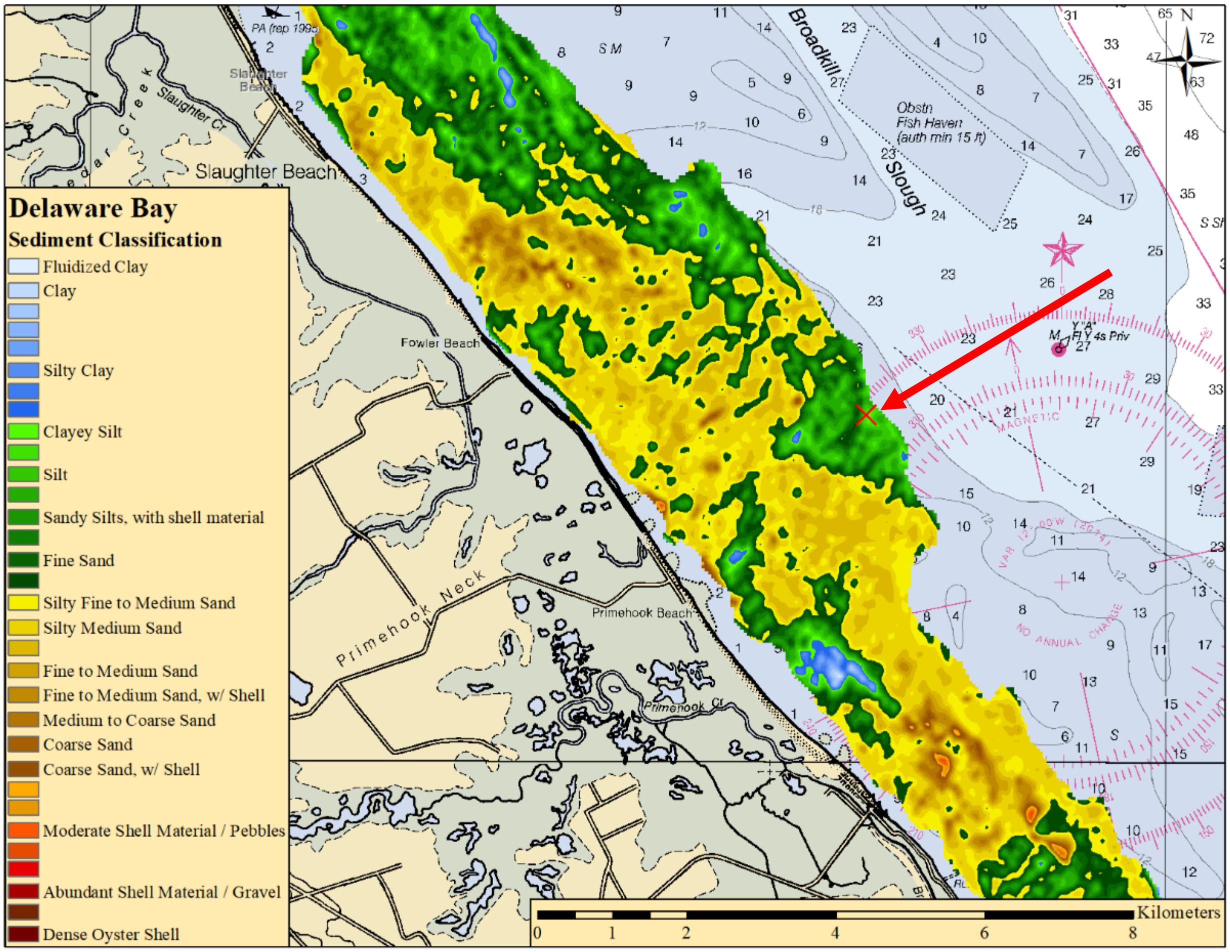

Figure 3: A sediment classification map of the Broadkill, DE area from previously collected Roxan sonar data and sediment sampling (NOAA 2004) with the MR-2730 field site location indicated. The field site is located 10.5 km northwest of the UD Marine Operations facilities and Marine Sciences Campus, which allowed for easy access and frequent site monitoring.

A munitions tracking study area was proposed in the lower Delaware Bay, a large estuary characterized by muddy or mixed sand and mud sediments (Wilson et al., 2010) in a region often buffeted by high-energy events (Wright 1993; Trembanis et al., 2012). After preliminary research, a site location was selected in the area of the Broadkill Slough, where cohesive sediments have previously been sampled (figure 3). The wider Broadkill Beach and nearshore area has previously been monitored for changes in beach profile and benthic habitat (Raineault et al., 2011) by the University of Delaware and a current NOAA Seagrant study by Trembanis is monitoring and modeling beach response to storm activity (NOAA SG 2016-18 RRCE-8 TREMBANIS). This data is being leveraged for wider hydrodynamic and morphological context within this study.

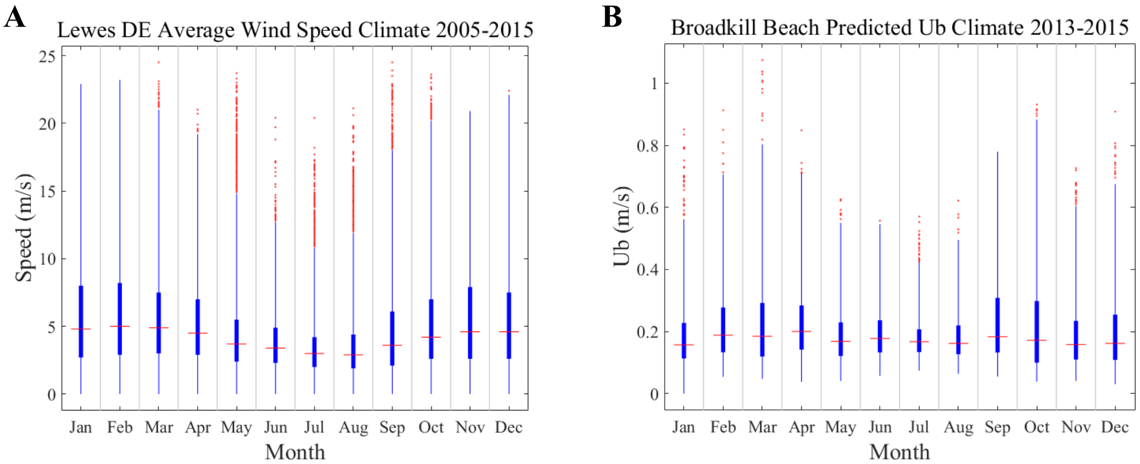

Figure 4: a) Local historic wind and b) predicted near-bed wave orbital velocity climate for Broadkill Beach field site.

Local climate data was collected from nearby NOAA monitoring stations and used to narrow down ideal deployment windows for capturing large energy events necessary for munitions movement (figure 4). Historic average wind speed records (figure 4a) show increasing winds from late Aug – Nov., or what is typically hurricane season for the mid-Atlantic Region. Two recent hurricanes, Irene (2011) and Sandy (2012) occurred within this period and both storms had significant impacts on the coastal zone of Delaware Bay. Average winds remain high during the late winter and early spring months, which is characterized by periodic winter storm or nor'easter events. In March 2013, a large nor'easter generated waves larger than Hurricane Sandy (see DuVal et al., 2016), and recently, Winter Storm Jonas generated the highest near-shore waves on record at the local NOAA observational buoy 44009 (see NOAA National Data Buoy Center). Using local wave records for Delaware, monthly near-bed wave orbital velocity distributions were estimated for the region of Broadkill Beach from 2013 – 2015. Similar to the wind climate, higher average near-bed orbital velocities are estimated in late summer – early fall and late winter – early spring. Thus, when considering both winds and estimated near-bed orbital velocity, the months to expect highest forcing in the lower Delaware Bay range from Sept.-Nov., and Feb.-Apr. (figure 4b). These "weather windows" were targeted for two deployments to take place in the fall of 2017 and winter/spring of 2018.

3.2.3.1. VPS Grid and Surrogate UXO Deployment Plan

The VPS tracking network was designed with consultation from Vemco. The grid consisted of 6 HR2 receivers set in pentagonal grid with one receiver on each corner and one in the center thereby ensuring overlap of the study site by multiple receivers (figure 5). The estimated effective range for the receivers in this environment was 50m, and thus the grid was designed to be no larger than 50m radius around the center receiver. The HR2 acoustic receivers were fitted to rigid mounts that could be firmly augured into the sediment. This allowed for accurate positioning by restricting the potential for receiver moment over the course of the deployment. Once deployed, positions were surveyed in on the surface using sonar equipped with Real-Time Kinematic (RTK) GPS, capable of centimeter horizontal accuracies. Each HR2 receiver is equipped with an internal synchronization tag to correct for clock drift between the receivers. Additional reference "synctags" were placed within the grid at GPS marked positions to measure overall system performance during the deployment. Once deployed, surveyed and verified to be working, surrogate were placed within grid. Each surrogate was equipped with two acoustic tags, each emitting two different coding schemes, which allows Vemco data analysts to sort out and exclude most multi-path problems should they arise. The acoustic tags emit at temporal frequencies that allow for multiple positions per minute.

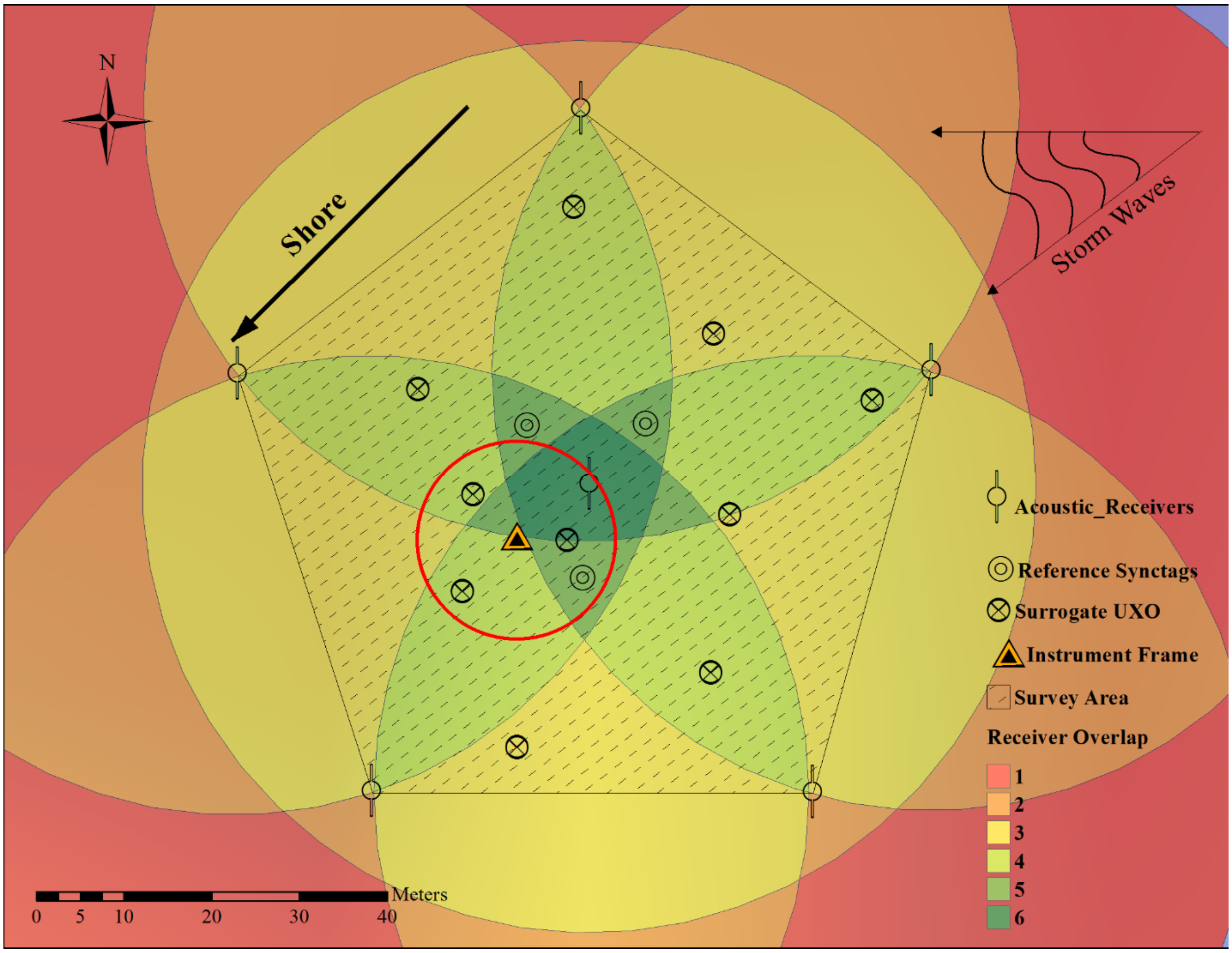

Figure 5: VPS receiver arrangement designed with assistance from Vemco to maximize acoustic detection overlap and positional accuracy. Minimum anticipated receiver overlap is overlaid with example reference tag, surrogate UXO, and instrument frame placement.

3.2.3.2. Instrument Frame Configuration

Hydrodynamic forcing was directly monitored using an instrumented bottom frame. The frame, built specifically for this study, has a 2 m x 2 m footprint and is customizable depending on instrumentation (figure 6). For water column currents and wave characterization, the frame was fitted with an upward facing 600 kHz Teledyne RDI Acoustic Doppler Current Profiler (ADCP) set 1 meter above the bed. The ADCP was set to collect wave and current data every 0.5 hours in 25 cm bins. A downward facing 2 MHz Nortek Pulse-Coherent ADCP (PC-ADCP) is fitted for high-resolution, near-bed current measurements and turbulence estimates. The PC-ADCP was configured to collect data every 0.5 hours with 3 cm bin resolution. Conductivity, temperature, depth, and turbidity are measured with an AML Plus-X, configured to sample every

0.5 hours. For time-lapse acoustic imagery, the frame is equipped with a 2.25 MHz Imagenex 881 fan-beam rotary sonar. The rotary sonar is capable of effectively scanning a 360° sector around the sonar at up to 12m ranges with sub-cm resolution. The remote sonar head is connected to a self-contained data logger and battery unit that allows for 4-6 week deployment depending on data collection frequency, with a quick turn-around time for battery replacement and data retrieval. While capable of making multiple scans per hour, to maximize endurance, the rotary sonar made a 6 m sector scan every 0.5 hours. Similar frame configurations have been used with success in previous mine-burial studies (e.g. Hutton et al. 2007; Traykovski et al., 2007) and current SERDP funded studies (e.g. Calantoni SERDP MR-2320, Traykovski MR-2319). The importance of *in situ* hydrodynamic characterization in combination with time-lapse acoustic imagery, cannot be overstated, especially in studies modeling object scour/burial/mobility (e.g. Traykovski et al., 2007).

Figure 6: Instrument frame developed for MR-2730. Shown here with Teledyne RDI Sentinel ADCP, Nortek Aquadopp HR PC-ADCP, AML Plus-X CTD, and Imagenex 881 Tilt-Head rotary sonar.

3.2.3.3. Site Survey and Monitoring

Periodic munitions mapping was conducted using the UD Gavia AUV (figure 7). The Gavia AUV is a modular designed vehicle customizable to individual projects. Available sensor modules include a Marine Sonics dual-frequency 900/1800 kHz high-resolution side-scan sonar, a GeoAcoustics GeoSwath 500 kHz phase-measuring bathymetric sonar, 2 MP Point Grey Color Grasshopper Camera, and environmental sensors (e.g. salinity, temperature, dissolved oxygen, and turbidity). The Gavia AUV is navigated by a Kearfott T-24 "SEANAV" inertial navigation system (INS) coupled with an RD Instruments 1200 kilohertz (kHz) Workhorse Navigator Doppler velocity log (DVL). The DVL measures velocity of the vehicle over the seafloor and provides these measurements to the INS to constrain navigational drift error. While on the surface, a Wide Area Augmentation System (WAAS)-capable L1/L2 receiver Global Positioning System (GPS) in the AUV's sail provides position fixes to the INS before missions. When submerged, the published drift rate for the INS with an integrated DVL during submerged operation is 0.1% of distance traveled. Additional methods in survey design can further constrain AUV positional error. The Gavia has a depth rating of up to 500 meters, and can run for over 3.5 hours and cover up to 20 linear kilometers per mission.

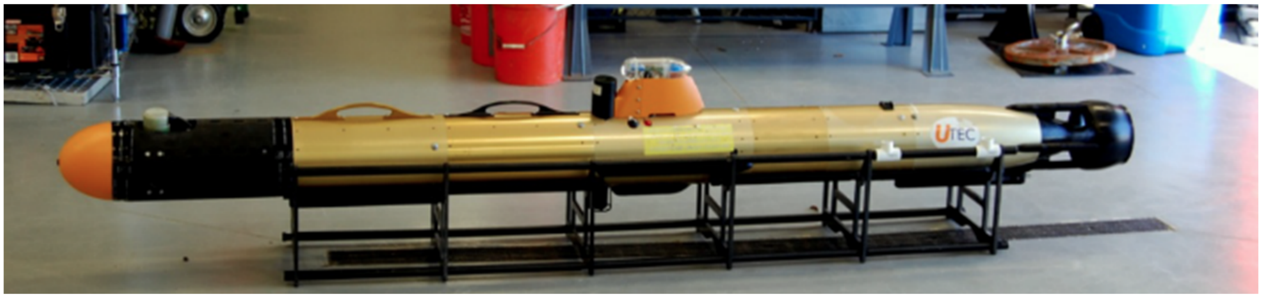

Figure 7: The University of Delaware Teledyne Gavia modular autonomous underwater vehicle with Geometrics G-880 magnetometer.

For this study, a marine magnetometer developed for the UD AUV in an Environmental Security Technology Certification Program (ESTCP) funded program (MR-201002) was utilized as an additional surrogate tracking method. The AUV magnetometer module houses a Geometrics G-880AUV self-oscillating split-beam cesium vapor (non-radioactive Cs133) total field magnetometer with automatic hemisphere switching coupled with an Applied Physics 539 fluxgate compass (see MR-201002 Report). In a blind field test (figure 8), the system demonstrated reliable detection of munitions as small as 60 mm mortars and larger munitions at 1.5-m altitudes and 75 mm projectiles and larger at over 2-m altitudes. More recently, the AUV magnetometer was used in a Bureau of Ocean Energy Management study to develop methods for UXO detection in offshore wind energy areas. Preliminary results indicate that the magnetometer was capable of detecting UXO surrogates of 155mm shells at altitudes between 2 to 6-m.

Repetitive magnetometer surveys were conducted at the test grid site and will be compared to VPS tracking results. Additionally, should the surrogates become buried to depths at which acoustic tracking is no longer feasible, the magnetometer should still be capable of determining the surrogates locations. Following surrogate retrieval, magnetometer survey data will be compared to VPS tracking data to determine the effectiveness of the magnetometer for UXO detection in muddy environments. Conversely, potentially buried surrogates obscured from VPS detection may be located and retrieved by successful magnetometer analysis.

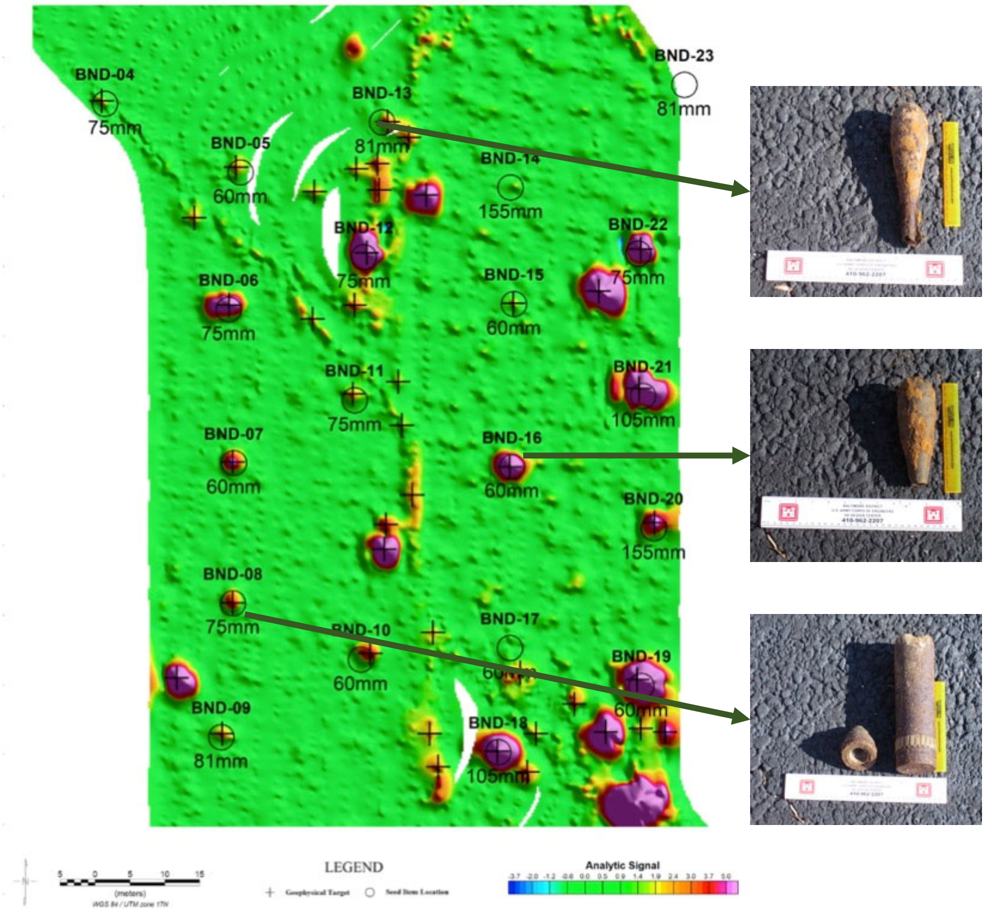

Figure 8: Magnetometer results from blind ordnance detection survey. The peaks are strong magnetic signals, compared to the ordnance test subjects (ESTCP Project MR-201002).

3.2.4. Task 3 – Data Analysis, Project Review, and Reporting

Task 3 regards data synthesis and product development. This task includes the preparation of monthly financial reporting, Quarterly Progress Reports, Final Technical Report, Cost & Performance Report, in progress reviews, project publications, and a final briefing in accordance with SERDP requirements. Task 3 will focus also on in-depth processing and the production of final data products for distribution to the wider SERDP UXO research community.

3.2.5. Interim Milestone 2: Task 4 Go / No-Go Decision

A central facet of Task 2 regards the characterization of surrogate UXO during energetic conditions. Due to the episodic nature of storm events in the Mid-Atlantic, there was no guarantee that such an event would occur during the timing of Task 2. As such, a second interim milestone was added. Were no event captured during Task 2, an optional Task 4 may be initiated, which will enact an additional two field efforts over the winter of 2018 – 2019. This optional task may also be initiated for any additional purpose, including the application or adaptation of the methods outlined in Task 2 to this proposed site or any additional field sites.

4. Results and Discussion

4.1. Results

4.1.1. Task 1 – Tracking and Motion Sensor Technology Design

Task 1 was initiated in May, 2017. The Vemco VPS system, previously tested in Sept. 2017 (see section 4.1.1.2), and tags were received in July 2017. Manufacturing of the surrogate munitions began in June and the surrogates were delivered in August 2017. Configuration of the surrogates, including fitting for IMU's, batteries, and pressure sensors (155mm only), occurred over Sept.-Oct. 2017. Concurrently, the instrument frame, delivered in July, 2017, was customized for the study's needs. This included the introduction of a new AML Plus-X CTD sensor to help constrain errors in acoustic position with *in situ* sound speed measurements. Task 1 was completed with the successful configuration and bench top testing of the instrumented surrogates and VPS system.

4.1.1.1. Surrogate Fabrication and Instrumentation

The surrogate UXO were fabricated by CHPT Manufacturing, Inc., a local company that also fabricating surrogates for Puleo (MR-2503). The surrogates were constructed from steel and aluminum, the former to allow for detection by magnetometer and the latter to lighten surrogate weight and allow for varying densities within the estimated density parameter space. Each surrogate was undercoated with anti-corrosion primers and painted with anti-biofouling paint. White paint was chosen to maximize contrast from sediments and allow for easier visual identification / discrimination by divers or remotely operated vehicles (ROV). Each surrogate was also clearly labeled "INERT" in case of unintended interaction with commercial fisherman or the wider public (figure 9). For Task 1, three 60mm, four 81mm, and three 155mm surrogates were manufactured and prepared for the study.

Figure 9: Ten surrogate munitions prepared for deployment on Nov. 2, 2017

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Each surrogate was fitted with an IMU sensor. Previously SERDP studies (Calantoni SERDP MR-2320, Traykovski MR-2319, Puleo MR-2503) utilized the x-io IMU, a small, self-contained IMU with micro-SD card logging and Li-Ion battery. The model used by those studies had been replaced by the NGIMU (Next Generation IMU), which was selected for use in this study. Despite upgrades from the previous generation, including lower latency, the battery life of the 1000mAh battery was too limited (~17 hours bench test) for the duration of the study. To work around this with the previous model, Calantoni (MR-2320) constructed complex battery packs, fitted with multiple cell-phone style Li-ion batty packs controlled by a circuit module. After discussion with the designer of the NGIMU, it was determined that a simpler work around might be achieved by using off-the-shelf USB battery packs, which could plug directly into the micro-USB slot on the NGIMU board. These come in a variety of sizes and capacities, which allowed for maximizing battery life and best using the limited space within the smaller surrogates. Bench top tests indicated that this method should be sufficient to extend the battery life for the planned deployment duration (8 weeks). Three battery capacities (3300mAh, 8000mAh, and 23000mAh) were selected and fitted to the surrogates. For the 60mm and 81mm surrogates, the battery packs were stripped of their housing and fitted to mounts that were fixed in the tail cone. For the 155mm, the batteries were fixed to a longitudinal plate near the center of mass of the surrogate. The IMU's were fitted to the same plates and placed as close to the center longitudinal axis and vertical axis as possible (figure 10c). In the 60mm (figure 10a) and 81mm (figure 10b) mortars, the IMUs were fit to plates in the nose cone section, due to spatial constraints.

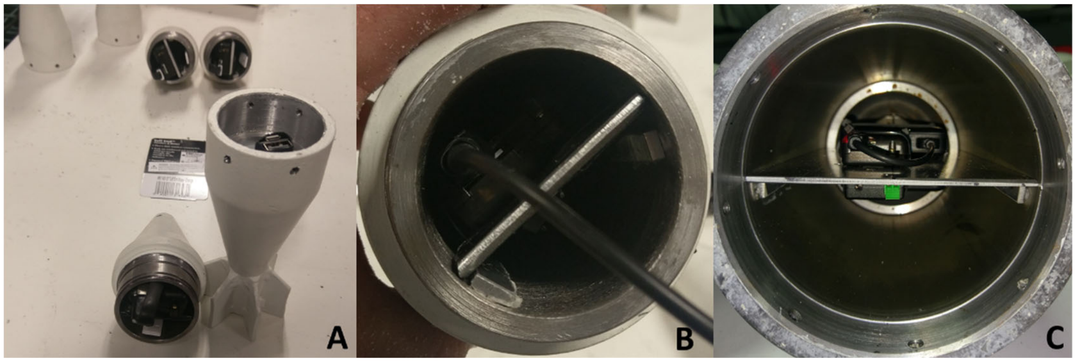


Figure 10: IMU and battery configurations in 60mm (A), 81mm (B), and 155mm (C) surrogates.

At the suggestion of Puleo (MR-2503), the 155mm surrogates were also fitted with TE Connectivity LM Series pressure sensors, which are capable of ±1% accuracy and wide operating temperature range. The LM series require a nominal voltage of 5V, which are the same output as USB battery packs. An additional 23000mAh USB battery was configured to power the pressure sensor and fitted to the to 155mm longitudinal plate. A 1/2-14 NPT threaded slot was fabricated in the tail-cone of the 155mm to fit the pressure sensors, with 4 small outlet holes drilled in the cone to allow seawater exchange. The pressure sensor output, in ratiometric voltage, was logged by a Madgetech Volt101A data logger with battery, capable of recording over 2 million readings with a 10yr battery life. The pressure sensor and data logger were bench tested successfully. All configuration and testing for the surrogates was completed in Oct. 2017.

4.1.1.2. Vemco Position System Testing and Configuration

In collaboration with Vemco, preliminary lab and field experiments of the VPS receivers were conducted prior to field deployment to test for the effects of burial, steel housing, acoustic noise, and multi-path propagation on positional accuracy and acoustic tag performance. In Sept. 2016, a VPS grid was set up and tested in the University of Delaware Marine Operations Base boat basin. The boat basin had ideal characteristics to test the VPS array, consisting of highly fluidized mud overlaying a stiff clay mud in a shallow (1.5m depth at the array site), brackish, and often acoustically noisy environment. The VPS array consisted of four HR2 receivers set up in a square array measuring roughly 20m on a side. The HR2 receivers were mounted to stakes and fixed approximately 1m above the bed. A single reference tag was fixed to a cinder block and placed in the center of the array. To serve as the surrogate, a section of steel pipe (30.5cm x 10.2cm) was equipped with 2 acoustic tags, mounted on either end of the pipe. The surrogate was initially set on the surface of the bed within the grid. RTK GPS positions were taken at the VPS receivers, reference tag, and surrogate at the start of the test. The grid was left running overnight to test for multipath prorogation across a tidal cycle (ebb-flood-ebb in a semi-diurnal tide). In the morning, the surrogate was pushed into the stiff clay mud to test for acoustic signal loss with burial. After several hours, the surrogate was excavated, and moved throughout the grid to test the VPS's ability to track a mobile object. Periodically, the surrogate was placed on bed and left for 5 minutes, during which an RTK GPS position was taken. The surrogate as moved and placed within, on the boarder, and at distances of approximately 5x, 10x and 20x water depth outside of the grid. Final RTK GPS positions were taken at the HR2 receivers, reference tag, and surrogate before removal. The data was sent to VPS for processing.

The acoustic positioning results from Vemco were compared to the RTK GPS positions (figure 11). A comparative analysis indicated that the positional estimates of the VPS were within 50cm of the RTK positons when moved within the array, and less than 20cm for the initial static position of the surrogate (figure 12). The positional error increased as the distance outside of the array increased. However, the positional error was less than 1m within distances of 10x water depth, and less than 3m at distances up to 20x water depth. Vemco also estimated the distance between the two tags on the surrogate at 33cm, which was within 2.5 cm of the actual distance (30.5 cm). In further discussion with Vemco, the field test indicated that multipath propagation was not a significant factor, and false detection could be filtered out in processing. Acoustic noise from the surrounding environment (dock activity, recreational boats and UD research vessel activities) also did not appear to have a significant effect on the detection rate and signal strength. It was, however, determined that the tags could not be detected when buried only a few cm below the surface of the stiff clay mud. Thus if buried, the magnetometer and the last known positions from the VPS would be needed to reacquire the surrogates. Field testing was completed in Oct. 2016, and the results used to inform the configuration for the field deployments (see section 3.2.3.1).

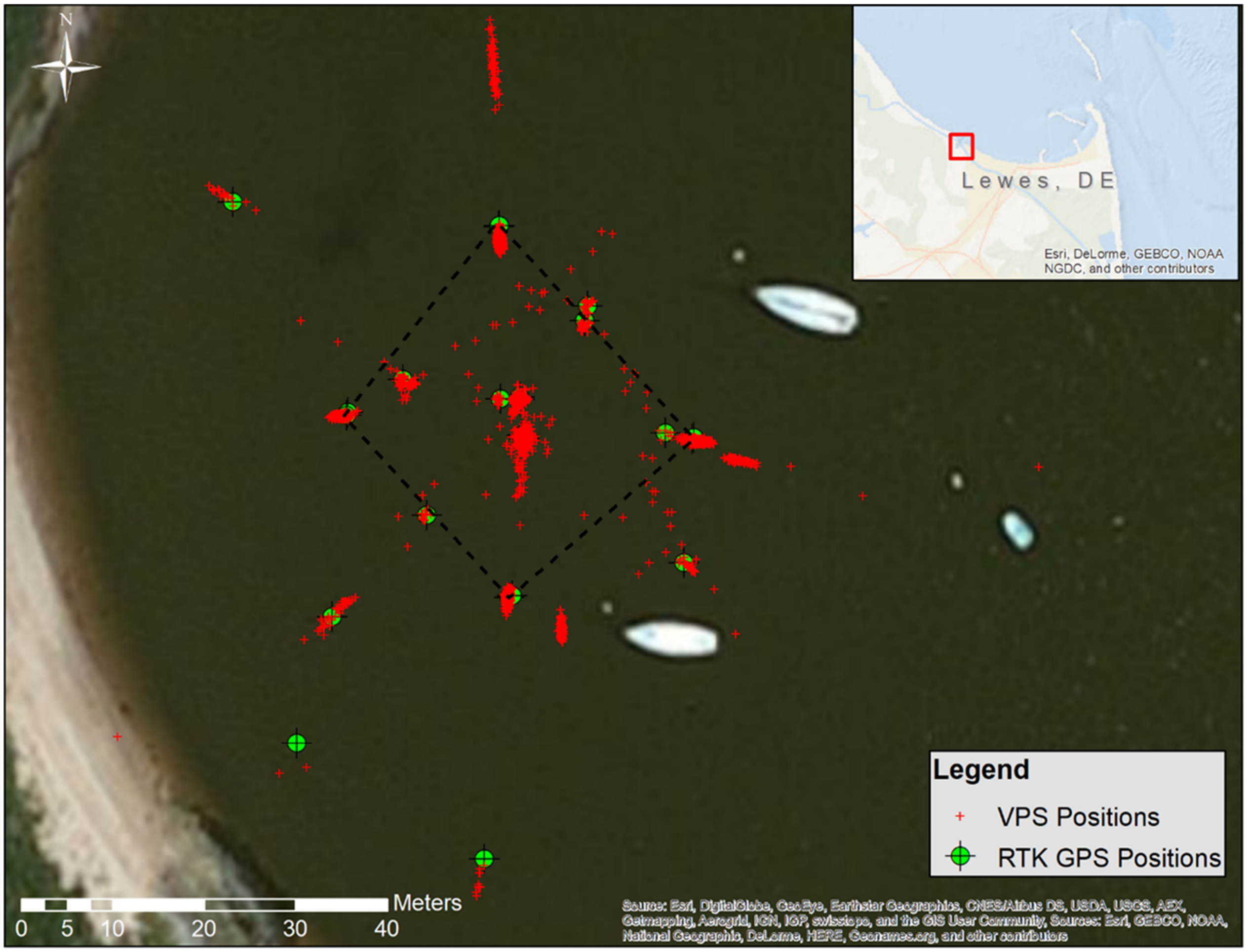


Figure 11: Comparison of Vemco estimated positions versus RTK GPS positions taken during the 2016 UD boat basin field test of the VPS acoustic tracking network.

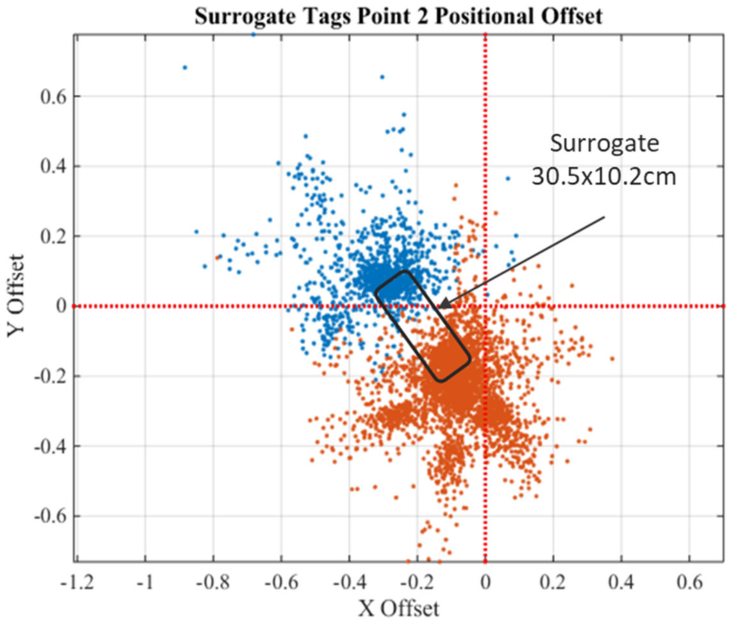


Figure 12: RTK GPS and VPS positional offset (with model overlay) for the surrogate in the 2016 UD field test.

4.1.2. Interim Milestone 1: Go / No-Go Decision

Prior to field implementation (Task 2), an assessment would be rendered based on the ability to complete the quantitative performance metrics established in Task 1 (section 3.2.2.). This milestone was used to assess development and performance of the Vemco VPS system, and sensor-integrated surrogates, and as well as provide SERDP and MR-2730 with quantitative results to support a go / no-go decision to continue with the project. This decision was rendered a Go Decision based on the successful development of the smart surrogate munitions and preliminary tests of the VPS system. Task 1 was completed in October 2017, and Task 2 was initiated immediately following the Go Decision.

4.1.3. Task 2 – Field Implementation

Task 2 was initiated in mid-October 2017 and completed in early May, 2018. During that span, two field deployments were conducted, and the preliminary data analysis from Task 2 is presented here. The field deployments and associated activities are summarized in table 2. Results from the initial Fall 2017 deployment were used to improve performance during the Spring 2018 deployment. Improvements were made in smart surrogate design, reference tag placement, and VPS data processing over that period.

Fall 2017 Deployment					
Deployment Dates	*HR2 Receiver*	*Reference Tags*	*Surrogates*	*Instruments*	
11/2 - 12/4/2017 (32 Days)	6	3	10	ADCP, PC-ADCP, CTD, Rotary Sonar	
Survey Dates	*Side-Scan*	*Bathymetry*	*Sub-bottom*	*Magnetometry*	*Sediment Sampling*
10/18-10/20/2017	X	X	X	X	X
11/02/2017	X	X			X
11/09/2017	X	X		X	
12/02/2017	X			X	X
Spring 2018 Deployment					
Deployment Dates	*HR2 Receiver*	*Reference Tags*	*Surrogates*	*Instruments*	
02/09-04/11/2018 (64 Days)	6	4	10	ADCP, PC-ADCP, CTD, Rotary Sonar	
*Survey Dates**	*Side-Scan*	*Bathymetry*	*Sub-bottom*	*Magnetometry*	*Sediment Sampling*
03/06/2018	X	X		X	X
04/10/2018	X			X	X
04/12/2018	X			X	
*ROV survey 03/18/2018					

Table 2: Summary of activities associated with Task 2 deployments

4.1.3.1. Fall 2017 Field Deployment

Upon completion of Task 1, preliminary field work for the Fall 2017 deployment was initiated. Field data from previous studies were leveraged to narrow down an optimal field site for the VPS grid. On Oct. 18, 2017, a wide-area assessment (WAA) was conducted using an Edgetech 6205 Phase-Measuring Echo-Sounder (PMES), which collects simultaneous dual-frequency 230 kHz and 550 kHz side-scan sonar, with bathymetry on the 550 kHz channels. The system is fitted with a Coda Octopus F190R+ IMU for vessel motion and Novatel RTK GPS receivers, allowing for sub-decimetric horizontal positional error. Survey efforts were focused on the region of the Broadkill Slough, known to contain cohesive sediments. Through strategic sediment sampling, the study area was narrowed to an area to the SW of slough (figure 13). This area sits at 4.5m mean lower-low water depth and contains sediments qualitatively categorized as silty muds. On Oct. 20, 2017, a more targeted sonar survey was conducted (inset figure 13), including an AUV magnetometer survey to sweep for any ferrous debris that could interfere with the study. No debris was detected from the surveys, and the location of the field site was finalized.

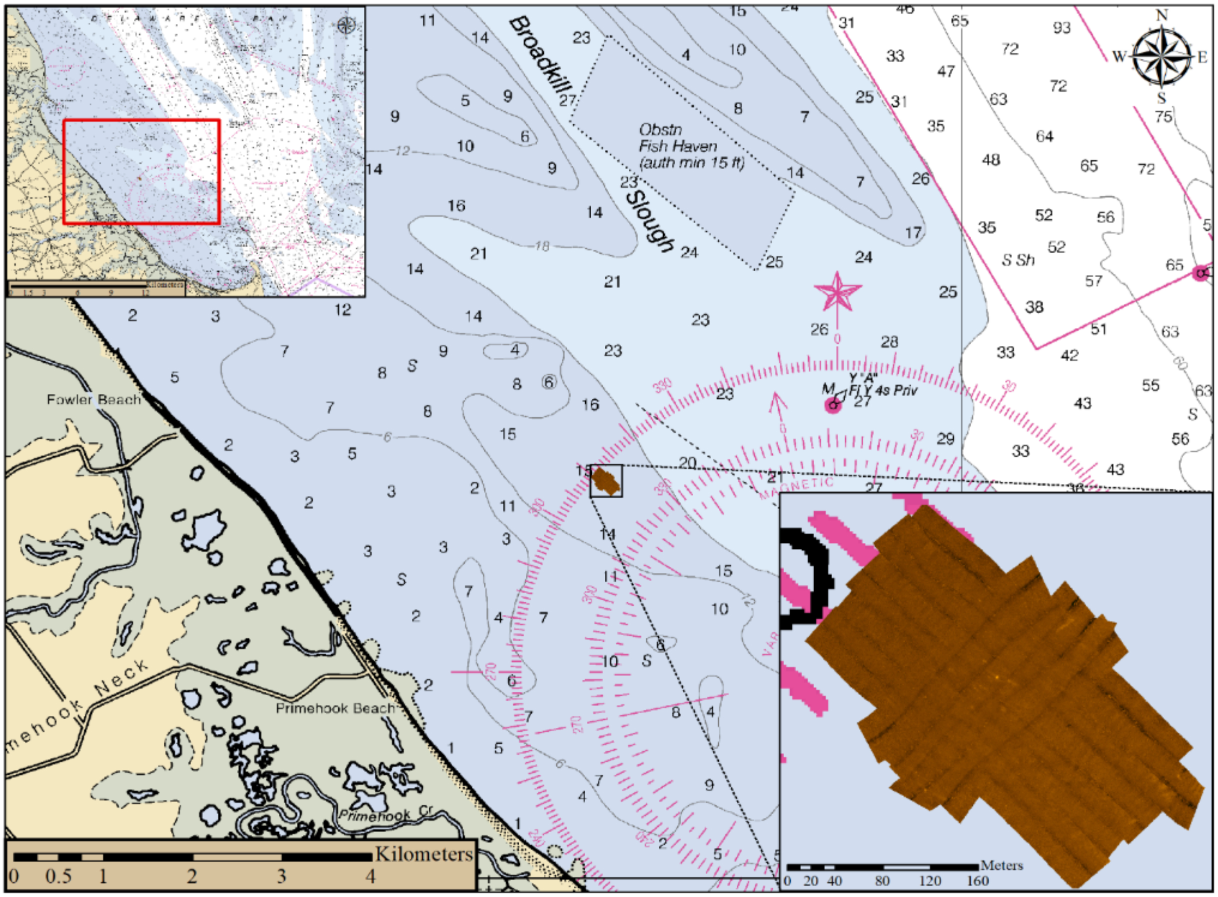


Figure 13: Task 2 study area. The VPS array was located in the center of the inset sonar mosaic.

In preparation for the VPS installation, the instrument platform was deployed at the site on Oct. 27, 2017 to begin hydrodynamic data collection. Scuba diver operations were scheduled to follow shortly after, on Oct. 30-31, 2017, but weather conditions required the deployment be pushed back. For all diving related activities, the University of Delaware team collaborated with the Delaware State Police Scuba Unit (DSPSU). It was determined that the DSPSU would bring expertise and experience with scuba operations low visibility conditions, and would facilitate the deployment requirements of MR-2730, while MR-2730 provides a practical training exercise for the DSPSU. Conditions were optimal on Nov. 2, 2017, and the VPS installation commenced. Buoys were placed by the UD team to mark the positions of the VPS pole installation (figure 14a). The VPS poles were constructed with a 2-part system (figure 14b and 14c). The lower sections were augured 1 meter into the seafloor by the DSPSU divers. Once secured, the upper sections, containing the HR2 receivers, were slipped over the base and locked into place. This allowed for subsequent retrieval of the upper pole and receiver, while leaving the base in place for the second deployment. Once installed, the HR2 receivers sat 2m above the seabed

Following the receiver installation, three reference tags, fitted to 1m tall custom-built posts (figure 14d), were lowered in place. The tags posts were designed to be easily identifiable in the PMES for georeferencing purposes. Next, the surrogates were placed on the seafloor by the DSPSU. One surrogate of each type (60mm, 81mm and 155mm) was set within view of the rotary sonar on the instruments frame. The remaining 7 surrogates were distributed throughout the grid. Lastly, three shallow surface core samples were collected across the study area by the divers. Due to the efficiency of the DSPSU, all operations were successfully completed within 5 hours of arrival on site. Immediately following diver operations, a PMES survey was conducted to obtain precise GPS locations for each of the HR2 receivers, reference tags, and instrument platform (figure 15). An AUV survey was also conducted on Nov. 9, 2017, to collect magnetics and high-resolution sonar of the deployment site.

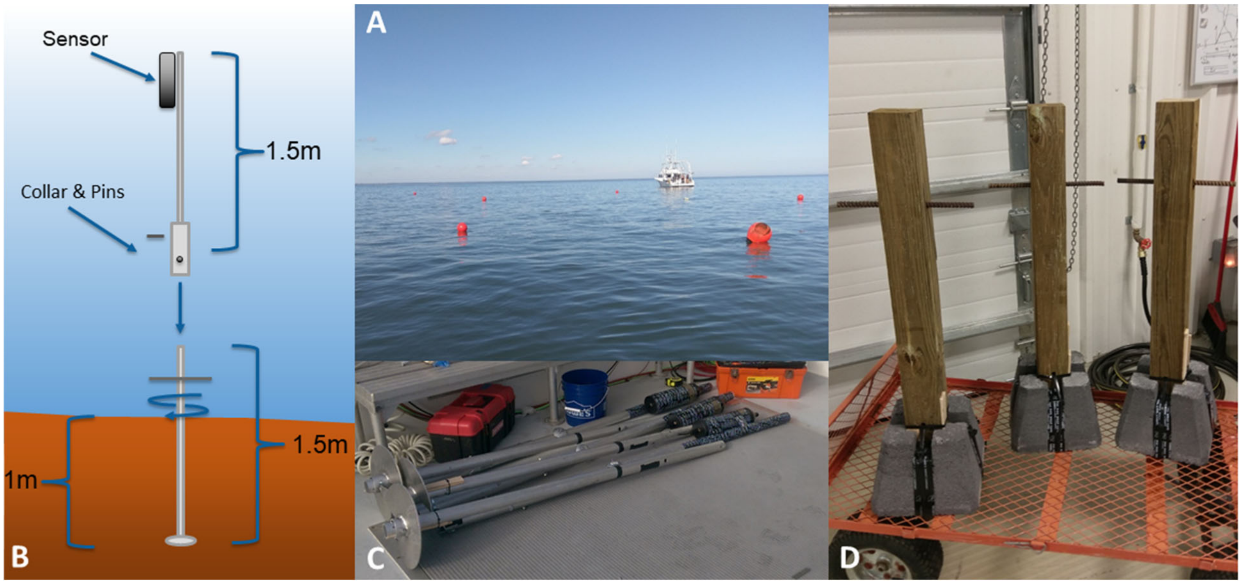


Figure 14: HR2 receiver locations (A), HR2 pole mounts installation design (B), HR2 receivers and pole mounts prior to deployment (C), and reference tag pole mounts (D).

Recovery of the VPS sensors, surrogates munitions, and instrument frame was planned for the week of Dec. 4-8, 2017, contingent upon the first opportunity with good weather conditions. On Dec. 2, 2017, an additional AUV survey was conducted prior to the recovery to assist in locating the surrogates in case mobility had occurred, although no movement was anticipated as no storm conditions were recorded over the deployment window. This was supported by the preliminary survey data analysis, which indicated that little if any mobility had occurred. Recovery operations commenced on Dec. 4, 2017 with the assistance of the DSPSU. For recovery, the DSPSU utilized a hard-hat diver with surface supply and communications (figure 16a). A sector scanning sonar (figure 16b) was lowered at the site and used to guide the diver to targets (figure 16c). All VPS sensors and reference tags were recovered, but low-visibility at the site restricted diver operations and only 7 of 10 surrogates were located and recovered. The decision was made to leave the instrument frame on site to record conditions until the remaining 3 surrogates could be recovered. The VPS tracking data was sent to Vemco for rapid processing to assist in locating the remaining 3 surrogates. Recovery operations resumed on Dec. 7, 2017, with the aid of the Vemco processed data. All 3 surrogates were located and recovered within 30 minutes of diver operations due to the accuracy of Vemco positioning. The instrument frame was subsequently recovered. Fall 2017 deployment operations were completed on Dec. 7, 2017.

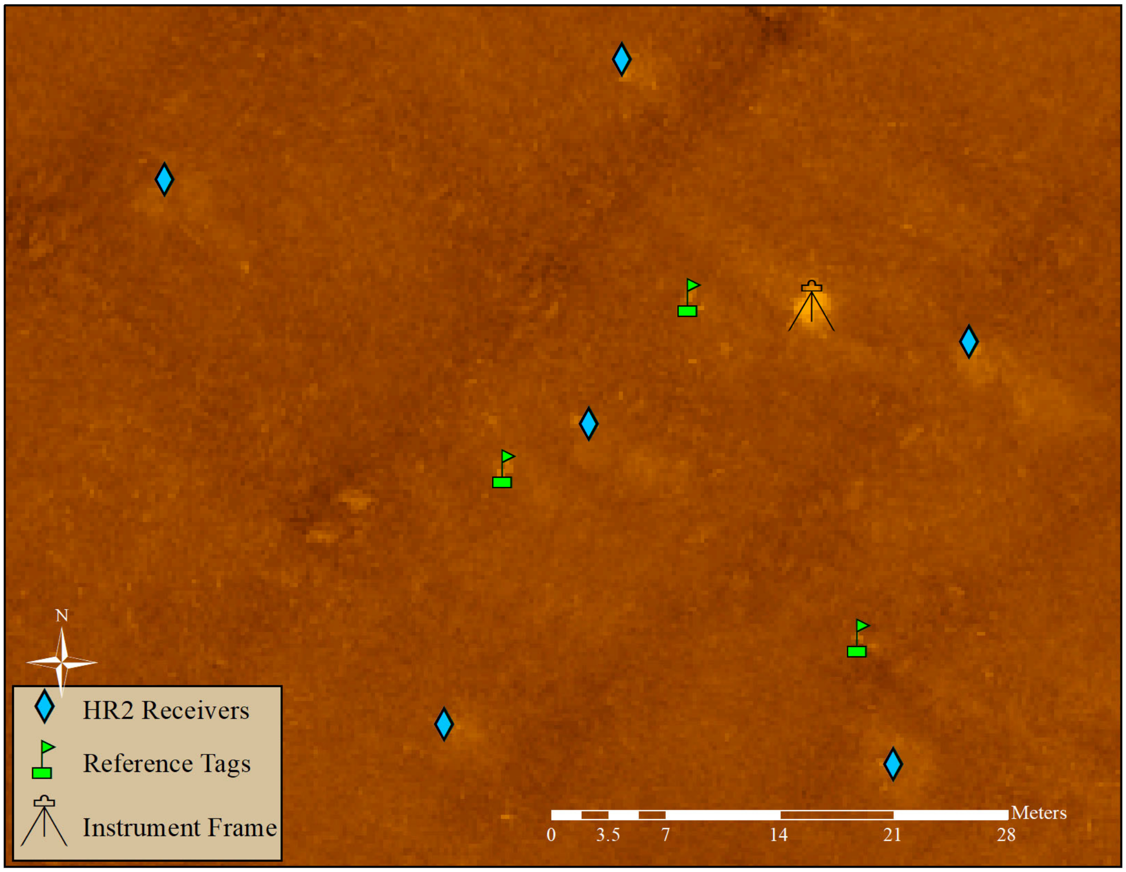


Figure 15: VPS array in Fall 2017 deployment.

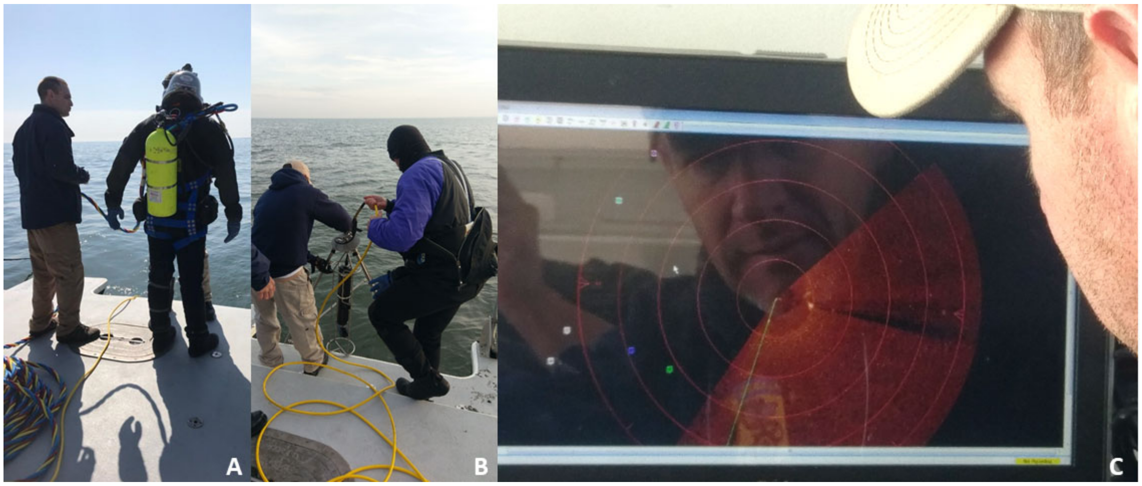


Figure 16: Delaware State Police Scuba Unit operations during the Fall 2017 VPS retrieval. A hard-hat diver with surface supply with communications (A) was monitored and guided to targets by the surface team using a sector-scanning sonar (B). The diver can be seen as the bright return in the center of sonar image (C).

4.1.3.1. Fall 2017 Preliminary Results

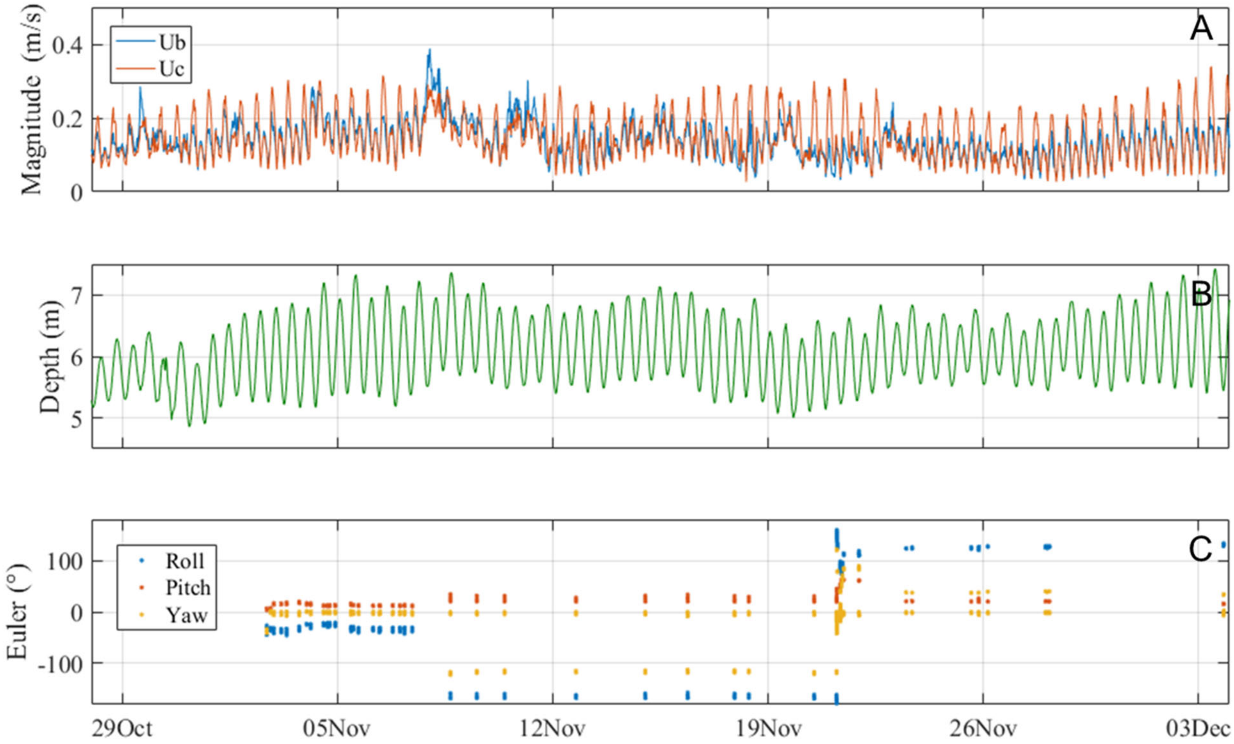


Figure 17: Time-series measurements from the Fall 2017 deployment showing near-bed orbital and unidirectional current (A), pressure depth (b), and example IMU data from a 60mm mortar (C).

Over the course of the Fall 2017 deployment, no storm activity was observed. The hydrodynamic data from the instrument frame indicated only one small wave event on Nov. 8, with the majority of the bottom currents driven by semi-diurnal tides (figure 17a). Despite this, the IMU data from all three 60mm mortar and one 81mm mortar did record motion data. These IMU were set to “motion trigger wake-up,” upon which only minimal motion is required to start the IMU logging. After a period of 5 minutes of no activity, the IMU would go back to “sleep” mode. There were multiple instances in the aforementioned surrogates where the IMU would wake up, but little to no motion was recorded. In the case of one 60mm mortar (figure 17c), the IMU was triggered frequently after deployment, but with little motion. This continued until the unit appeared to roll approximately 120 degrees, after which the IMU was triggered less frequently. This motion was captured 16 hours after the peak of the small wave event on Nov. 8, so it is unclear whether the two are associated. It is possible the small wave event initiated scouring and a small scour pit was formed, which the surrogate later rolled into. Such behavior was noted in similar mine burial studies (e.g. Jenkins et al., 2007). One more series of close temporal measurements occurred on Nov. 21, in which slight deviation in roll, pitch, and yaw are measured. This occurred during slack tides (low current velocity) and with no significant wave conditions. The lack of current forcing suggests that another source, perhaps biologic in nature, resulted in the movement on Nov. 21. Data from the other surrogates do not indicate recorded movement at that time. Direct observations from the rotary sonar were limited, as the unit developed a leak around the cable connector running from the data logger to the sonar head.

Despite the limited observations, images that were recorded infrequently suggest that some limited scour and setting occurred. In figure 18, the smaller surrogates become notably less distinguishable as the deployment progresses, and the 155mm surrogate appears to settle into the sediments. Although difficult to discriminate in the limited rotary sonar images, the DSPSU divers did not observe any of the surrogates to have undergone burial.

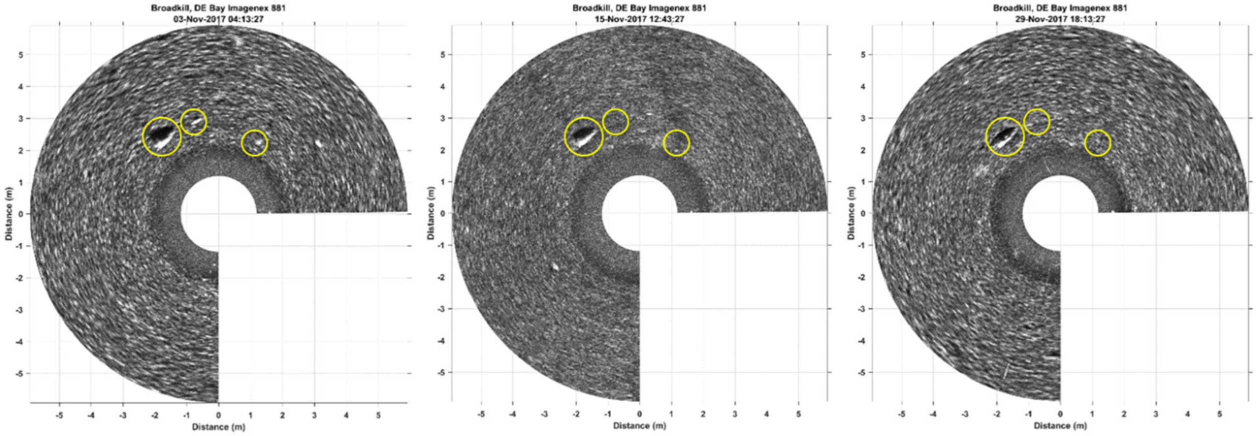


Figure 18: Snapshots from the rotary sonar data collected in the Fall 2017 deployment. Note the smaller surrogates become less distinguishable as time progresses from Nov. 3 (left), to Nov. 15 (center), and to Nov. 29 (right).

Data from the VPS array was processed by Vemco and delivered in late January. Vemco reported that the data quality was excellent overall, and only suggested the addition of one more reference tag for the Spring 2018 deployment. A filtered snapshot of the VPS results are presented in figure 19. The VPS tracking data was filtered using a simple threshold filter to remove points with large Horizontal Positional Error (HPE) and Root Mean Square Error (RMSE). The more robust data points did not show significant lateral shifts, although limited scattering was noted (see figure 20). This was likely due to a sharp change in sound speed velocity resulting from tidal activity, since no corresponding motion was recorded in the IMU data. The filtered data was further analyzed to estimate the offset in tag positions between the nose and tail, which would indicate the overall length of the surrogate (figure 20). Estimated length from the VPS data proved to be within 2-3 centimeters of the measured surrogate length, suggesting precise observations are possible from the acoustic tracking data. Thus, the inclusion of two tags on the surrogates should allow for robust estimates of surrogate orientation as well. Preliminary analysis indicates that no significant change in orientation was recorded for any of the surrogates in the Fall 2017 deployment. As well, the overall VPS time series supports the initial conclusions derived from the geophysical survey data, IMU data, and diver operations: no net lateral migration was distinguishable. In-depth analysis of the Fall 2017 VPS data, and comparisons to hydrodynamic and IMU motion data, is currently ongoing.

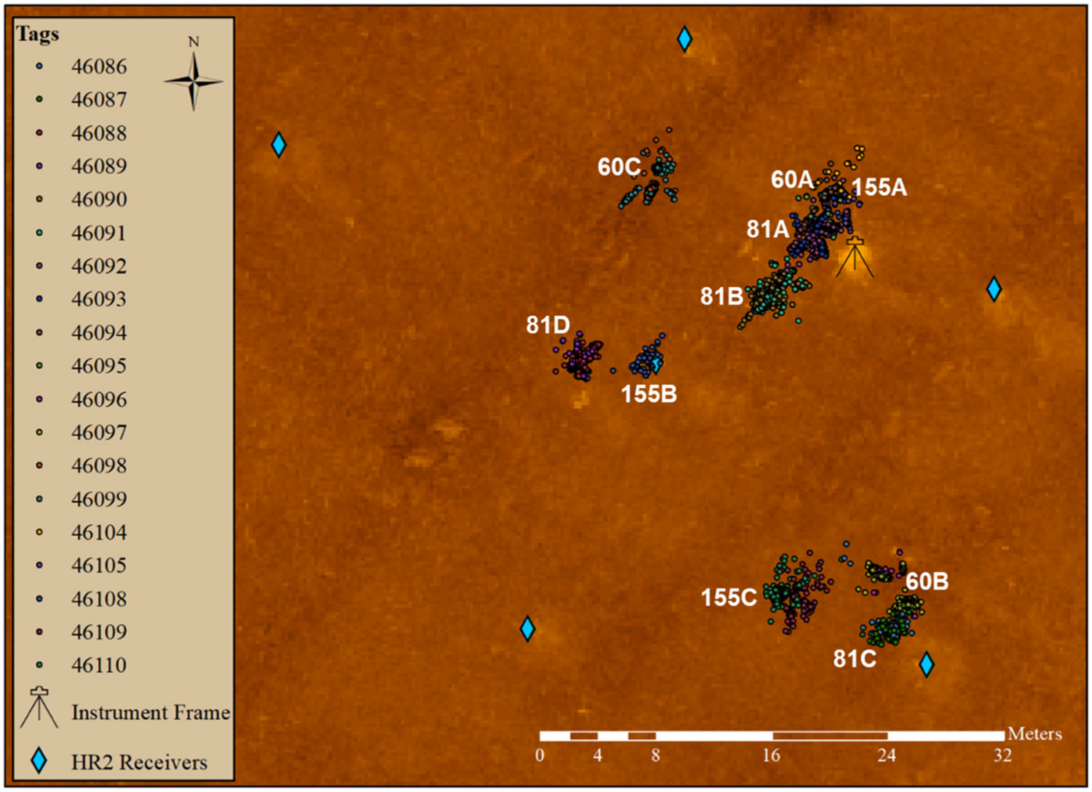
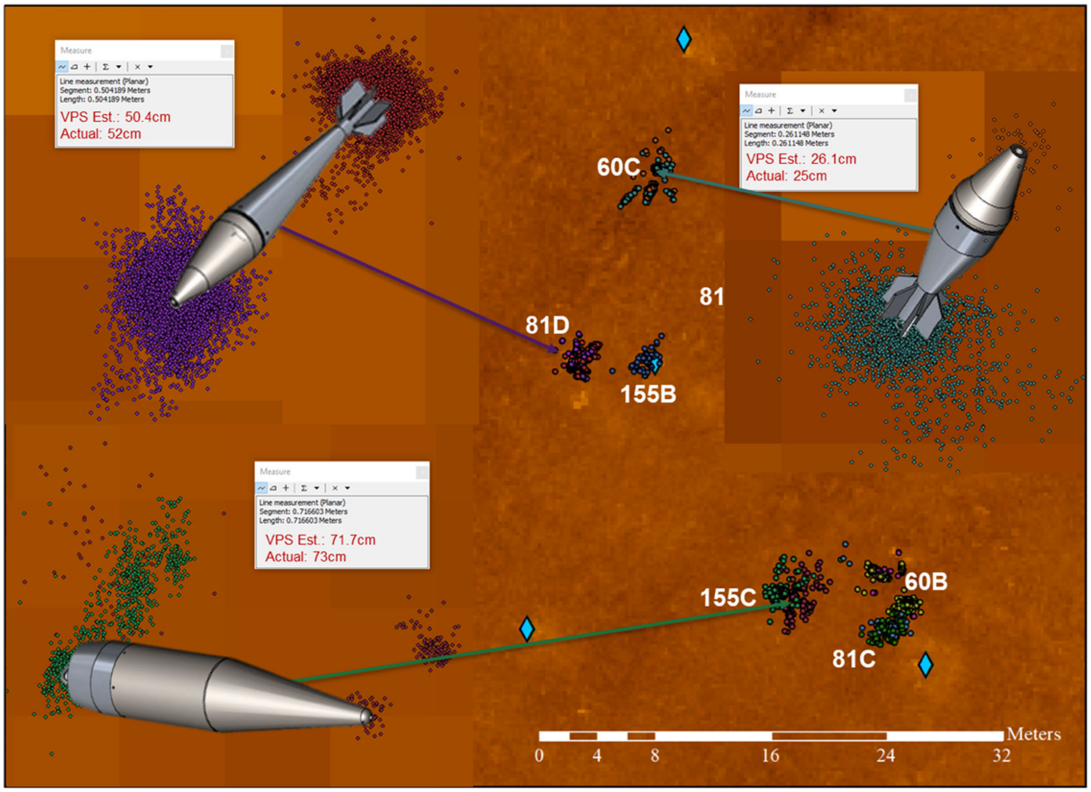


Figure 19: Preliminary VPS acoustic tracking results from the Fall 2017 deployment.



Line measurement (Planar)
Segment: 0.504189 Meters
Length: 0.504189 Meters
VPS Est.: 50.4cm
Actual: 52cm

Line measurement (Planar)
Segment: 0.261148 Meters
Length: 0.261148 Meters
VPS Est.: 26.1cm
Actual: 25cm

Line measurement (Planar)
Segment: 0.716603 Meters
Length: 0.716603 Meters
VPS Est.: 71.7cm
Actual: 73cm

Figure 20: Examples of VPS estimated measurements of surrogate length derived from acoustic tag locations compared to true surrogate length. Note the shift in position of the 155mm is likely due to a sharp change in sound speed.

4.1.3.3. Spring 2018 Field Deployment

The Spring 2018 deployment was set for the week of Feb. 5, 2018, contingent upon weather conditions. A weather window occurred on Feb. 6, 2018, and the deployment was initiated with the assistance of the DSPSU once more. Poor visibility, strong currents and cold water hampered diving operations, and the VPS installation was halted after only 4 of 6 sensors and the oceanographic instrument frame were placed at the site. No reference tags or surrogates were put in place at that time. Operations resumed with better weather on Feb. 9, 2018, during which the 2 remaining sensors, 4 reference tag posts and 10 instrumented surrogates were placed on site. Three of the surrogates were once again placed near the instrument frame to be observed by the rotary sonar, and the remaining 7 were lowered from surface vessel in various locations around the grid. The deployment operations were completed on Feb 9, 2018.

A site survey could not conducted until, March 6, 2018, due to weather conditions and vessel availability. A complete survey was conducted with the surface-vessel PMES bathymetric and side-scan sonar, AUV side-scan sonar and magnetometer. Sediment samples were also collected at the study site and in the surrounding region. The survey data confirmed the locations of the VPS, reference tags, and instrument frame. The 155mm surrogates were also visible in the AUV sonar (figure 21a) and magnetometer data (figure 21a), although acoustic image quality was low due to high backscatter from high turbidity following a nor'easter. On March 18, an ROV was used to attach a surface line to the instrument frame, and the frame was then recovered, as the batteries for the instruments were expected to be nearly depleted. During ROV operations, an 81mm surrogate was observed to be partially buried (figure 21b). Data was downloaded from the instruments, batteries replaced, and the frame placed back at the site on March 19, 2018. The frame was not returned to the same location within the grid, as there were concerns regarding entanglement with the VPS sensors during deployment. The frame was instead placed 20m to the east of the VPS grid.

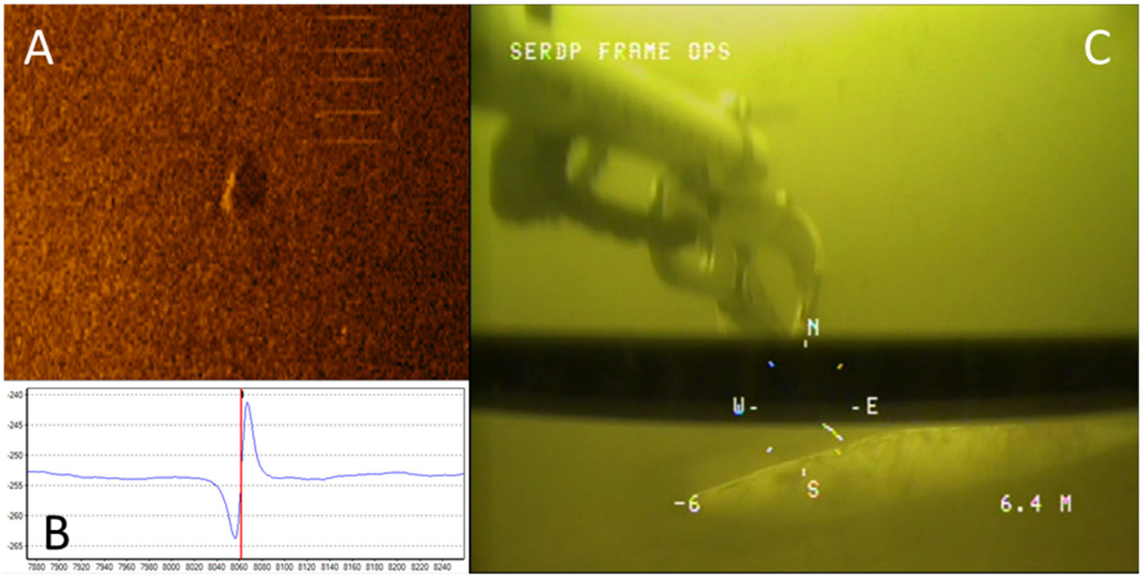


Figure 21: Sonar image of a 155mm surrogate (A) and associated magnetic signature (B). ROV image of a partially buried 81mm surrogate taken on March 18, 2018 (C).

Recovery operations commenced April 11, 2018, after 62 days of deployment. The site was re-surveyed on April 10, 2018, using the AUV to collect side-scan sonar and magnetometer. This data was used to aid DSPSU diver operations. The DSPSU divers were able to recover all of the VPS receivers, 4 reference tags and 6 of the 10 surrogates. The divers reported significant scour and burial with the surrogates that were located. In the process of searching for the remaining 4 surrogates, numerous targets on the sonar were determined to be whelk and horseshoe crabs. Operations were halted, as it was unlikely that the remaining surrogates would be located using the sector-scanning sonar. The data from the VPS was downloaded and sent to Vemco to assist in determining that last known locations for the remaining surrogates, believed to be partially or fully buried at the site. While Vemco was processing the data, another AUV survey was conducted on April 12, 2018, and the instrument frame was also recovered. Without the VPS receivers or reference tag posts at the site, the AUV was able to survey nearer to the seafloor (1.5m versus 2m altitude) and there was less magnetic clutter. The survey located two descript clusters of targets within the grid. The last estimated surrogate locations were sent from Vemco on April 13. The estimates suggested that the two 81mm mortars were located near the AUV magnetometer targets (figure 22), although no magnetic targets were distinguishable in the vicinity of the two missing 60mm surrogates. Using the available magnetometer and VPS positions, operations to recover the missing surrogates resumed on April 26 using DSPSU Scuba divers. Despite strong currents and no visibility, the two 60mm surrogates, both partially buried, were recovered by the divers. The 81mm surrogates, which were fully buried, were not recovered until May 7 via hard-hat diving operations. All four surrogates were recovered within 3 meters of the Vemco estimated positions. Field operations were completed as of May 7, 2018.

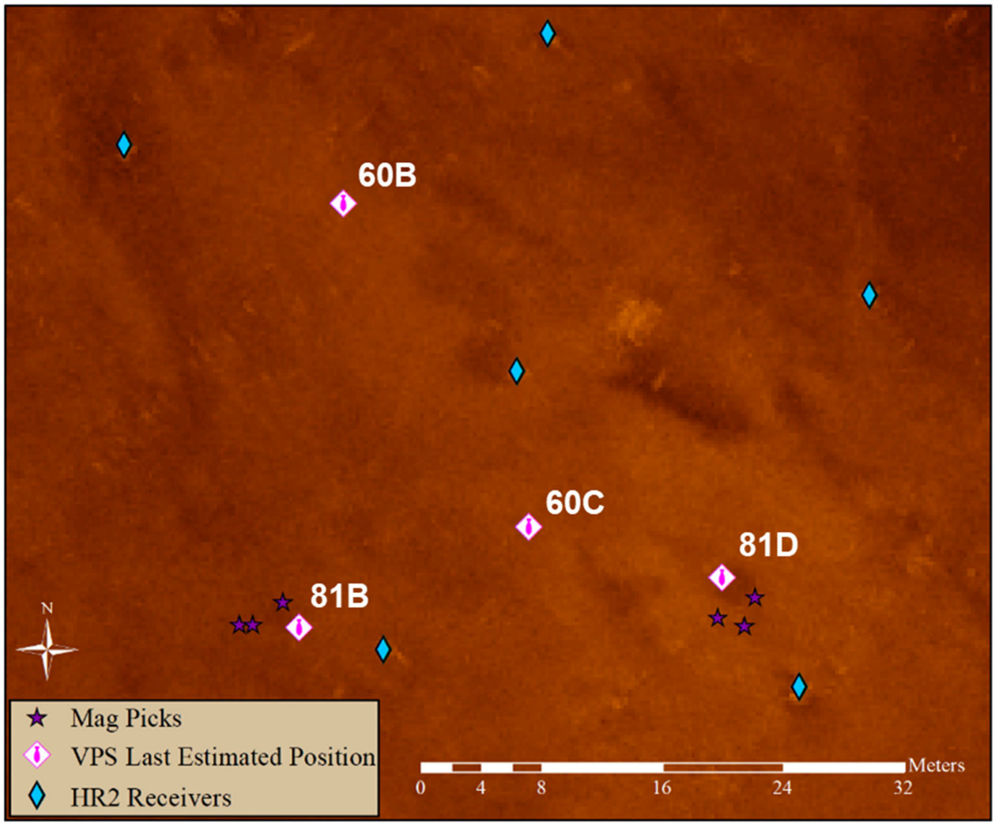
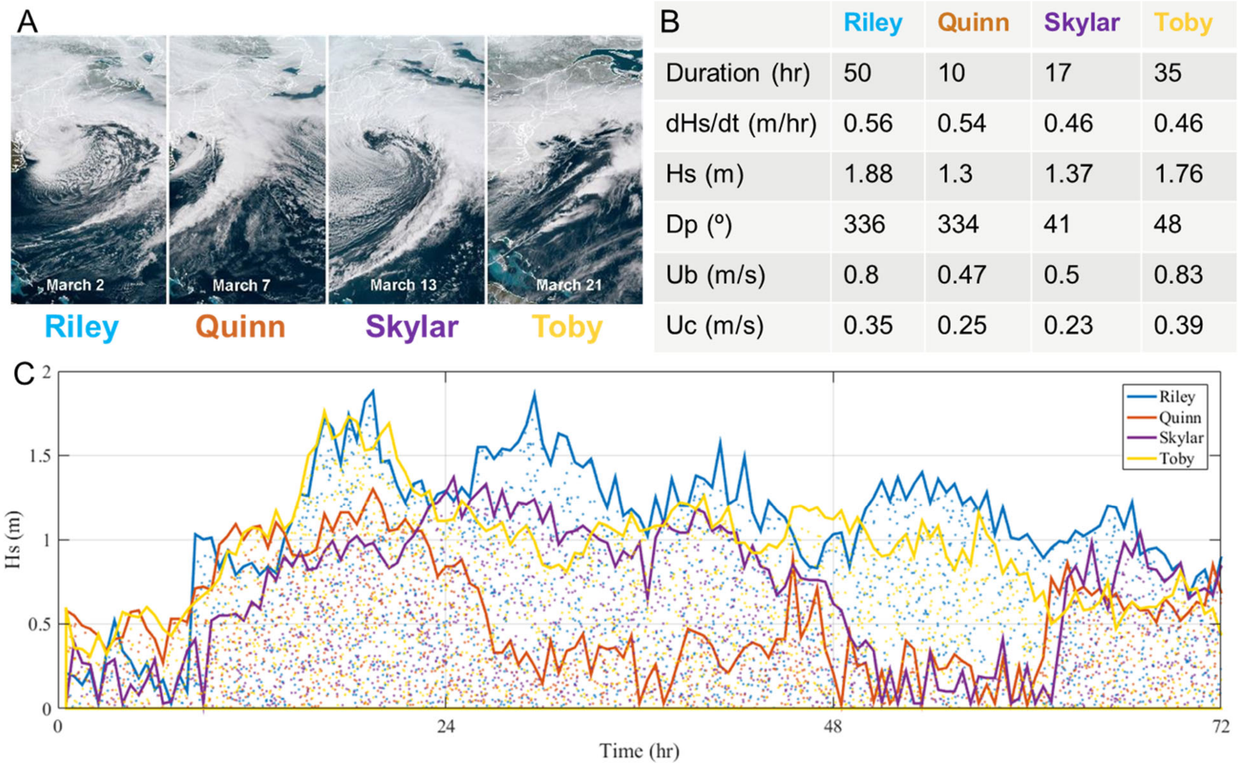


Figure 22: Comparison of magnetometer targets and VPS estimated last known position for the missing 81mm and 60mm surrogates.

4.1.3.4. Spring 2018 Preliminary Results

Whereas the Fall 2017 deployment had no storm activity, the Spring 2018 deployment captured 4 nor'easter storms and several other energetic wave-driven events. All 4 nor'easters occurred in March, bookended by "Winter Storm Riley" on Mar. 3, and "Winter Storm Toby" on Mar. 20, 2018 (figure 23a). The *in situ* hydrodynamics sensors recorded conditions for each of the storms, and were augmented by meteorological data from the nearby NOAA station at Lewes, DE. A side-by-side comparison of the nor'easters (figure 23) shows the duration, peak conditions, and approach of the storms as they passed over the study site. Most notable are Riley and Toby, both of which exceeded significant wave heights (Hs) of 1.75m and near-bed orbital velocity (estimated) above 0.8m/s. Despite these similarities, Riley and Toby varied strongly. Riley approached from the northwest, or shore-parallel, driving waves down the Delaware Bay towards the study site. From this direction, Riley was more fetch-limited, despite topping 1m wave heights for 50 hours. Conversely, Toby approached from the northeast, or shore perpendicular, and was not as fetch limited as Riley. Although exceeding wave heights of 1m for only 35 hours, Toby generated higher wave orbital and mean currents (figure 23b). The impact of the different directional forcing of the storms appears to have been significant in terms of impact to the surrogates at the site, as discussed below.



	Riley	Quinn	Skylar	Toby
Duration (hr)	50	10	17	35
dHs/dt (m/hr)	0.56	0.54	0.46	0.46
Hs (m)	1.88	1.3	1.37	1.76
Dp (º)	336	334	41	48
Ub (m/s)	0.8	0.47	0.5	0.83
Uc (m/s)	0.35	0.25	0.23	0.39

Figure 23: Comparison satellite imagery (A), table (B), and significant wave height plot (C) of the four nor'easter events in March 2018 (satellite imagery courtesy of weather.com).

The Mar. 6 survey took place immediately after Riley and just prior to Quinn. As shown in figure 21a, the surrogates largely appeared unburied, with little to no scour pit discernable in the sonar. The ROV survey, which showed a partially buried 81mm surrogate (figure 21c), was conducted on Mar. 18, after Riley, Quinn, and Skyler, but only two days before Toby. During the recovery operations on April 10-11, 2018, the surrogates were not observed as described above. In the AUV sonar data from April 10, the 155mm surrogates are shown sitting in large scour pits (figure 24). This corresponds with the April 11 observations from DSPSU divers, who noted that the 155m larger surrogates were sitting in large scour pits and were buried 50-60%. The DSPSU divers also noted, over the course of the 3 retrieval operations (Apr. 11, Apr. 26, and May 7), that the smaller surrogates (81 and 60mm mortars) were either mostly or fully buried. With the 81mm mortars, two were observed to be entirely buried, laying at a slight pitch angle, with the tail fins closest to the surface and under 1" of overburden. A third was observed with only 2 fin blades exposed (the condition of the fourth 81mm was not described). Two of the 60mm mortars were described by the divers as lying mostly buried at a nearly vertical pitch, with the tail fins exposed (the condition of the third 60mm was not described). Figure 25 illustrates the divers' descriptions.

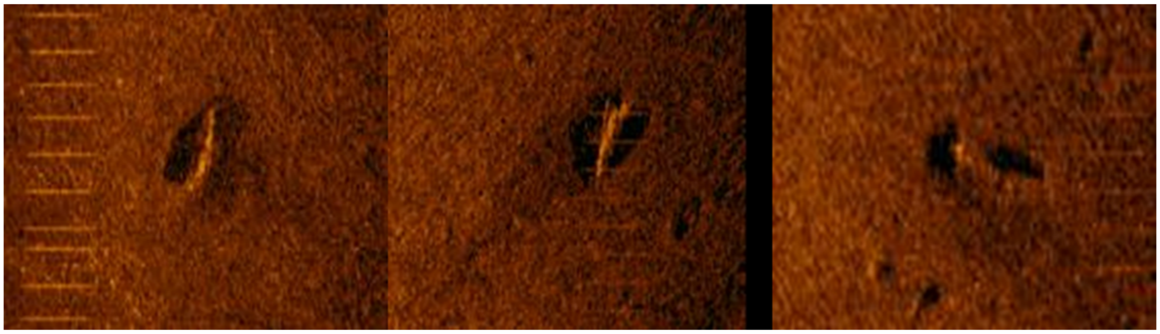


Figure 24: Sonar imagery of the 155mm surrogates on April 10, 2018. Note the scour pits around the surrogates.

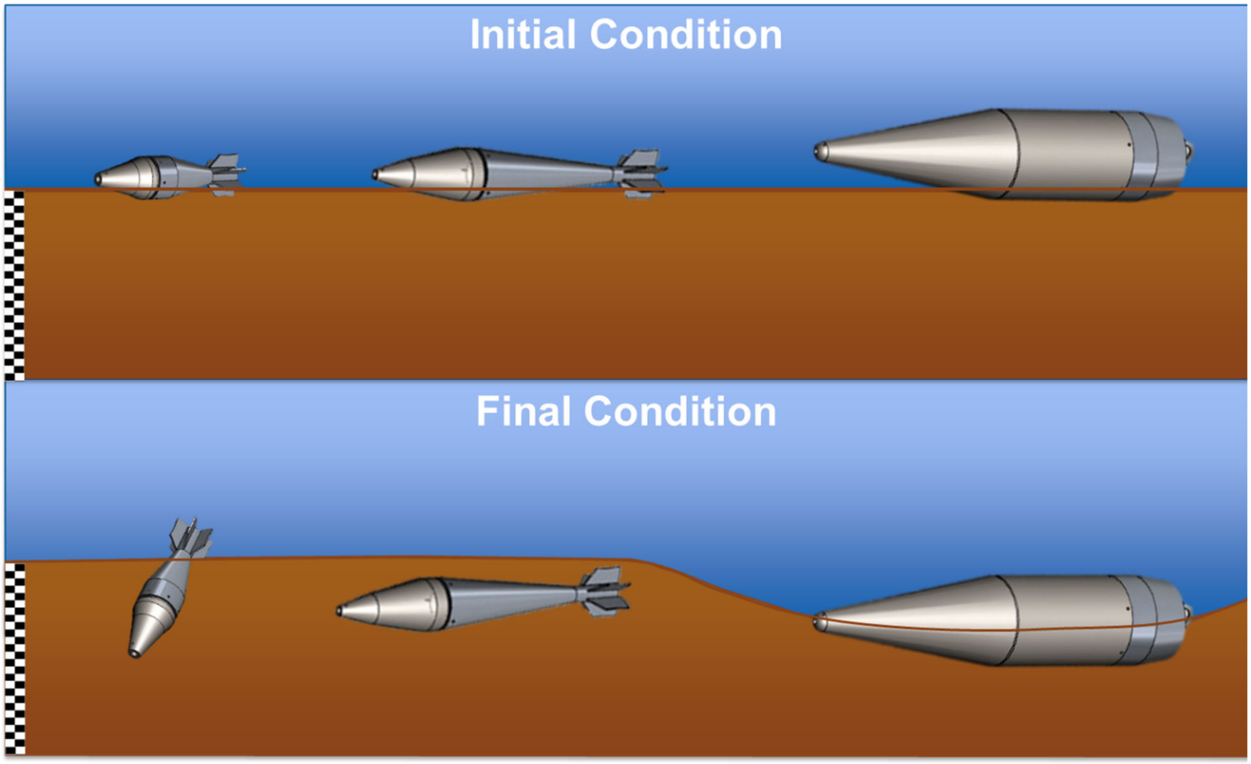


Figure 25: Diagram illustrating the general conditions of each surrogate type at deployment and upon recovery based on the Delaware State Police Scuba Unit observations for the Spring 2018 field study.

Similarly, preliminary analysis of the IMU data indicates that Toby had more impact on surrogate mobility. In the case of all three 60mm mortars, episodic oscillatory rolling was recorded over the course 1700-2100 UTC March 20, 2018. This time frame corresponds with the most energetic conditions recorded during nor'easter Toby. An example of this rolling is shown in figure 26. Most notable is the variation of both yaw and rolling, suggesting that the 60mm surrogates were rolling back and forth in an arc. This corresponds to laboratory tests by Garcia (MR- 2410), who noted that mortar shaped surrogates would roll in an arc due to their shape. IMU data from the 81mm mortars also showed activity during Toby, although not as pronounced as with the 60mm.

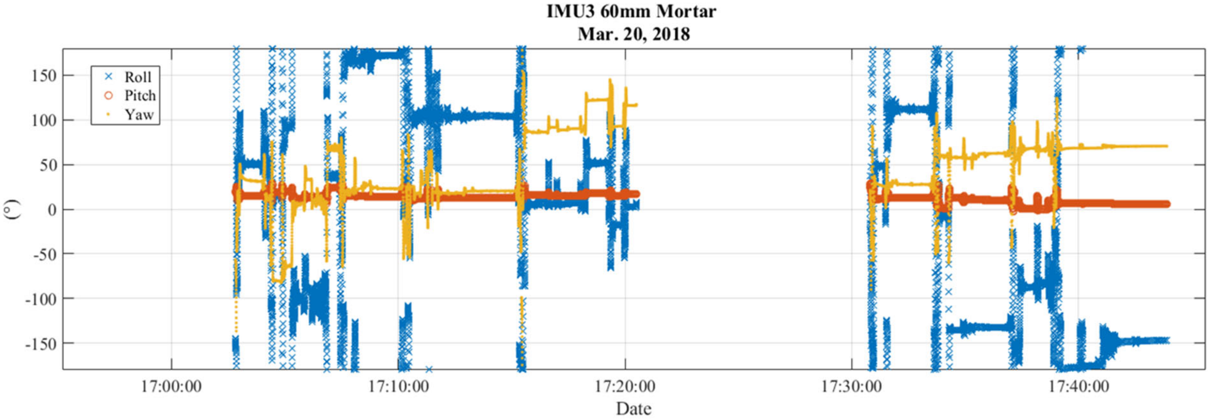


Figure 26: An example of IMU data from a 60mm surrogate showing oscillatory rolling during nor'easter Toby.

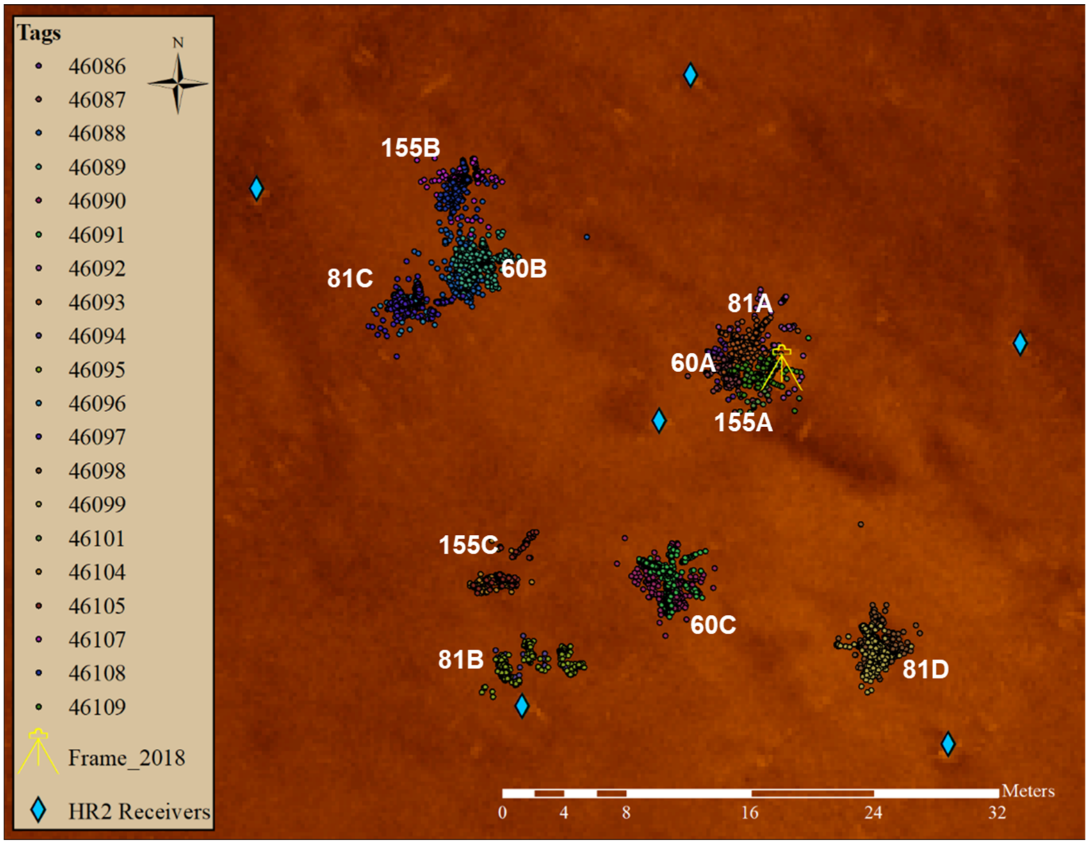


Figure 27: Preliminary VPS tracking results from the Spring 2018 deployment.

The processed VPS tracking data was delivered from Vemco on May 9, 2018. While rolling was noted in the 60mm surrogates, preliminary analysis of the VPS data does not indicate that any substantial net migration occurred laterally. The VPS time-series does indicate that burial did occur in several of the 81mm and 60mm surrogates in the quiescent period following nor'easter Toby: the detection count of several of the acoustic tags decreases during this period, with a few tags completely disappearing from detection. Advanced analysis will further characterize the timing and extent of this behavior, although preliminary results corroborate diver observations of burial.

4.2 Discussion

Task 2 field deployments spanned 93 days over the 2017-2018 storm season (figure 28a). Of that period, four storm events were recorded, all within the month of March. When considering historical averaged wind speed for the month of March at Lewes, DE (10.5 km southeast of the field site), the four nor'easter storms register as above average to outlier events compared to recorded speeds over the period of 2005-17 (figure 28b). Nor'easter Riley (indicated by the blue X), recorded the second highest average wind speed of any event in March since 2005. Overall, the average wind speed distribution was higher than historical conditions for March in the lower Delaware Bay. This suggests that the Spring 2018 deployment recorded conditions that were unusually high in storm activity, and would qualify as outlier events for the purposes of the UnMES model (Rennie-2227).

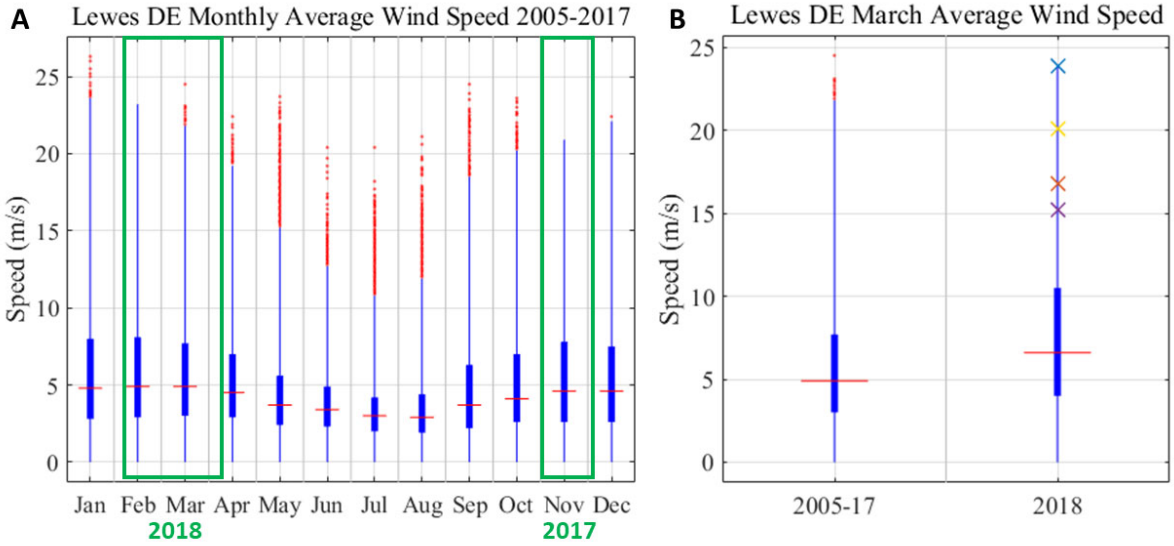


Figure 28: A) Historical monthly average wind speeds at Lewes, DE with deployment dates overlaid. B) Comparison of hourly averaged winds for the month of March historically (left) and during the deployment (right). The highest average wind speed for the nor'easters are overlaid indicating that nor'easter Riley was an outlier event (B).

4.2.1. Morphodynamics

Although direct comparisons are available to historical meteorological records, no such observation have been recorded for hydrodynamics in the Delaware Bay. Prior instrument deployments by the MR-2730 team are available for episodic hydrodynamic measurements taken over the course of 2016-2017 in the Broadkill Beach region. Only one these deployments overlapped the seasonal time frame of the Task 2 deployments. During this prior deployment, which spanned from Mar. 13 – Apr. 11, 2017, one storm event, referred to as “Winter Storm Stella” or the “March 2017 North American Blizzard,” was recorded. Although Stella locally generated significant wave heights up to 1.47m, the storm duration was much shorter than the four nor’easters of 2018, with waves topping 1m for only 5 hours. Near-bed orbital velocities also reached 0.77 m/s during Stella, but only topped 0.5m/s for 6 hours. In comparison to the four nor’easters, the 2017 event would fall just below Riley and Toby for maximum wave height and velocities, but below all four storms in terms of duration.

Along with the four nor’easters, several wave events of shorter duration were recorded (figure 29a). Further analysis will consider whether these wave events resulted in surrogate motion (from the IMU data), but estimates of the Shield parameter and critical threshold for silts anticipated at the site (pending confirmation from sediment analysis) suggest that sediment transport was occurring during these events (figure 29b). The periods of estimated sediment transport also compare well to turbidity measured by the AML Plus-X at the site (figure 29c). The apparent correlation between wave-dominated conditions, estimated sediment transport, and measured turbidity suggest that waves forcing is largely responsible for active morphodynamics in this region, despite relatively strong tidal currents (> 0.25 m/s) recorded near the bed. Thus, storm and large wave events may be the most expected contributor to surrogate scour, burial, or mobility at the study area.

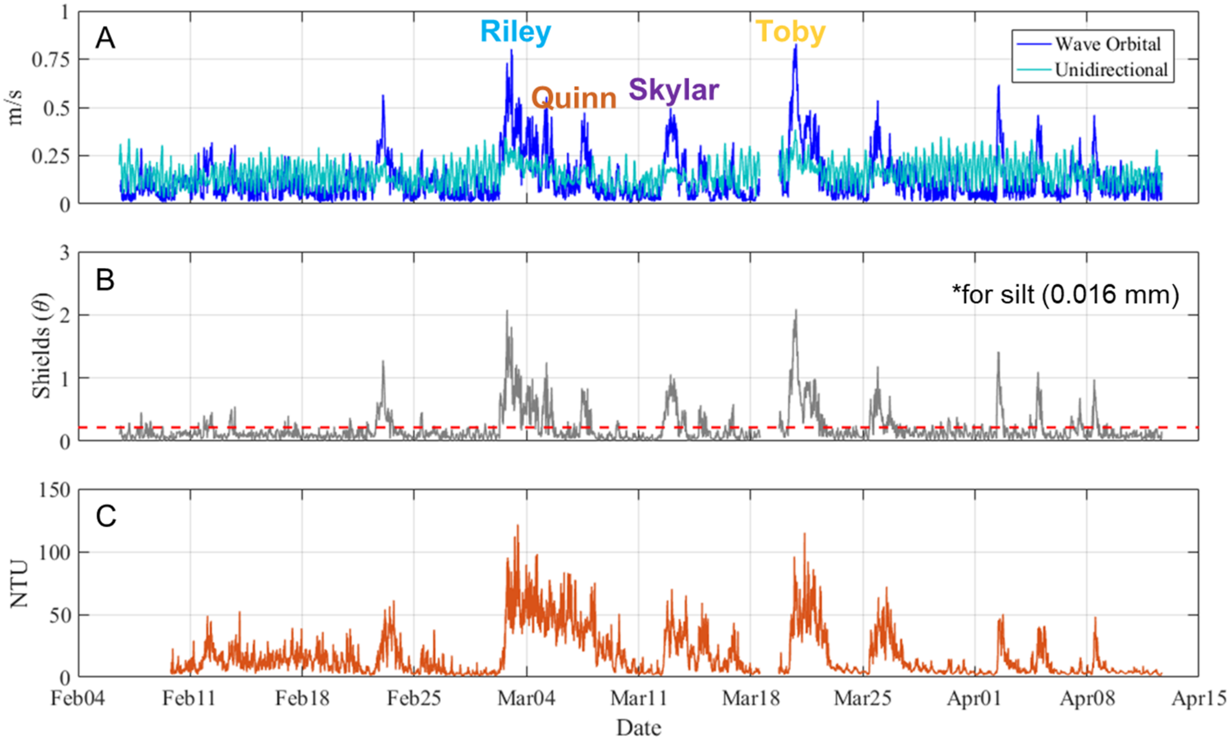


Figure 29: Near bed currents recorded over the Spring 2018 deployment (A), estimated Shields and critical threshold for sediments anticipated at the site pending confirmation from sediment analysis (B), and *in situ* recorded turbidity (C).

4.2.2. Surrogate Scour, Burial, and Mobility

The combined observations from the DSPSU divers, ROV, and geophysical data, although episodic, suggest that scour and burial dominated at the site, and largely occurred during or after Toby. This is supported by the VPS data, from which it may be inferred that burial largely occurred after Toby, particularly in the case of the 81mm surrogates. As mentioned above, the number of detections for the tags associated with several of the smaller surrogates decreased over the days following Toby, with several disappearing from the filtered VPS positions. The 60mm, which were described as being partially buried with a near vertical pitch, do not appear to have been buried until after the Toby. The IMU data for the 60mm surrogates recorded active oscillatory rolling during Toby, but become dormant after Toby. Burial for the 60mm would thus be anticipated in the quiescent period following Toby. Analysis of the IMU's is ongoing, although early indications suggest the IMU batteries were expended by the time burial fully occurred.

The 155mm surrogates were recording pressure during the 2018 deployment, although only one function properly over the entire deployment (the pressure ports were clogged after a few days on other surrogates). This pressure record can be compared to the CTD pressure sensor on the instrument frame (figure 30). After removing initial elevation offsets due to the CTD's location above the bed, any additional offset over time would likely indicate the scour and settling of the 155mm surrogates. The offset between the two begins almost immediately, with a nearly steady growth in offset until the wave event on Feb. 23, at which time the offset ceases to grow. A negative offset occurs during nor'easter Riley, which is likely caused by the frame settling in during the storm. After Riley, the offset remains largely constant, but grows slightly during the final two weeks of the deployment. The final offset reaches 50cm, which would suggest the 155mm (with a diameter of 15.5cm) scoured and settled over twice its diameter below the surrounding seafloor. Although the diver observations do not indicate the depth of the scour pit, it is unlikely, considering the 155mm surrogates were only 50-60% buried, that scour occurred to such an extent. Rather, an additional factor, perhaps voltage drift in the 155mm pressure sensor power supply, may be accentuating the offset.

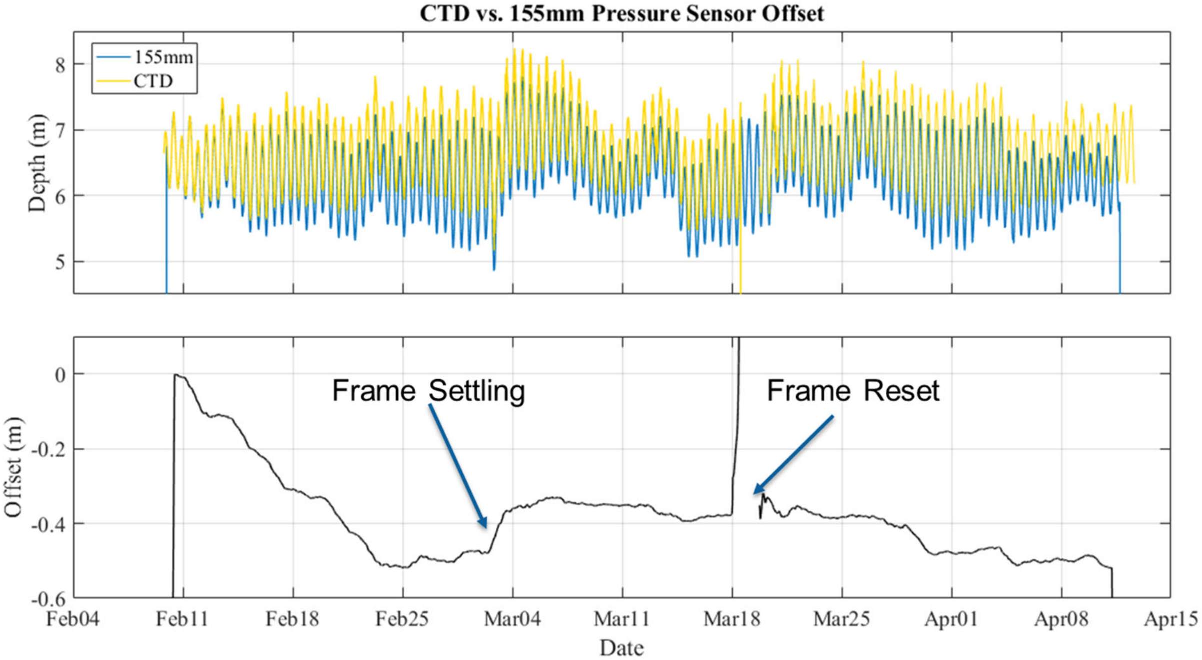


Figure 30: Comparison of water level records and calculated offset between the CTD and a 155mm surrogate during the 2018 deployment suggest scour and settling of the 155mm surrogates started early in the deployment.

Further analysis will focus on the cause of this offset, but taken qualitatively, the record would indicate that significant scour burial did occur, and occurred much earlier in the deployment with the 155mm surrogates than the smaller surrogates, as inferred from the VPS and IMU data. The high-resolution sonar imagery does not show a large scour pit around the 155mm on Mar. 6, as was observed in the sonar on Apr. 10. If scour burial did occur prior to the Mar. 6 survey, as suggested by the 155mm pressure sensors, then it is possible that sediment infill buried the scour pit prior to the Mar. 6 survey. Sediment infilling was observed in non-cohesive sediments in mine burial studies, including the episodic intrusion of cohesive sediments into pits formed around mines in non-cohesive sediments (Traykovski et al., 2007; Inman and Jenkins, 2002). By Mar. 18, the 81mm surrogates were partially buried, possibly due to similar scour pit infill, but were eventually completely buried and as much as 1" below the surrounding seabed. Given that the VPS tags for the 81mm surrogates were still recorded during Toby, but detection rates decreased after Toby, scour infill likely occurred after the storm. Strong spring tidal currents (>0.25m/s) were recorded during this period, and may have contributed to the apparent sediment infill and burial of the 81mm surrogates. This would also compare to the observations noted during mine burial studies (Baeye et al. 2012, Traykovski et al., 2007), although Traykovski et al., (2007) noted mud deposition during slack tides, and partial excavation during strong tidal currents. Eventually, however, Traykovski et al. (2007) noted that the infill mud became resistant enough to limit resuspension and burial occurred. It is possible that strong spring tidal currents transported sediment that infilled the scour pits around the 81mm mortars during slack tides, with eventually enough cohesive sediment infill to prevent periodic excavation. This would correspond to the preliminary VPS observation, with burial protracted over a period of time rather than a quick singular event, and this will be the subject of further analysis. With the 155mm surrogates, the observed partial burial may indicate that not enough time had passed for this process to result in total burial, and indeed the process described by Traykovski et al. (2007) for the total burial of a large cylindrical mine occurred over 28 days.

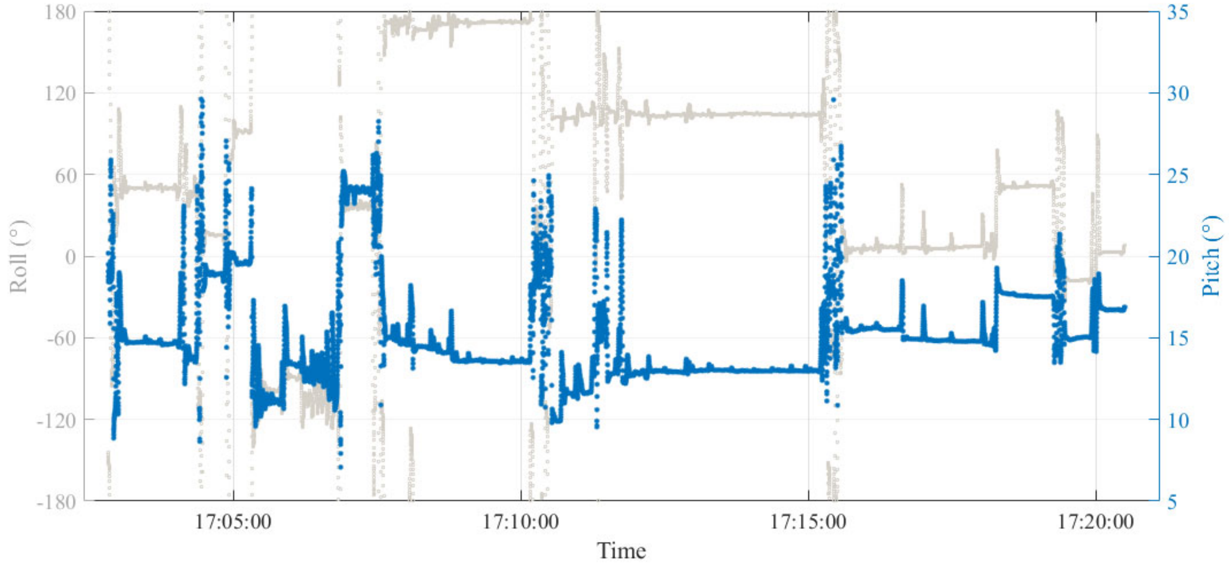


Figure 31: Roll and pitch recorded during Toby in a 60mm surrogate. Note the 10-15 degree increase in pitch, which appears during periods of rolling and for extended periods in static moments, suggesting the unit may have rolled into and out of a scour pit.

The status of the 60mm mortars prior to Toby is unclear: no observations were made by the ROV, and the surrogates were too small to resolve in the side-scan sonar. Unfortunately, the three surrogates next to the instrument frame were also placed too close to the rotary sonar, and fell within the blanking distance of the unit. Thus, no time-series observations are available for the 60mm mortar prior to the frame's relocation out of the VPS grid. The mobility of the 60mm mortars during Toby suggests if scour burial had occurred prior to Toby, then the 60mm mortars were fully excavated by the time Toby reached peak forcing. Slight periodic perturbations are observed in the pitch of one 60mm mortar during its oscillatory rolling, occurring on the order of 10-15 degrees (figure 31). With pitch angle reaching over 25 degrees, and at points sustained for nearly a minute at angles as much as 23 degrees, this may indicate the unit was rolling into and out of a scour pit. The unit eventually settled out with a nominal pitch of 15 degrees, but by recovery, was described as mostly buried and having a near vertical pitch. This was not measured in the IMU. The cause of the near vertical pitch of the 60mm mortars is currently unclear and will be the focus of further analysis.

4.2.3. VPS Performance

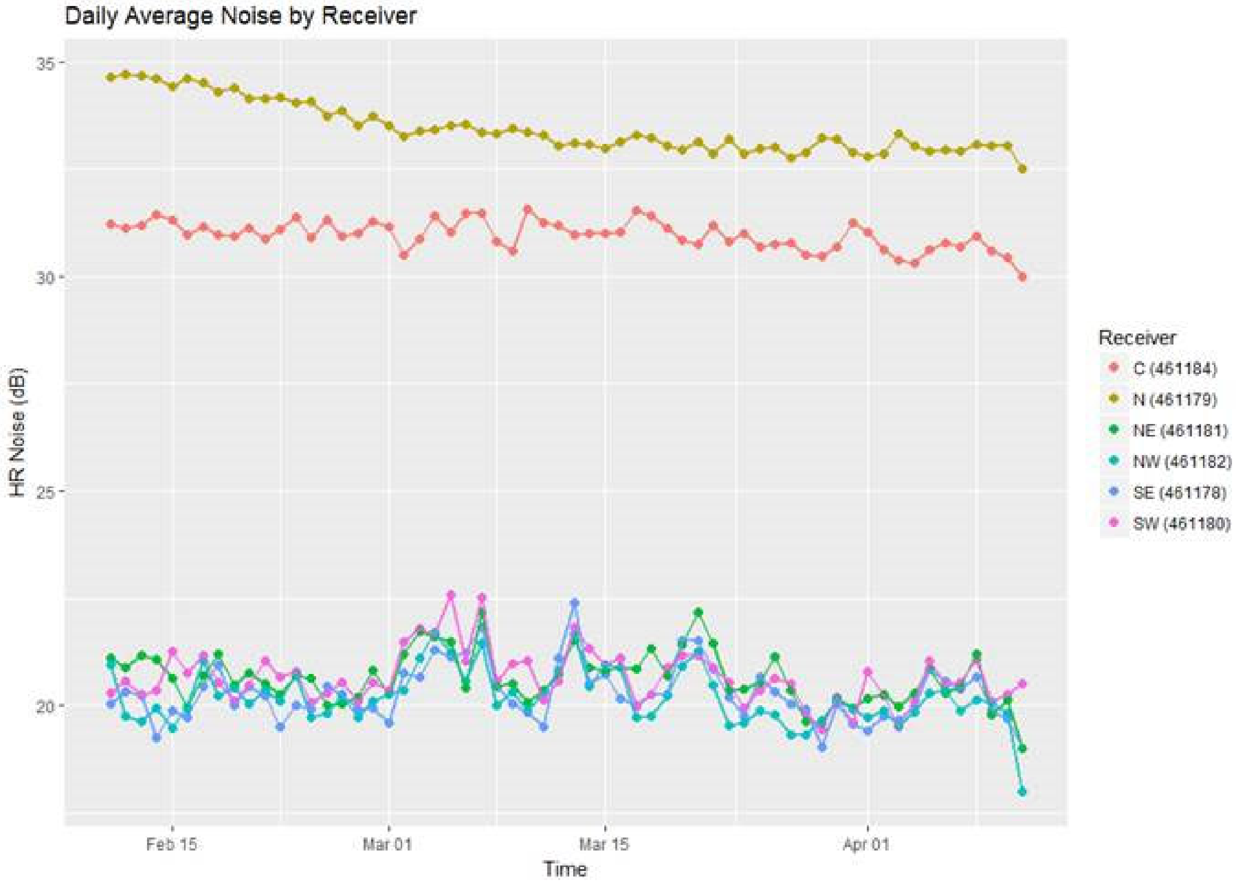


Figure 32: Acoustic noise for at each HR2 receiver during the 2018 deployment. Storm activity did not significantly introduce noise, although consistently high noise are noted in both the central and northern receivers.

Analysis of the VPS for surrogate positional accuracy is ongoing. Preliminary analysis suggests that the VPS operated consistently throughout the deployment. Although detection loss may have been expected during the storms, the VPS results indicate neither significant noise addition nor signal loss during the storm events (figure 32). However, HR2 receivers on the north and central poles recorded significantly higher noise throughout the deployment. The instrument frame, which was moved outside of the grid on March 18, has been ruled out. Analysis is still ongoing to determine the cause of the noise. Despite the noise, the positioning for the 2018 data was within the quantitative performance metric set in table 1 (50% of detections within a horizontal position error < 1m). To determine horizontal position error (HPE) in meters, the positions of the HR2 receivers are derived from triangulation of the sync tags within the HR2 receivers (used to sync receiver time and track HR2 movement on non-fixed mooring) over the course of the deployment. These positons were compared to the positions derived from PMES survey with RTK positioning. After filtering for high HPE (filtering out 44.8% of detections), the median error for the remaining 55.2% of sync tag positions was only 0.23m, with 75th error percentile at 0.54m and while 95th error percentile at 1.01m.

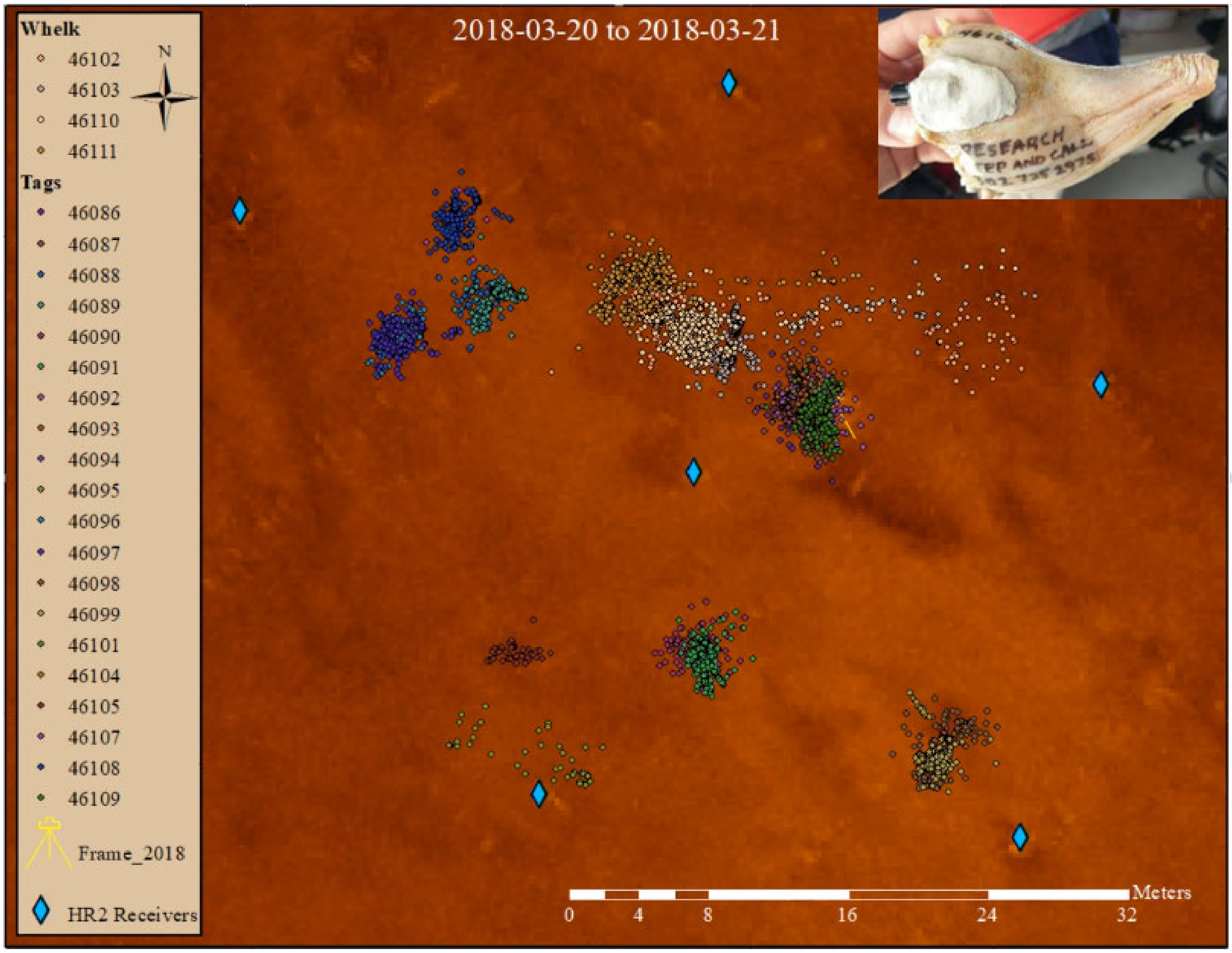


Figure 33: VPS results on Mar. 20, showing the initial position and subsequent movement of the four tagged whelk (inset) to the east and out of the grid. The whelks' positions continued to be recorded beyond the grid but were filtered out for low reliability in this image.

Although preliminary analysis suggest no detectable net migration of the surrogates in the VPS data, the VPS was able to record tag movement. This occurred through the use of tagged whelks, four of which were deposited at the site on March 11, 2018. The whelks were released to both ensure the VPS was capable of recording movement (should none have occurred with the surrogates) while simultaneously testing the systems capabilities for a study on whelks by the Delaware Natural Resources and Environmental Council. Although the whelks initially remained in place following their release, nor'easter Toby appears to have caused three of the whelks to migrate out of the site and to the east, towards deeper water. The remaining whelk also moved east but stayed within the grid, and was recovered on Apr. 11 with the surrogates (figure 33 inset). The whelks' movement is shown in figure 33, having been clearly captured by the VPS during nor'easter Toby. Overall, the performance of the VPS during the 2018 deployment indicates the system is well suited for use in munitions mobility studies and under varying hydrodynamic conditions.

5. Conclusions to Date

5.1. Conclusions: Tasks 1 and 2

5.1.1 Task 1 – Tracking and Motion Sensor Technology Design

The surrogate munitions design and instrumentation met the minimum performance standards of the study. The motion trigger wake-up setting, customized for this project with the help of x-io, was sensitive enough to capture moments of only minimal movement, and extended the battery life of the IMU. Although several of the surrogates were still recording upon retrieval, future work will look to maximize battery capacity and utilize the limited space more efficiently. The pressure sensors in the 155mm, despite working in the benchtop test, did not operate during the 2017 deployment. It was determined after the deployment that the pressure sensors did not draw enough current to keep the selected USB battery pack active for long periods of time. The battery pack was replaced with a unit featuring an "always on" setting, which allowed for the pressure sensors to work throughout the 2018 deployment. However, 2 of the 3 sensor ports became clogged early in the deployment, and the ports will be milled out to prevent clogging in future deployments. Regardless, the inclusion of the pressure sensor has proved to be a useful tool for analysis, and incorporation into any surrogates large enough to house the units is recommended.

The VPS system proved to be a robust and simple system to program and deploy. The acoustic tags are small enough to allow for use on surrogates smaller than the 60mm surrogates used in this study, and have operational life-spans (>7 months) that would allow for much longer deployment durations. The only limiting factor for time would be the HR2 receiver battery life-span, which is still only limited to 6 months. In this case study, the lifespan of the IMU batteries, pressure sensors, and hydrodynamic sensors were the limiting factor. The VPS system can be easily customized for many different site locations, water depths, test areas, salinity, and sediment types, making it an ideal tool for further munitions mobility research or other similar research. Vemco's assistance in VPS system configuration and data processing, including pushing data through rushed analysis to successfully locate and recover the lost surrogates, contributed to the success of the field operations.

5.2.2. Task 2 – Field Implementation

The location of the field site proved ideal for deployment, recovery, and site monitoring operations. The proximity of the field site to the University of Delaware Marine Operations Base (10.5km southeast of the site), allowed for short travel time, maximized vessel time on the field site, and reduced cost. The site's location in the lower Delaware Bay also maximized the potential for stronger observed hydrodynamic conditions; the Delaware Bay is at its widest near the location of the field site, which allows for greater fetch for wave formation. For example, the nearby areas of Fowler and Broadkill beach have undergone significant beach erosion and overwash in the past two decades due to storm activity in the area.

The assistance of the Delaware State Police Scuba Unit for all diving related operations was invaluable to the study, and the DSPSU divers often contended with adverse conditions. Despite issues with weather, poor visibility, strong currents, and cold temperatures, the deployment and recovery operations were successfully conducted by the DSPSU. With their assistance, the VPS system was correctly installed and performed to the standards set for this study. All surrogates were successfully deployed and recovered by the DSPSU.   Geophysical surveys were conducted as frequently as weather conditions would permit, and sensor performed up to specifications throughout field operations. Aside for an issue with intermittent signal in the rotary sonar during the 2017 deployment, all hydrodynamic instrumentation functioned normally. It is suggested that future work look to extending the battery life of the hydrodynamic sensors, through the acquisition of external battery sources, to extend the deployment window.

5.2. Tasks to Perform

5.2.1. Task 3 – Data Analysis, Project Review and Reporting

As of this writing, Task 3 is on-going, with only preliminary data analysis (Task 2.2) completed. In light of surrogate mobility, geophysical, geotechnical, and hydrodynamic characterization will be analyzed for parameters that influence surrogate mobility, including shear stress and inertial dissipation estimates, near-bed velocities, and estimated suspended sediment concentrations. Complete site acoustic backscatter, bathymetry and magnetometer map products will generated for each survey, and used to analyze changes to site-wide surficial sediment distribution and bathymetry during the study. Sediment samples and short cores will be processed for grain size analysis, sediment type and distribution, and shear vane analysis. Hydrodynamics will be used to generate progressive vector diagrams for exceedance of sediment transport thresholds; these diagrams will be calculated from site sediment distribution maps based on geophysical survey products and ground-truthed by sediment samples collected at the site, and related to incipient motion and observed tracking path of surrogate ordnance. Both raw data and products will be stored in Mathworks Matlab .mat structures, geotiff image format, and tabular ASCII form, with associated metadata information. All data will be made available for distribution. Surrogate tracking products, both raw recorded receiver times and Vemco processed positions, will be summarized in tabular form. Vemco reported positions will be compared to position estimates generated by the study team, as well as compared to positions observed in magnetometer and side-scan sonar data collected by the AUV. All reported positions and raw receiver times will be made available for outside comparison. Surrogate mobility will be analyzed with time-series hydrodynamics to determine which parameters have the most influence on surrogate mobility in muddy environments. Contrasts will be made between surrogates with different densities to determine difference mobility or burial response as related to object density. Final analyses will compare surrogate UXO behavior in shallow, muddy environments to similar measurements derived in studies of UXO mobility in sandy sites (e.g. Calantoni SERDP MR-2320, Traykovski MR-2319).

5.2.2. Interim Milestone 2: Go / No-Go Decision

As of this report, Task 2 was successful in capturing multiple storm events (section 4) during the second deployment of the VPS system. Although the goals of Task 2 were met, discussions with Rennie (MR-2227) determined that additional field data collection would be beneficial to the continued development of the Underwater Munitions Expert System, as there is a noted dearth of observations of UXO behavior in varied environments and extreme events (personal comm. Sarah Rennie, April 24, 2018). These extreme events, which may be best described as outlier events, are those in which significant scour/burial/mobility would most likely be anticipated (or potentially predicted by the UnMES). Additional field data, likely collected in conditions not represented by the field work in Task 2, would increase the observations and parameters to further develop the UnMES.

5.2.3. Task 4 – Additional Field Deployments

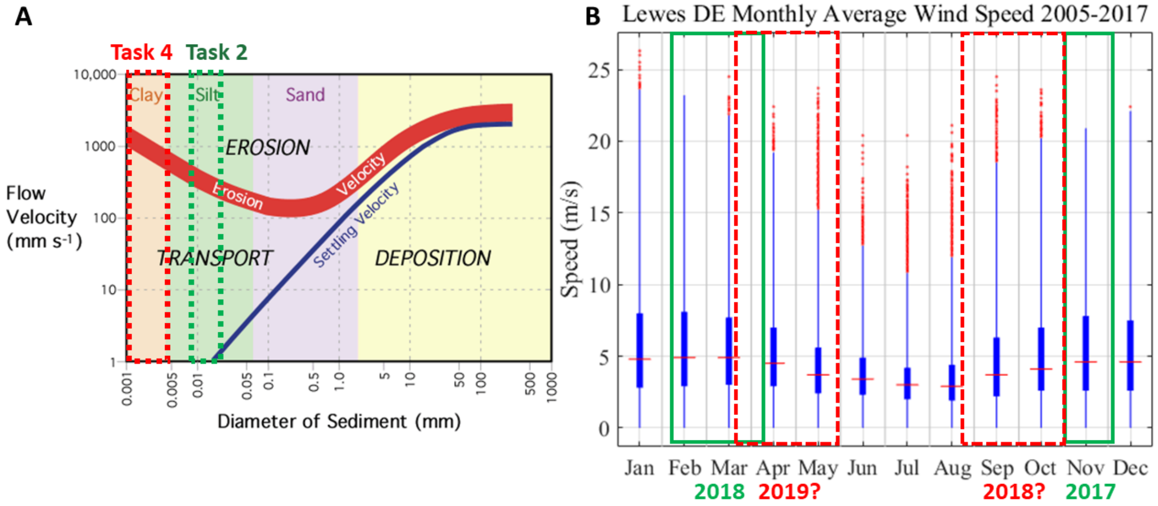


Figure 34: Example Hjulstrom diagram (A) and historic wind record (B) illustrated remaining data gaps potentially addressed through additional deployment in Task 4.

The additional field deployments for Task 4 should be considered in light of the parameter space addressed by Task 2, and the remaining gaps in data required to further develop the expert system model. Figure 34a illustrated the sediment size parameter space in which the Task 2 field site was conducted. Future deployments might be conducted in sites with more clay sized cohesive sediments. Sites selected with shallower or varied depth or bathymetric profile may also be considered, as the Task 2 field site was a nominal 4.5m MLLW throughout the area. The grid could also be expanded, depending on site depth, to include more area, or perhaps more HR2 receivers. An additional surrogate type should also be considered to address that large gap between the 81mm and 155mm surrogates. Smaller, expendable surrogates, such as the 40mm used by Puleo MR-2503, could also be considered, or less dense surrogates, such as those modeling pyrotechnics (as suggested by Rennie MR-2227). As well, the impact of corrosion or growth on munition mobility may also be considered, as the surrogates used by all recent MR studies have been pristine. Lastly, although storms were captured by the Spring 2018 deployment, the Task 2 deployments did not include the often energetic late Spring storm season or the late Summer / early Fall hurricane season (figure 34a). Future MR-2730 deployments will continue working to address these data gaps.

6. Literature Cited

Baeye, M., Fettweis, M., Legrand, S., Dupont, Y., and V. Van Lanker, 2012. Mine burial in the seabed of high-turbidity area- findings of a first experiment. *Continental Shelf Research* 43, pp. 107-119.

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

Cataño-Lopera, Y. A., Demir, S. T., and M. H. García, 2007. Self-burial of short cylinders under oscillatory flows and combined waves plus currents. *IEEE J. Ocean. Eng.,* 32(1), pp. 191–203.

Cataño-Lopera, Y. A., and M. H. García, 2006. Burial of Short cylinders Induced by Scour under Cominedd Waves and Currents. *J. Waterway, Port, Coast, Ocean Eng*. 132, 439-449.

Edwards, M., Wilkens, R., Kelley, C., DeCarlo, E., MacDonald, K., Shjegstad, S., Van Woerkom, M., Payne, Z., Dupra, V., Rosete, M., Akiba, M., Fineran, S., Zheng, W., King, J.C., and G. Carton, 2012. Methodologies for Surveying and Assessing Deep-Water Munitions Sites. *Marine Technology Society Journal,* 46 (1), 51-62.

Heupel, M.R., Semmens, J.M., and A.J. Hobday, 2006. Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. *Marine and Freshwater Research* 57(1), pp. 1-13

Hunter, A.J., van Vossen, R., Quesson, B.A.J., and A.L.D. Beckers, 2013. Detection of Underwater UXO's in Mud. Final Report. SERDP MR-2200.

Inman, D. L. and S.A. Jenkins, 2002. Scour and Burial of Bottom Mines: a Primer for Fleet Use. SIO Reference, Scripps Institution of Oceanography, University of California, San Diego, La Jolla.

Jain, M. and A.J. Mehta, 2009. Role of basic rheological models in determination of wave attenuation over muddy seabeds. *Continental Shelf Research* 29, pp. 642-651.

Jenkins, S.A., Inman, D.L., Richardson, M.D., Weaver, T.F, and J. Wasyl. 2007. Scour and Burial Mechanics of Objects in the Nearshore. *IEEE Journal of Oceanic Engineering,* 32 (1), 78-90.

Keller, B.M., Hamilton, T., and S. Hird, 2015. Low-Logistics AUV Pipelin Inspection: Acquiring High-Resolution Geophysical data in Very Shallow Water. Sea Technology 56(12), 37-41.

Letter, Jr., J.V., and A.J. Mehta, 2011. A heuristic examination of cohesive sediment bed exchange in turbulent flows. *Coastal Engineering* 58, pp. 779-789.

Mayer, L., Raymond, R., Glang, G., Richardson, M.D., Traykovski, P. and A. Trembanis, 2007. High resolution mapping of mines and ripples at the Martha's Vineyard coastal observatory. *IEEE Journal of Oceanic Engineering* 32 (1), 133-149.

Nelson, H., Kaye, K. and A. Andrews. 2009. Geophysical System Verification (GSV): A Physics-Based Alternative for Geophysical Prove-Outs for Munitions Response. ESTCP Report. SERDP/ESTCP Program Office.

SERPD Final Report, 2013. SERDP/Office of Naval Research Workshop on Acoustic Detection and Classification of UXO in the Underwater Environment, Sept. 2013.

SERDP Draft Report, 2014. Program Review for Burial and Mobility Modeling of Munitions in the Underwater Environment. Draft Version 1.2, 15 Oct. 2014.

Sheremet, A., Mehta, A.J., Liu, B., and G.W. Stone, 2005. Wave-sediment interaction on a muddy inner shelf during Hurricane Claudette. *Estuarine, Coastal and Shelf Science* 63, pp. 225-233.

Soltanpour, M., Haghshenas, S.A., and A.J. Mehta, 2009. Fluidized Mud-Wave Interaction under Regular and Irregular Waves. *Journal of Coastal Research* 25 (3), pp. 616-626.

Steigerwalt, R., Trembanis, A.C., and M. Tchernychev, 2012. Autonomous Underwater Vehicle Munitions And Explosives Of Concern Detection System. May 2012. ESCTP IPR. Arlington, VA.

Raineault, N.A., Trembanis, A.C., and D.C. Miller, 2011. Mapping benthic habitats in Delaware Bay and the coastal Atlantic: acoustic techniques provide greater coverage and high resolution in complex, shallow-water environments. *Estuaries and Coasts,* 35(2), pp 682-699.

Traykovski, P., Richardson, M.D., Mayer, L.A., and J.D. Irish, 2007. Mine Burial Experiments at Martha's Vineyard Coastal Observatory. *IEEE Journal of Oceanic Engineering* 32(1), pp. 150-166.

Trembanis, A., C., DuVal, J., Beaudoin, V., Schmidt, D., Miller, L., Mayer. 2013. A detailed seabed signature from Hurricane Sandy revealed in bed forms and scour, *Geochem. Geophys. Geosyst.*, 14(10), 4334-4340.

Trembanis, A.C., Friedrichs, C.T., Richardson, M.D., Traykovski, P., Howd, P.A., Elmore, P.A. and Wever, T. F., 2007. Predicting seabed burial of cylinders by wave-induced scour: application to the sandy inner shelf off Florida and Massachusetts. *IEEE Journal of Oceanic Engineering* 32(1), pp 167-183.

Wald, R.J., and A.K. Cooper. 1989. *Marine Magnetic Gradiometer: A Tool for the Seismic Interpreter*. EG&G Geometrics: Sunnyvale, CA

Wilson, B.D., Madsen, J.A., Fox, D., Simpson, P., Moore, J., Bruce, D., and D.B. Carter, 2010. Delaware Bay Benthic Mapping Project: Mapping the Distribution of Bottom Sediments, Key Habitats, and Sub-bottom Imaging in Delaware Bay and River. Delaware Department of Natural Resources and Environmental Control. Access at: http://www.dnrec.delaware.gov/coastal/Documents/ Benthic%20Mapping/Benthic_Mapping_Presentation.pdf

Wright, L. D., 1993. Micromorphodynamics of the inner continental shelf: a Middle Atlantic Bight case study. *Journal of Coastal Research*, Special Issue No. 15 Beach and Surf Zone: 93-124.