FINAL REPORT

Development of Surf-Zone Capable Unmanned Surface Vessels

SERDP Project MR20-1494

NOVEMBER 2021

Peter Traykovski
Woods Hole Oceanographic Institution

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 02/11/2021	**2. REPORT TYPE** SERDP Final Report	**3. DATES COVERED** *(From - To)* 9/6/2019 - 9/6/2021

4. TITLE AND SUBTITLE Development of Surf-Zone Capable Unmanned Surface Vessels	**5a. CONTRACT NUMBER** 19-P-0113
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Peter Traykovski	**5d. PROJECT NUMBER** MR20-1494
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution
266 Woods Hole Road
Bigelow 109A (MS#12)
Woods Hole, MA 02543-1535

8. PERFORMING ORGANIZATION REPORT NUMBER
MR20-1494

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Strategic Environmental Research and Development Program (SERDP)
4800 Mark Center Drive, Suite 16F16
Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
SERDP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
MR20-1494

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
One of the critical areas for underwater munition detection and remediation is very shallow water less than 5 m deep. In many environments there will be occasional to frequent breaking waves in depths from 0.5 m to 3 m, and there are very few platforms that have been optimized to work in this region. The current most used approaches consist of specialized large amphibious vessels or small personal watercraft (jet-skis) that are not optimized for survey work.

15. SUBJECT TERMS
Surf-Zone Capable Unmanned Surface Vessels

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Peter Traykovski
UNCLASS	UNCLASS	UNCLASS	UNCLASS	22	**19b. TELEPHONE NUMBER** *(Include area code)* 508-289-2638

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

Table of Contents

List of Figures

Acronyms

GPS	Global Positioning System
AHRS	Attitude Heading Reference System
ASV	Autonomous Surface Vessel
AUV	Autonomous Underwater Vehicles
CRAB	Coastal Research Amphibious Buggy
COTS	Commercial off the shelf
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CNC	Computerized Numerical Control
DEM	Digital Elevation Map
EMI	Electro-Magnetic Induction
FY	Fiscal Year
GPS	Global Positioning System
Hmax	Maximum Wave Height
Hm0	Zero'th moment wave Height
HoM	Head Of Meadows
IMU	Inertial Motion Unit
LIDAR	Light Detection and Ranging
MVCO	Martha's Vineyard Coastal Observatory
MEMS-IMU	Micro-Electromechanical System Inertial Motion Unit
MEMS	Microelectromechanical Systems
MRSEED	Munitions Response Exploratory Development Solicitation
MRSON	Munitions Response Statement of Need
NAD	North American Datum
NAVD	North American Vertical Datum
PINWR	Pea Island National Wildlife Refuge
PWC	Personal watercraft
PPK	Post-Processed Kinetic
PID	Proportional Integral Derivative
RTK	Real-Time Kinetic
RC	Remote Control
REMUS	Remote Environmental Monitoring Underwater System
SNR	Signal-to-Noise Ratio
SSV	Small Surf Vessel
SUP	Stand Up Paddle Board
sUXO	Surrogate Unexploded Ordnance
SERDP	Strategic Environmental Research and Development Program
USBL	Ultra-Short Base Line
UXO	Unexploded Ordnance
USGS	United States Geological Survey
USV	Unmanned Surface Vessel
USACE	US Army Corps of Engineers
WHOI	Woods Hole Oceanographic Institution

Abstract

Objectives: One of the critical areas for underwater munition detection and remediation is very shallow water less than 5 m deep. Very shallow water is emphasized since munitions are most likely to be encountered by the general public in depths that are suitable for wading, swimming and scuba diving, with potential encounters more likely in the shallowest water. In many environments there will be occasional to frequent breaking waves in depths from 0.5 m to 3 m, and there are very few platforms that have been optimized to work in this region. The current most used approaches consist of specialized large amphibious vessels or small personal watercraft (jet-skis) that are not optimized for survey work. The objective of the project is to develop and test a range of Unmanned semi-autonomous Surface Vessels (USVs) for use in shallow water and surf zone conditions.

Technical approach: In the past 5 years, our laboratory at WHOI has developed two shallow water USVs. The Jetyak is a 3.5 m long, 1 m wide gas powered, 150 kg, jet drive vessel capable of carrying payloads of up to 100 kg with moderate hydrodynamic drag, moderate endurance (~ 8 hrs), moderate speed (~ 4 to 6 m/s maximum), and relatively poor surf zone performance due to the air intake of the gas engine. The small surf vessel (SSV) is a 1.8 m long, 50 cm wide, 10 kg electric motor/battery powered, jet drive vessel capable of carrying small, low drag payloads of up to 5 kg, with low endurance (~ 1.5 hrs), high speed (~ 10 m/s) and good surf zone performance due to the semi-submersible hull and drive system and self-righting design. Neither vessel is optimized for munitions response work in the surf zone as the Jetyak cannot handle breaking waves reliably, and the SSV is too small to carry sensors for munition detection. The goal of the project is to develop and test USVs with lengths of approximately 3 m and weight less than 100 kg, with wave piercing and self-righting hulls that can carry acoustic sensors capable of detecting proud UXO in and outside the surf-zone. Based on our previous experience, extensive in-situ testing is required to determine the performance envelope of these vehicles with respect to wave height, breaking frequency, and mean currents and to optimize maneuverability characteristics which are essential for navigation in the surf zone with endurance and speed. The in-situ testing will be combined with numerical modelling analysis using COTS software to optimize performance.

Results: The work completed in this SEED project indicates that USVs are capable of launch, recovery and navigating in surf-zone conditions through a combination of direct remote control by the operators in the swash and autonomous waypoint following modes in regions of intermittent breaking. Smaller single person portable USVs (1.7 m long, 10 kg, Small Surf Vessel-SSV) have been proven to take high quality single beam echosounder data with vertical accuracies of under 10 cm. A larger (3 m long, 55kg) USV was developed that is capable of carrying a bathymetric sidescan sonar such as the PingDSP 3DSS to detect proud UXO under certain conditions.

Benefits: The USVs developed in this project will benefit both munition response work and near-shore research in general. Unmanned semi-autonomous surface vessels that can carry acoustic munition detection and swath bathymetry sensors while operating in and outside the surf zone in nearshore water depths offer many cost and performance advantages over the manned systems that are currently used. In addition to allowing more efficient surveys of munitions, the bathymetric survey capability of these systems will improve our ability to understand coastal

erosion processes, which will become increasingly important in the next century with anticipated rising sea levels.

1. Objectives

One of the critical areas for underwater munition detection and remediation is very shallow water less than 5 m deep. In many environments there will be occasional to frequent breaking waves in depths from 0.5 m to 3 m, and there are very few platforms that have been optimized to work in this region. The current most used approaches consist of specialized large amphibious vessels or small personal watercraft (jet-skis) that are not optimized for survey work. The objective of the project is to develop and test a range of unmanned semi-autonomous surface vessels (USVs) for use in shallow water and surf zone conditions. We envision due to the accurate trackline following abilities of USVs with moderate to fast speed (2 to 3 m/s) that this type of platform equipped with suitable sensors could provide timely and cost-efficient surveying of large areas with a modest probability of detection even with existing commercially available sensors, and that this would be followed by more detailed, slower surveying methods (e.g. seafloor crawler with a towed sled) in regions of interest identified by the USV.

SERDP Relevance: One of the areas outlined in the SERDP munitions response program area FY 2020 statement of need (MRSEED 20-S1) was "Wide Area and Detailed Surveys: Technologies are needed to allow rapid assessment of large areas to identify concentrations of munitions and areas free of munitions…there is a specific need for systems that can operate in depths less than 5 meters." The very shallow water emphasis of the MRSON comes from the fact that munitions are most likely to be encountered by the general public in depths that are suitable for wading, swimming and scuba diving, with potential encounters more likely in the shallowest water.

2. Background

In the past 5 years, our laboratory at WHOI has developed two shallow water USVs. The Jetyak is a 3.5 m long, 1 m wide gas powered, 150 kg, jet drive vessel capable of carrying payloads of up to 100 kg with moderate hydrodynamic drag, moderate endurance (~ 8 hrs), moderate speed (~ 4 to 6 m/s maximum), with relatively poor surf zone performance due to water and spray entering the air intake of the gas engine [1] (Figure 1a). The small surf vessel (SSV) is a 1.8 m long, 50 cm wide, 10 kg electric motor/battery powered, jet drive vessel capable of carrying low drag payloads of up to 5 kg, with low endurance (~ 2 hr), high speed (~ 10 m/s) and good surf zone performance due to the fully watertight hull and drive system and self-righting design (Figure 1b) [2]. Neither vessel is optimized for munitions response work in the surf zone as the Jetyak cannot handle breaking waves reliably, and the SSV is too small to carry sensors for munition detection.

Existing methods for surveying the near shore, including the surf zone, typically involve manned platforms such a personal water craft (PWC) or amphibious vehicles which require large teams to operate and place personnel at risk [3]. These types of vessels typically use single beam echosounders but have occasionally been equipped with multibeam or sidescan sonars. In the case of the amphibious vehicles, these are specialized craft which are not readily available. Crawlers, such as the "CRAB" used at the US Army Corps of Engineers (USACE) Duck, NC research station or the recently developed SurfROVer have also been successfully used in the surf zone [4], [5]. These vehicles are typically slow (~ 0.5 to 1 m/s), but are capable of towing

EMI sleds, which have excellent detection rates for shallow buried munitions in limited regions. They are optimized for detailed, high confidence surveys of small areas.

Autonomous Underwater Vehicles (AUVs) are a mature technology that are well suited for acoustic sensor surveys in water depths greater than 3 m [6]. In shallower water, the 5 to 10 x vehicle altitude swath width of the acoustic systems force the vehicle toward the surface in order to maximize the seafloor areal coverage. Near the surface the vessel effectively becomes an Autonomous Surface Vessel (ASV), but highly over-engineered and cost ineffective for this mode of operation. The ASVs are typically a factor of 10 less expensive to similar AUVs, although direct comparisons are difficult. In 2012 as part of the ONR New River Inlet experiment, our lab configured a REMUS-100 AUV with a 1 m long mast so the vehicle could operate 0.50 m below the surface to avoid vehicle motion associated short period surface waves and keep a PPK (5 cm accuracy) GPS above the surface. Although this worked well in calm conditions, in open ocean swell the vehicle was not able to track the surface well enough to keep the antenna from submerging. Without the constant GPS the vehicle would lose navigation lock in areas of mild breaking waves and did not have enough speed (max vehicle speed of ~ 2 m/s) to navigate against the strong tidal currents in the inlet, and thus was often washed into shallow areas or onto the beach. The energetic conditions of water less than 3 m deep with breaking waves are not a suitable location to run an AUV

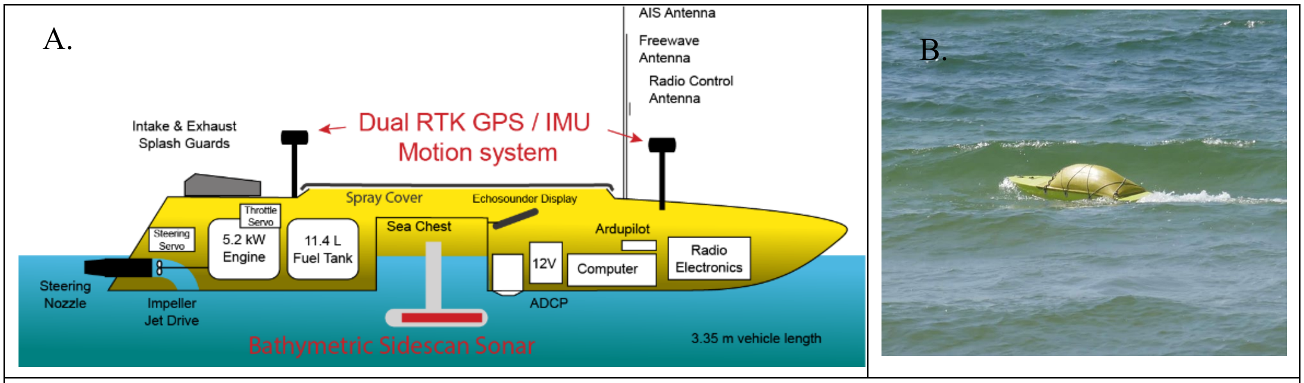

Figure 1. A. Schematic Diagram of the Jetyak Autonomous Survey Vessel (ASV) The Jetyak was equipped with a swath bathymetry sensor from PingDSP and a Dual Antenna RTK GPS/IMU system B) SSV underway in small (0.2 m) waves during local testing.

Unmanned or Autonomous Surface Vessels have been demonstrated to work well in energetic shallow water nearshore conditions including the surf-zone. The distinction between unmanned and autonomous is that unmanned vehicles may be remote controlled, which is the most common mode of operation in the surf zone, and autonomous vehicles have some form of autonomy, usually GPS waypoint following and not obstacle (or beach) avoidance and thus supervised autonomy would be a more appropriate description. Most commercially available USVs are either too big and difficult to launch and recover from the beach (e.g., L3-ASV C-worker 3 through 7) and several catamaran designs (e.g. SeaRobotics 3.6), or the few that can handle surf zone conditions are too small to carry the necessary payload for munition detection (e.g. 2 m long ASVs). Catamarans are difficult for surf use as they are equally stable upside down as right side up.   Many of the smaller USVs (e.g., Clearpath Heron and Ocean Sciences z-boat) are underpowered for surf-zone operations as a top speed of 4 to 6 m/s and rapid acceleration is required to make it through the waves.

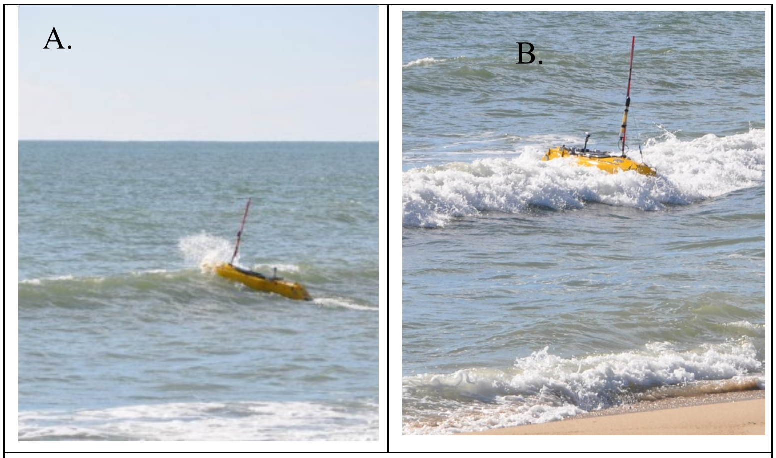

Figure 2. A&B. The Jetyak Autonomous Survey Vessel (ASV) underway in 1 m wave height surf zone conditions.

The WHOI Jetyak [1] and similar USVs based on the Mokai es-kape hulls (Figure 1a) have been shown to have performance characteristics consistent with use in small surf (H < 1 m). Our Jetyak development has inspired similar designs at Scripps, Oregon State [7] and Univ. of South Carolina [8]. However, the air intake for both cooling and combustion of the Jetyak's gas engine is not well suited for consistent use in surf-zone conditions. On the survey day on the coast of Martha's Vineyard, MA on which the photos in Figure 2 were taken, the vessel performed well during the survey, with small deviations from the preprogrammed track-lines, but was swamped on recovery at the beach, requiring extensive engine repair and re-conditioning. In this survey the Jetyak was equipped with a single beam echosounder, so closely spaced accurate survey lines and interpolation of the data between the lines was required. In larger surf conditions ($H \sim 1.5$ m) such as the survey in Nauset Inlet on the East facing coast of Cape Cod, MA shown in Figure 3, the Jetyak could operate onshore of the surf zone and offshore of the surf-zone, but we did not think it could go through the breaking waves. In the later surveys in Nauset Inlet, the Jetyak was equipped with PingDSP wide swath (8 to 12 x water depth) bathymetric sidescan sonar and a high-performance Novatel dual PPK-GPS and MEMS-IMU based AHRS for motion compensation. The Jetyak was designed as a planning hull and is not efficient in displacement mode with its blunt nose. With high energy density gas power this is not a significant issue, but with the lower energy density of battery power an efficient hull shape is required.

Figure 3. A) Bathymetric Jetyak underway just onshore of large (1.5 m) breaking waves. The Jetyak could not go through these waves safely.

Based on our experience with the Jetyak in the surf zone and imagery of the EMILY unmanned surf vessel (1.3 m long) from Hydronalix [9] successfully navigating the surf zone, we built a small (1.8 m long) electric powered jet drive USV (Figure 1b). With a watertight lid and no requirements for air intake (the electric motor is water cooled), this design is fully submersible. A self-righting flotation module was designed and built using Rhino3d naval architecture CAD software to ensure that in case of capsize in the surf it would immediately right itself and be able to continue operations. This vessel was built in summer through fall of

2018 in preparation for measuring bathymetric change and tracking surrogate UXO with active acoustic pingers as part of our MR-2739 project. Due to the short time between completion of the vessel and the beginning of the survey work, we were not able to test and evaluate performance in a large range of conditions. Since we only had one vehicle, we were conservative in our testing and did not use it in conditions energetic enough for it to fail in order to determine the limits of operation. This small surf vessel (SSV) performed very well during the survey work with single beam echosounder and PPK GPS for bathymetry and ultra-short base line (USBL) for tracking the sUXO [10] .With pre and post storm surveys, it measured large bathymetric change due to a 4 m wave event that forced offshore migration of a sandbar burying most of our sUXO (Figure 4a). The small size and light vehicle (~ 15 kg) made for very easy deployment, recovery and use by a single operator. While a powerful (5 kW max rate motor) small vehicle such as this can navigate the surf zone, it is very limited in payload capacity and endurance (~ 2 hrs) due to the small battery capacity (0.5 kW Hr). This vehicle could not carry a larger acoustic package required to detect actual UXO as opposed to sUXO with active pingers.

3. Materials and Methods

Based on our previous experience, extensive in-situ testing is required to determine the performance envelope of these vehicles with respect to wave height, breaking frequency, and mean currents and to optimize maneuverability characteristics which are essential for navigation in the surf zone with endurance and speed. At the start of the project, we already had developed the 1.8 m long SSV and the larger swath bathymetry sensor 3 m USV was yet to be developed so two different types of testing were performed. The smaller vessel was tested in a wide range of conditions by performing bathymetric surveys in open ocean sites in combined autonomous and remote-control driving modes. A second series of tests were aimed at design optimization for the larger vehicle under development. These consisted of towing a variety of hull shapes to measure the hydrodynamic drag. The in-situ drag testing was combined with numerical modelling analysis using COTS software to optimize performance.

Specific tasks completed were:

1. Test the smaller USV in a variety of surf zone conditions ranging from short fetch, short period wind waves to larger open ocean unlimited fetch swell in order to determine performance bounds for these vessels, navigation systems and optimum tradeoffs between maneuverability and efficiency for bathymetric surveys.
2. Numerical modelling of the performance characteristics of various length and geometry hulls using Rhino/Orca3d naval architecture software combined with in-situ towing measurements.
3. Design of a hull and power system in Rhino/Orca3d naval architecture software and optimization of the design for computer aided manufacture (CAM) using a CNC cut male mold and composite lamination.
4. Construction of the hull and power system, including testing of various composite lamination schemes.
5. Integrate our existing PingDSP 3DSS bathymetric sidescan sonar and dual PPK-GPS AHRS into the new 3 m long USV and perform tests of detection and characterization of unburied steel cylinders.

4. Results and Discussion

4.1. Small USV Bathymetric surveys

4.1.1. Study Sites

In addition to the three bathymetric surveys that were performed as part of MR-1490 at Long Point, Martha's Vineyard, MA in relatively mild wave conditions, seven additional surveys were performed at other sites with a wider variety of wave conditions. These sites included Head of the Meadow (HoM) Beach in Truro, MA and Marconi Beach, MA where the USGS has a beach monitoring camera system; and Pea Island National Wildlife Refuge (PINWR), Hatteras Island, NC. The PINWR surveys were funded by the U.S. Army Corp of Engineers through the US Coastal Research Program as part of the upcoming DUNEX experiment but will be discussed in this report as it helps establish performance bounds for the system. The HoM and Marconi surveys were also partially funded by a USGS-WHOI cooperative agreement and were conducted with assistance from USGS personnel. All of the sites are exposed to open ocean waves and are in national parks so survey methods such as PWC Jetski based systems would be prohibited. As indicated by the bathymetric maps, all of these sites have a relative steep beach with an energetic swash zone, and offshore sand bars that have intermittent breaking waves depending on the wave height and tidal water levels. Future work is planned at a low slope dissipative beach with a wide surf zone.

4.1.2. Wave Conditions

The PPK GPS sea surface elevation as a function of boat position and time can be used to estimate the frequency and wavenumber spectra for each survey. Table 1 reports the zeroth moment wave height (Hm0), maximum wave height (H_{Max}) and Peak Period (Tp) for each survey:

Table 1. Wave Statitics For SSV Surveys

Location	Date	H_{Max} (m)	Hm0 (m)	Tp (s)
Long Point, Martha's Vineyard, MA	10/26/2018	0.66	0.26	15.5
Long Point, Martha's Vineyard, MA	10/31/2018	1.49	0.46	9.2
Head of Meadow Beach, Truro, MA	3/10/2020	0.64	0.26	9.0
Head of Meadow Beach, Truro, MA	2/11/2021	1.42	0.43	4.8
Marconi Beach, Wellfleet, MA	3/10/2021	1.94	0.65	9.8
Pea Island Wildlife Reserve, Hatteras Island, NC	11/22/2020	1.17	0.63	8.3
Pea Island Wildlife Reserve, Hatteras Island, NC	11/27/2020	1.60	0.49	9.3
Pea Island Wildlife Reserve, Hatteras Island, NC	4/19/2021	1.04	0.51	6.4
Pea Island Wildlife Reserve, Hatteras Island, NC	4/20/2021	1.85	0.49	9.5

While the Long Point surveys were performed in relatively calm conditions with Hm0 less than 50 cm, subsequent surveys at Marconi Beach and Pea Island Wildlife Reserve had Hm0 of between 50 and 70 cm and maximum wave heights of up to 2 m as the wave shoaled on the sandbars. Outside of the swash zone the SSV vessel was able to maintain control in autonomous mode during all of these wave conditions with typical cross track errors of less than 2 m, and no catastrophic loss of control failures in either autonomous or remote-control modes. Launch and recovery operations were slightly more difficult in larger waves but were successful with attention to the timing of the sets of incoming waves.

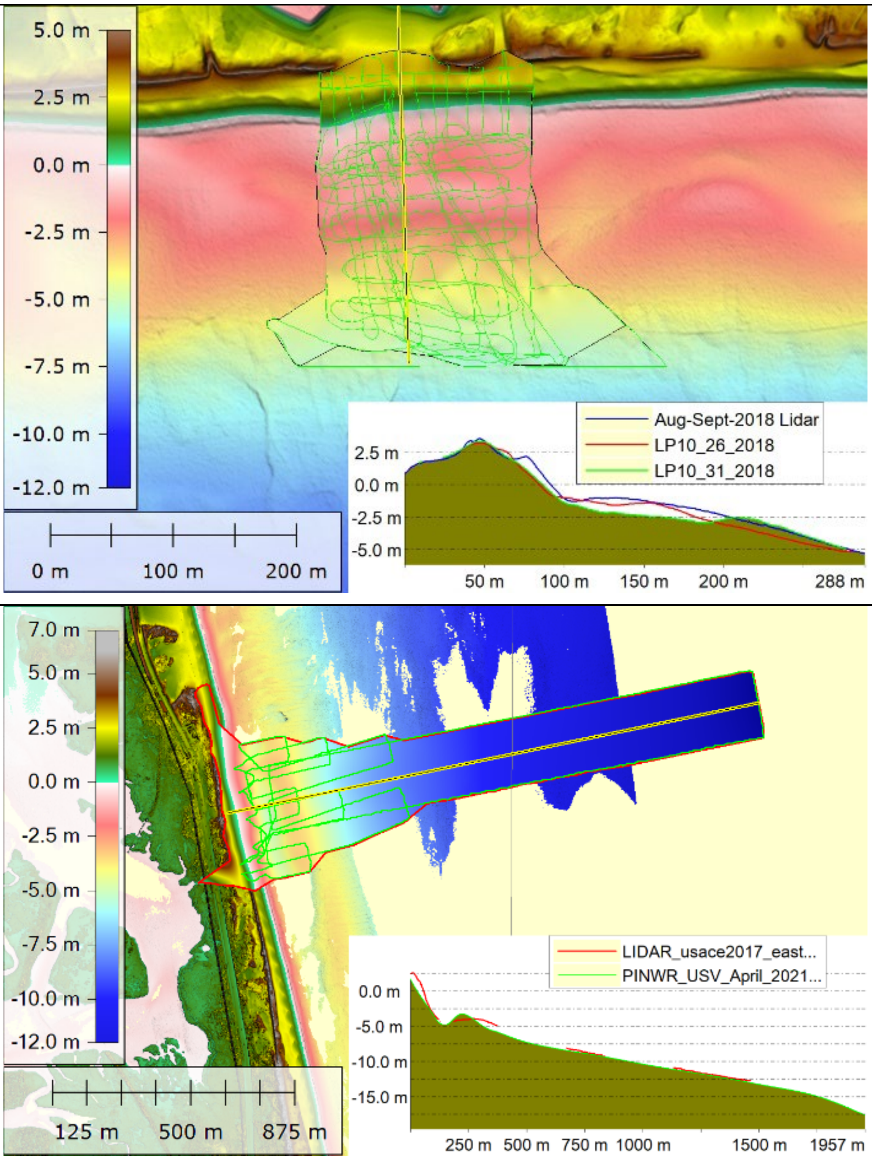

Figure 4. SSV Bathymetric map overlaid on LIDAR data from A) the Long Point Wildlife refuge surveys. The green line represents the track of the vessel. Inset: profiles along the yellow line in the map. B) Pea Island Wildlife refuge surveys. The green line represents the track of the vessel. Inset: profiles along the yellow line in the map.

4.1.3. Survey results and Error Analysis

Results from the surveys conducted as part of MR-1490 at Long Point were presented in the final report for that project (the 10/26 data is repeated here as Figure 4a) and show the ability of the SSV to measure large bathymetric change associated with offshore sand bar migration in response to a 4.5 m wave height event. The LIDAR (ref 2018 USACE NCMP Topobathy Lidar DEM: East Coast (CT, MA, ME, NC, NH, RI, SC)) data collected between 5/9/2018 and

8/27/2018 is used as a background in Figure 4. It has complete coverage of the study area, but the nearshore sandbar topography did change, with some offshore bar migration between the time of the LIDAR measurements to the first bathymetric survey on 10/26/2018. The ability of the USV to track mobile UXO with tethered active pingers was also documented in the final report and will not be repeated here.

The survey results from Pea Island (Figure 4b) which cover a larger spatial area with lines extending 1.5 km into 15 m water depth show similar variability in depths less than 5 m due to sand bar migration. In the vicinity of the study area, the LIDAR data has many gaps, presumably due to turbidity, thus the USV provides a valuable continuous cross shore profile.

The accuracy of the bathymetric survey results depends on the accuracy of the individual echosounder and vessel altitude (via PKK GPS) and orientation measurements combined with errors due to interpolation of single beam data. As documented in Francis and Traykovski 2021 in situ comparison of the combined echosounder and GPS measurement to direct GPS measurement of the sea floor depth (via a 5 m mast) indicates the accuracy of the USV system is better than 10 cm during calm conditions.

To address the error due to interpolation a Monte Carlo Optimization routine was used, whereby data from one of the survey lines was not included in the interpolation scheme and then the error in predicting the measurements on that line via interpolation were calculated. This was then iterated over all the cross and along-shore transect lines to calculate an overall error. The interpolation was performed using the Matlab file exchange script RegularizeData3D, which requires a smoothing parameter. The optimization routine searches over a range of values of the smoothing parameter to find the one that minimizes the interpolation error. The results of this minimization procedure are shown for two surveys: the Long Point Survey as it has the smallest trackline spacing and a survey from Pea Island with larger trackline spacing (Figure 5). Two statistics are calculated for each interpolated trackline segment. The Median Absolute Deviation:

$$MAD = median(|z - median(z)|)$$

and the bias error:

$$Be = |median(z - median(z))|$$

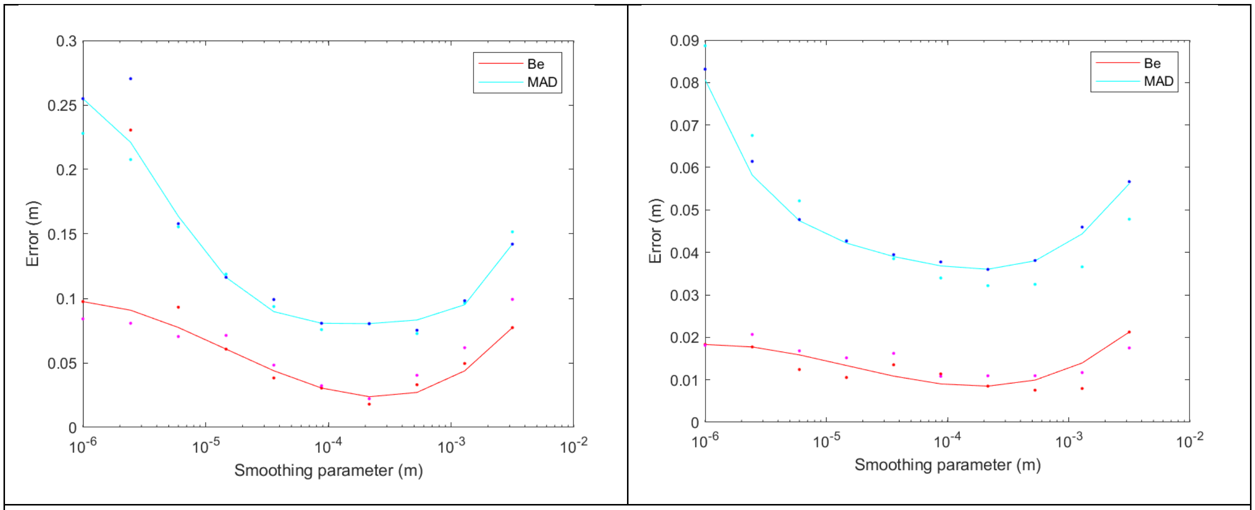

Figure 5.Smoothing parameter optimization results for A) PINWR, B) Long Point.

The errors from the interpolation as estimated by predicting omitted trackline segments for the Long Point data set are very small, less than the individual ping error, with MAD values of 4 cm at the optimum smoothing parameter and Be values of 1.5 cm, due to the dense track line coverage. At Pea Island, with larger track spacing, the errors were slightly larger, with MAD values of 10 cm at the optimum smoothing parameter and Be values of 2 cm. These errors are sufficiently small to accurately measure sandbar migration which has typical vertical variations of 50 to 150 cm.

4.2. In Situ towing measurements and comparison to predictions

Based on the success of the 1.8 m SSV in surf zone conditions the design of larger USVs capable of carrying a swath bathymetry sensor or larger payloads in the surf was initiated by towing a few available hulls behind a skiff with a digital recording dynamometer inline on the towing cable (Figure 6). The highest drag hull was a Jetyak USV with 50 kg of electronics and batteries including a PingDSP Bathymetric sonar (57 cm long by 9.8 cm Diameter) mounted underneath the hull. At a typical survey speed of 2 m/s the drag was 150 N, resulting in power requirement of 250 watts. At higher speeds of 4 m/s the power required increased to 2 kW. Assuming an efficiency of 40% this is roughly consistent with the maximum speed of this vessel of 3.5 m/s with its 7 Hp (5.2 kW) gasoline motor at full throttle. With both the sonar and electronics and battery weight removed the drag decreased by a factor of 2.5. A hull from a racing stand up paddleboard (Naish Glide SUP 4.25 m long, 70 cm wide) was also towed with a load of 45 kg, based on initial design estimates of an electric jet drive USV. This hull exhibited drag that was 8 times lower than the fully loaded Jetyak. The SUP hull was modelled in Rhino CAD software with the aid of Orca3d Naval Architecture software hull design assistant. This software has a built-in Holtrop hull analysis module to predict drag and power requirements based on a regression analysis to a variety of experimental data. The model was run with three different loading conditions of 35, 45 and 55 kg and the predicted drag agreed well with our tow test results. The Holtrop analysis is focused on displacement hull performance, so the upper part of the speed range (U>5 m/s) is outside the range of applicability as the hull is planing. The software also contains a planing hull analysis module, but the long and narrow hull shape of the SUP was outside the parameter bounds for this analysis.

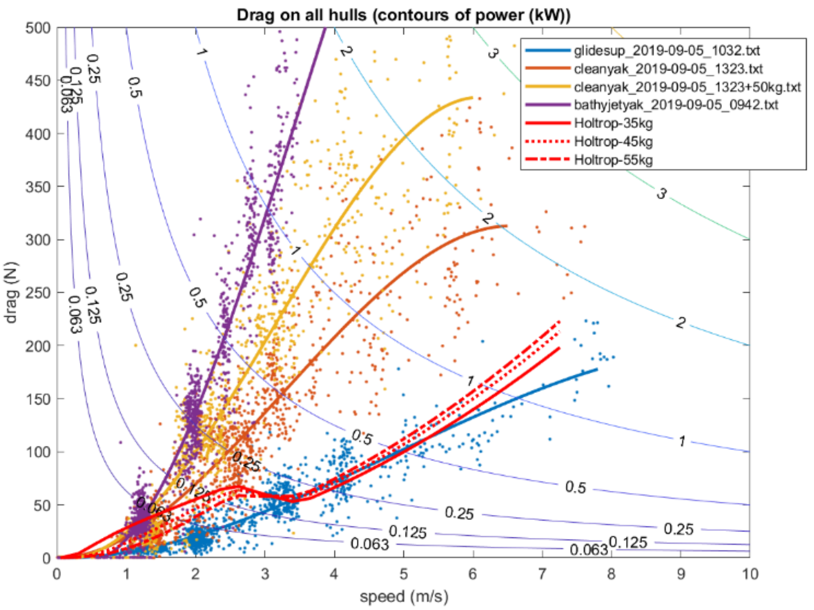

Figure 6. Tow tests drag as a function of speed for a variety of USV hulls.

These tow tests indicated we should design or obtain hulls with the minimum drag possible which is usually optimized by reducing width given the constraints on length for maneuverability and easy launch and recovery in the surf zone.

4.3. Hull and drive system design

Based on an anticipated power requirement from the tow test of 200 to 1000 watts for speeds ranging from 2 m/s to 5 m/s and an assumed efficiency of approximately 50%, a battery of at least 3 kWh would be required to attain run times of approximately 6 hours at 3 m/s. While it is possible to design a custom battery pack with the exact required specifications, a commercial off the shelf (COTS) marine rated 3.5 kWh LiNMC battery pack was available from Torqueedo with a long and narrow form factor that was well suited to the anticipated hull design. While a long hull typically has less drag in displacement mode due to the hull speed $V_{hull} = 1.3\sqrt{L_{wl}}$, where L_{wl} is water line length, the hull length was set at 3 m for ease of transportation, launch and recovery resulting in a hull speed of 2.25 m/s. This is just above the optimum survey speed of 2 m/s for bathymetric sidescan data acquisition based on previous experience with the Jetyak USV. The beam was set to the minimum required hold for the battery in the central portion of the hull. With the length and beam parameters set, the Orca3d Naval Architecture software hull design assistant was used to design a displacement hull, with an additional design feature of a fine bow for wave piercing to minimize pitch motion in short period seas and a relatively flat tail section for compatibility with a jet drive propulsion system. The bottom of the hull had a wide flat section to keep the battery low and for ease of mounting instrumentation. This combined with the flat tail and high power-to-weight ratio allows occasional planing to avoid breaking waves.

Jet Drive System: Based on the good performance of the 52 mm diameter impeller jet drive system form MHZ watercraft with a 5.8 kW maximum power brushless DC motor, the next available size larger jet drive and motor system (64 mm diameter jet drive, 22.4 kw max power) was chosen for the larger 3 m vessel. The motors are oversized for survey speeds but allow rapid acceleration for launching through the swash and longevity compared to an undersized motor which could endure thermal stress and failure during periods of high loads. The motor, jet drive, steering servo, and motor controller were all enclosed in an aluminum box that would fit into the stern of the composite hull and allow exchange of the jet drive system for a propeller drive system. This could result in greater efficiency but potentially more issues with safety during launch and recovery and failure due to running aground.

The hull design with the battery (red) and jet drive module (light grey) is shown in Figure 7a. The flotation above battery was designed using the stability analysis tools of Orca3d to ensure passive self-righting

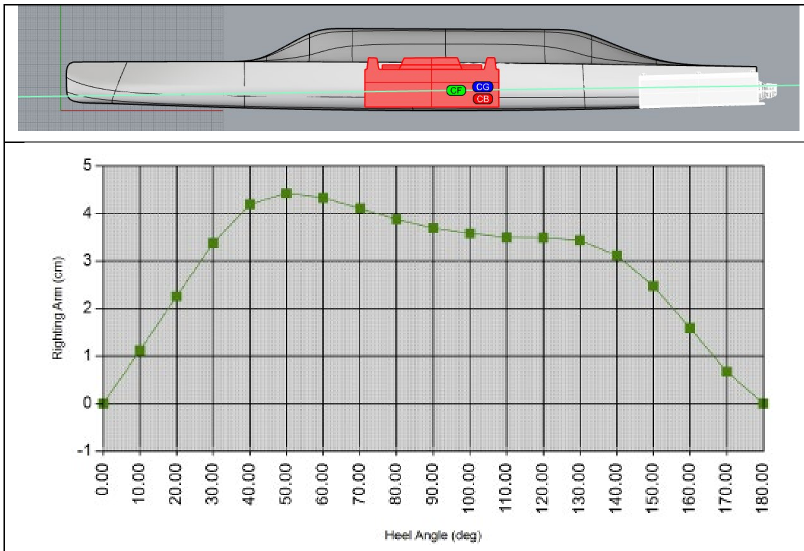

Figure 7. Hull design and predicted waterline B) Righting arm as a function of roll angle

dynamics at all roll angles (Figure 7b) where a positive righting arm indicates tendency to self-right.

4.4. Hull construction and lamination

The hull was constructed using a foam core composite skin construction technique, which is ideal for single build prototyping as it avoids the expensive mold manufacturing procedure typically associated with hull manufacturing. The foam core was manufactured in a large scale 3-axis CNC machine. The skin was laminated with innegra-basalt (IB) cloth and West Systems Epoxy resin. The IB cloth is characterized by higher stretch and breaking resistance than carbon fiber which leads to high impact resistance and has been used extensively in the white-water kayaking canoeing custom boat market where impacts with rocks are common. Test panels that we constructed with three layers of 8.8 oz/yard cloth of both carbon and IB showed triple the impact resistance before fracture for the IB as measured by a drop test with a 10 kg steel wedge. Additional details of the construction methodology are available in the video in supplementary material or online at https://youtu.be/U6vrFZQBv50

4.5. In-Situ testing without sonar systems

For initial water testing, the system was configured without the Novatel IMU-PPK GPS system Data Acquisition PC, and PingDSP sonar. A Pixhawk autopilot was installed to test the waypoint navigation capabilities, in addition to the direct remote control. The initial test was conducted in a calm harbor in Falmouth, MA. After some steering PID parameter tuning, the waypoint navigation performed similarly to the smaller SSV with cross track error less than 1m except in the vicinity of turns at the waypoints (Figure 8a). The minimum turn radius in remote control mode was approximately 3 to 4 m due to the longer hull length than the SSV. Due to the powerful motor the vessel could rapidly accelerate to a speed of 5 m/s in 4 seconds with roughly constant acceleration over that speed range. This speed change transitioned from the displacement mode to a planing mode (Figure 8b&c).

Maximum speed at full throttle was not tested, but at slightly over half throttle on the remote control the vessel would travel at 8 m/s on a full plane. This should be adequate for surf zone operations. Electrical power consumption at a variety of speeds was monitored for brief periods due to the 12-minute maximum logging interval on the internal recording of the power supply. Power as function of speed is shown in Figure 9. The large red dot represents the mean of a 12-

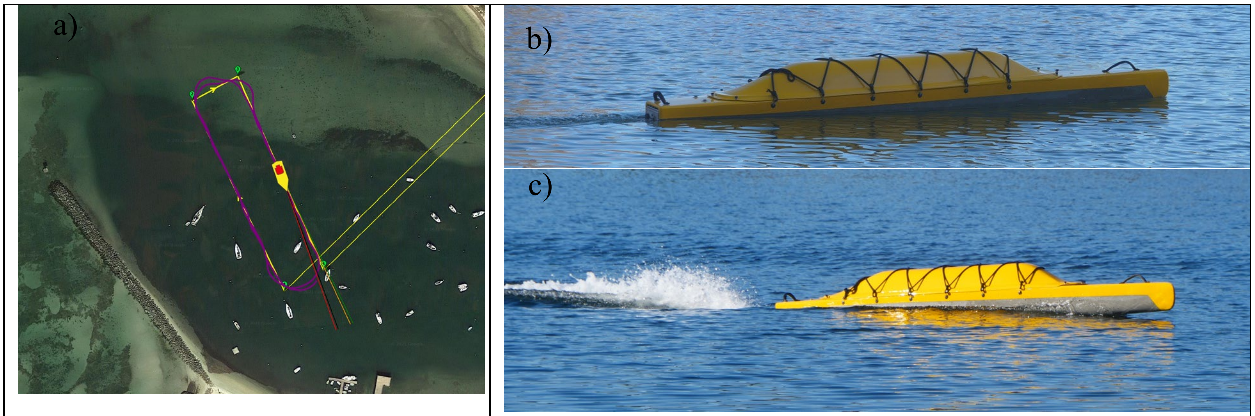

Figure 8. a) Track of 3m USV in waypoint navigation mode during initial testing, b) Vessel operating in displacement mode at 2 m/s, c) Vessel operating in planing mode at 5 m/s

minute run at constant survey speed of 2.2 m/s. Based on this with 3500 kWh battery discharged to 90% the system should have 3.7 hour endurance at surveys speeds. The endurance with the sonar sensor will be slightly less due to the electrical load of the sensor and data system (~ 40 watts) and additional hydrodynamic drag. Generally the power (*P*) appeared to vary linearly with speed (*U*) with a best fit model of *P*=372*U*, where the fit was forced to go through *P*,*U*=0,0. There was considerable scatter around the fit with prediction bounds of +/- 450 for a predicted observation with 95% confidence bounds. The predictions from the Orca3d modes were fit to the data by scaling the mechanical power (Drag * Speed) by an assumed propulsion efficiency. The default value for this in Orca3d is 50% for typical propeller-based drive systems, thus the scaling coefficient would be 2. In order to fit the Holtrop model to the data with the Jet Drive propulsion system in the displacement speed regime a scaling coefficient of 10.9 indicating a 9% efficiency for this system is needed. The planing model was fit with a coefficient of 3.6 indicating an efficiency of 28% at higher speeds.

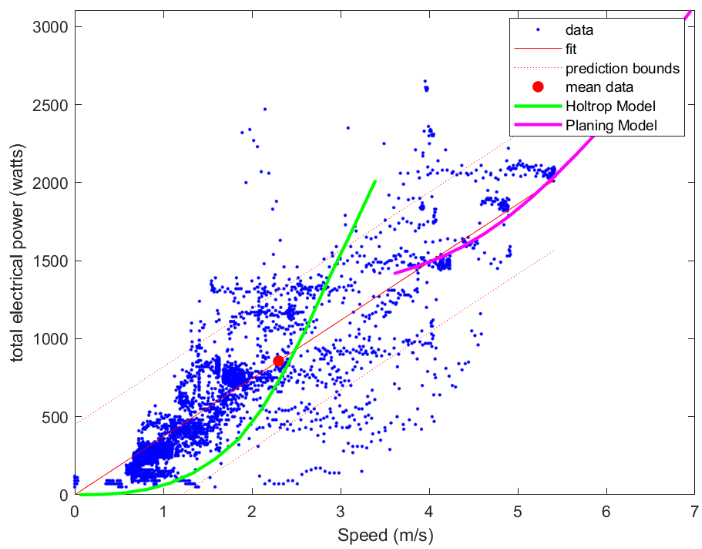

Figure 9. Power as a function of speed and Orca model results

The Holtrop model was assumed to correctly predict mechanical power since it was validated with measurements with a similar but slightly longer hull shape of the Glide-SUP. A propellor based drive system is under development for a situation where greater efficiency is needed; however, for surf zone operations where running aground is common and operation safety during launch and recovery is essential a jet drive has many advantages. A more recent test of power consumptions with the PingDSP sonar installed results in a best fit *P*=445*U*, indicating endurance will only be slightly worse, at 3.5 hours, with the sonar installed and running.

4.6. PingDSP 3DSS bathymetric sidescan sonar target detection and bathymetric survey

4.6.1. Bathymetry

After the initial tests of the navigation controller and power consumption for the PingDSP 3DSS interferometric sidescan, the Novatel dual antenna PPK GPS/IMU system and data acquisition PC was installed (Figure 10). Specifications of sonar can be found at https://www.pingdsp.com/3DSS-DX-450. Testing of the system's ability to collect bathymetric and sidescan data for target detection was conducted in calm conditions at a beach with a gentle sloping bottom in Woods Hole, MA.

The system was carefully measured to enter geometric offsets between the IMU, GPS antenna and sonar head. These sensors are mounted in a fixed location thus they will not vary from survey to survey. In particular, the IMU was mounted directly above the sonar with riding G10 composite post connecting the hull to the IMU to allow no flex in this region of the hull. The bathymetry data was of a similar quality to data collected with the Jetyak USV with the same sensor. Roll artifacts and seams between survey lines were generally not visible in the final processed data after some small corrections for sonar mounting position were accounted for using the patch test utility in the Chesapeake Technology SonarWiz sonar data software processing suite (Figure 11).

Figure 10. A) PingDSP 3DSS Mounted on the bottom of the hull and B) the dual GPS antennas of the upper surface.

The lateral extent of the processed data was limited to 8 times the water depth (± 4 x on either side of the sonar) which eliminated noisy data between 8 x and 12 x. The data was gridded at 1 m resolution but could support resolution up to 15 cm based on experience with the Jetyak USV. With alternative processing schemes that have less averaging raw point clouds could be exported with the potential to resolve the 3-D structure of surrogate UXO targets. Larger rocks in the NW corner of the survey were well resolved in the 1 m resolution gridded data.

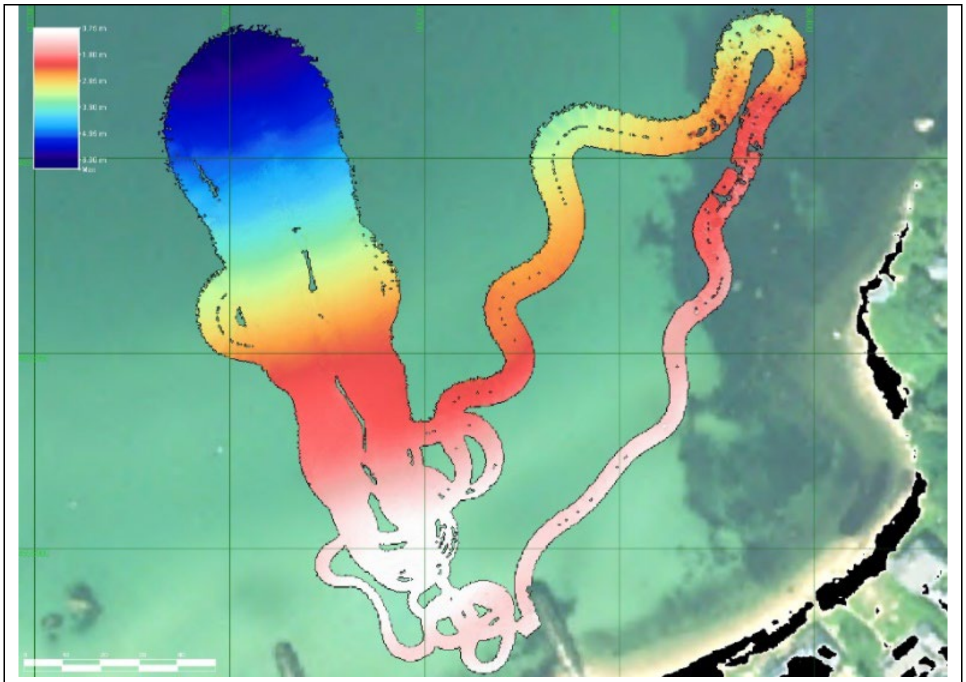

Figure 11. Gridded bathymetry results

4.6.2. Target Detection

A hollow stainless-steel cylinder (75 cm long, 14 cm diameter, 6.35 mm wall thickness) was deployed in 2 m water depth to evaluate the system's ability to detect a UXO-like target exposed on the seafloor. The intensity from the raw 3d points detected by the sonar was initially examined in the 3dss display software that is provided by PingDSP, which operates in a 3-d waterfall plot mode with correction for pitch and roll but not geographic position or heading. A cluster of high intensity pixels with an aspect ratio that resembled the target was occasionally seen in the data when the USV was passing the location of the target. In the data presented in Figure 12a, the target was located 15 m broadside to the vessel or well outside of the region where accurate reconstruction of the seafloor geometry is possible (~ 10 m based on 10 x coverage in 2 m water depth). While the aspect ratio (1.54 / 0.37) is consistent with the known target dimensions, the dimensions inferred from the sonar are twice the actual dimensions, perhaps due to beam spreading or inaccurate localization of the returns at these shallow angles. After geolocating the 3-D intensity data in SonarWiz an interesting pattern was revealed. The target was clearly visible in the same location from many passes if the target was oriented broadside to the direction of the pings from sonar. At angles greater than approximately 20° off broadside the intensity of returns from the target was not visible above the background returns from the seafloor (Figure 12b). Future work will include passes from a greater variety of angles at closer ranges and with filled, more geometrically complex targets.

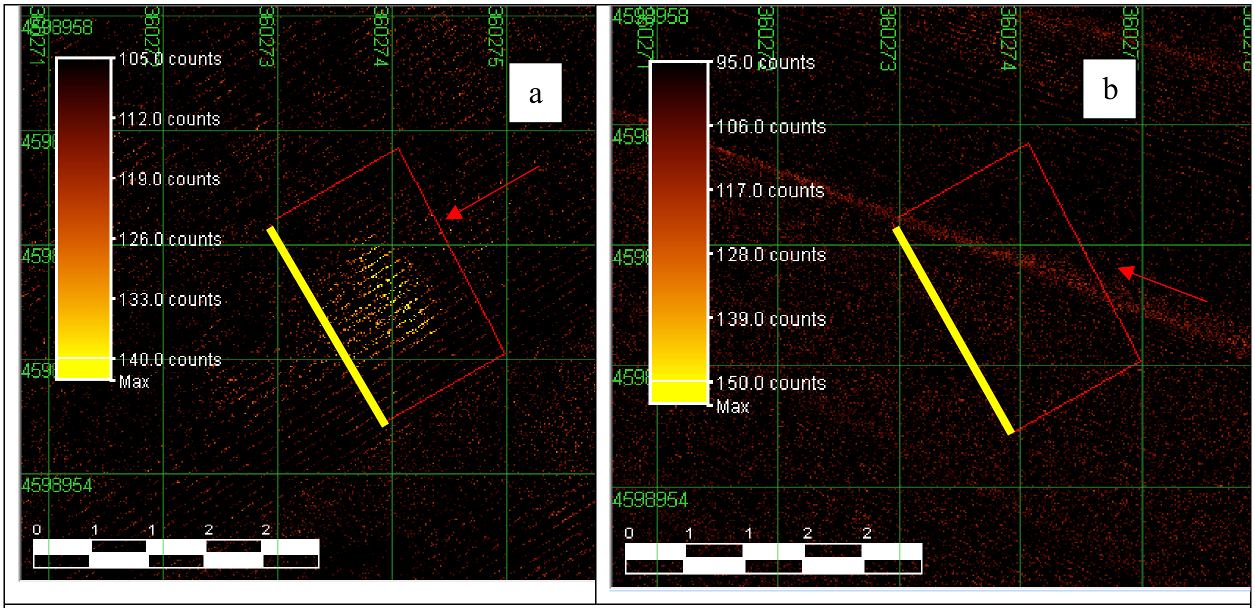

Figure 12. PingDSP 3DSS acoustic returns from a steel cylinder from two different incidence angles (As indicted by the red arrows) with red box in the same location. In (a) the pings are oriented almost perfectly perpendicular to the long axis of the target as indicated by a yellow line, while in (b) the orientation is close to 60 degrees.

5. Conclusions and Implications for Future Research/Implementation

The work completed in this SEED project and in the previous MR-1490 project indicate that USVs are capable of launch, recovery and navigation in surf-zone conditions through a combination of direct remote control by the operation in the swash and autonomous waypoint following modes in regions of intermittent breaking. Smaller single person portable USVs (1.7 m long, 10 kg, Small Surf Vessel - SSV) have been proven to obtain high quality single beam echosounder data with vertical accuracies of under 10 cm.

As part of the SEED project a larger (3 m long, 55kg) USV was developed that is capable of carrying a bathymetric sidescan sonar such as the PingDSP 3DSS. Initial testing of this system in calm sea conditions indicated similar performance in autonomous waypoint navigation modes as the SSV and similar bathymetric data acquisition capabilities as the proven Jetyak USV. The 3DSS sensor was also used in calm sea conditions to detect an unburied steel cylinder with results that indicated a strong dependence of the angular orientation of the cylinder relative to the acoustic ray paths. Future work will examine the larger USVs navigation and data acquisition performance in surf-zone conditions. Based on the success of the SSV in acquiring zone bathymetric data, a transition to a platform that is easier to manufacture is underway via a different project, and commercialization is being considered.

Appendices

Technical Publications:

Holly Francis, Peter Traykovski; Development of a Highly Portable Unmanned Surface Vehicle for Surf Zone Bathymetric Surveying. Journal of Coastal Research 2021; doi: https://doi.org/10.2112/JCOASTRES-D-20-00143.1

References:

[1] P. Kimball *et al.*, "The WHOI Jetyak: An autonomous surface vehicle for oceanographic research in shallow or dangerous waters," in *2014 IEEE/OES Autonomous Underwater Vehicles (AUV)*, 2014, pp. 1–7.

[2] H. Francis and P. Traykovski, "Development of a Highly Portable Unmanned Surface Vehicle for Surf Zone Bathymetric Surveying," *J. Coast. Res.*, 2021.

[3] J. P. Dugan, W. D. Morris, K. C. Vierra, C. C. Piotrowski, G. J. Farruggia, and D. C. Campion, "Jetski-Based Nearshore Bathymetric and Current Survey System," *J. Coast. Res.*, vol. 17, no. 4, pp. 900–908, 2001.

[4] W. A. Birkemeier and C. Mason, "The Crab: A Unique Nearshore Surveying Vehicle," *J. Surv. Eng.*, vol. 110, no. 1, pp. 1–7, Mar. 1984.

[5] T. Crandle, M. Cook, G. Cook, and E. Celkis, "SurfROVer: An ROV designed for traversing the littoral zone," in *OCEANS 2017 - Anchorage*, 2017, pp. 1–4.

[6] E. Bovio, D. Cecchi, and F. Baralli, "Autonomous underwater vehicles for scientific and naval operations," *Annu. Rev. Control*, vol. 30, no. 2, pp. 117–130, Jan. 2006.

[7] J. D. Nash *et al.*, "Autonomous CTD Profiling from the Robotic Oceanographic Surface Sampler," *Oceanography* , vol. 30, no. 2, pp. 110–112, 2017.

[8] J. Moulton *et al.*, "An Autonomous Surface Vehicle for Long Term Operations," in *OCEANS 2018 MTS/IEEE Charleston*, 2018, pp. 1–10.

[9] M. C. L. Patterson, A. Mulligan, and F. Boiteux, "Safety and security applications for micro-unmanned surface vessels," in *2013 OCEANS - San Diego*, 2013, pp. 1–6.

[10] F. M. Jaffre, P. Traykovski, M. Moulton, G. L. Lawson, and T. C. Austin, "Development of underwater acoustic backscatter and Doppler instruments from a small and versatile multi-frequency sonar board with software defined processing," in *OCEANS 2015 - Genova*, 2015, pp. 1–6.