AUTONOMOUS KAYAK PLATFORM AND BATHYMETRIC PERFORMANCE SURVEYING NEARSHORE STORM RESPONSE

by

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ABSTRACT

Autonomous platforms are at the forefront of science, particularly the marine sciences. Researchers deploy autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASVs) to answer many research questions in areas or conditions not conducive to manned systems, particularly in bathymetric and habitat mapping. However, these systems are usually expensive and highly technical. This project explores the possibility of using-off-the-shelf, recreational grade autopilots and parts to build a low-budget ASV, then evaluates the capabilities of such a vehicle.

A Delaware SeaGrant project, Coastal Imagery for Resiliency (CI4R), proposed the use of an ASV as a nearshore bathymetric survey tool, particularly in response to storm events. An autonomous kayak comprised of off-the-shelf materials, a hobby grade autopilot, and a consumer grade fish finder was evaluated for bathymetric survey performance. A kayak hull creates a stable platform but when powered by a trolling motor, proved to be limited in the conditions that it can operate in. The resolution of the consumer grade combination side-scan, echo sounder fish finder was found to be coarse. This platform deployed in a storm response capacity, surveying pre- and post-storm surveys for two nor'easter storm events on Broadkill Beach, Delaware. Despite the coarse resolution, the autonomous kayak resolved changes in the nearshore bathymetry of Broadkill Beach caused by storm events and proved to be an effective research platform.

Chapter 1

EVALUATING THE BATHYMETRIC SURVEY CAPABILITY OF A LOW COST AUTONOMOUS SURFACE VEHICLE

1.1 Introduction

Autonomous surface vehicles (ASV) emerged as research platforms both in the scientific and commercial communities in the past decade (Kimball et al., 2014)[15]. Limitations of other survey methods such as traditional survey vessels with deep drafts, autonomous underwater vehicles designed for deeper missions, or expensive Bathy/Topo LiDAR surveys incapable of penetration turbid conditions lead the scientific and government communities to turn to autonomous platforms (Ferreira et al., 2009)[16]. Many different purpose built ASVs exist in the market, however they often cost as much or more than the instrument payload they carry (Valada et. al 2014)[14]. As a result, low-cost autonomous research platforms have become increasingly prevalent in the marine sciences. Their uses include but are not limited to bathymetric mapping, habitat mapping, water quality data collection (Ferreira et al., 2009)[16]. As these platforms become more a commonplace standard, the performance of the platforms as well as the quality of the data they produce requires evaluation.

This chapter examines the components and cost of overhauling an existing autonomous surface vehicle comprised of "off the shelf" parts and evaluates the performance of the platform in the context of shallow water bathymetric surveying and side-scan surveying. In this chapter, first the components of the platform are addressed and priced. Several field tests evaluated the performance of the platform including testing the autopilot performance and then the instrument including accuracy, resolution, and the effects of motion.

1.1.1 Autonomous Surface Vehicles

While several turn-key ASV solutions to nearshore surveying exist, the price of the platform can exceed the price of the instrumentation. Small form factor shallow drafted ASVs such as Seafloor Systems' EchoBoat-ASV, Teledyne Marine's Z-Boat 1800, ASV Global's C-Cat 2 advertise sensor integration and "no assembly required," however the cost of these systems start at $15,000 and can be much more expensive depending on the level of autonomy and instrumentation. While the "turn-key" functionality offers benefits, academics and researchers also turn toward low component cost consumer grade platforms.

"Do it yourself" (DIY) purpose built autonomous surface vehicles have been built by various entities for various applications. Woods Hole Oceanographic Institute (WHOI) developed the Jetyak as oceanographic/bathymetric survey platform. This gas motor jet-drive kayak uses an automated winch for water column profiling, bathymetric and side-scan sonar, and an acoustic doppler current profiler (Kimball, 2014)[15]. At the Robotics Institute, Carnegie Mellon, a team developed very small form factor autonomous fan boats operated with smart phone technology to perform swarm interacting surveys (Valada et al., 2014)[14]. Autonomous Systems Laboratory (ASL) from Porto Polytechnic Institute (ISEP) built the catamaran ROAZ II for shallow water bathymetric and photogrammetric surveying (Ferreira et al., 2009)[16]. One of the first low-cost shallow drafted ASVs was MIT's SCOUT Kayak.

1.1.2 SCOUT Kayak

In the early 2000s, engineers and scientists at Massachusetts Institute of Technology (MIT) assembled several autonomous kayaks using a sit-in kayak as the hull and building hardware around and in the kayak to develop an autonomous surface vehicle. The SCOUT (Surface Craft for Oceanographic and Undersea Testing) kayaks were originally designed and built as an inexpensive platform to test autonomous underwater vehicle control software (Curcio et al., 2005)[10]. The SCOUT kayaks were built around Pungo 100 sit-in kayaks. With a payload of 110kg, this 3.05m long high-density polyethylene hull provides the base platform for this ASV. Three compartments divide the hull. The stern compartment houses an electric trolling motor, high torque steering servo, and water pump. The center compartment housing the control box, through-hull, power supply, and instrumentation. The control box contained the main vehicle computer. MOOS-IVP control software managed the ESC and servo to control the kayak (Curcio et al., 2005)[10].

Several of these platforms were later distributed to various research groups across the country, including the United States Naval Academy (USNA). As a part of an ongoing partnership between the USNA and University of Delaware, Dr. Joseph Smith, Professor, USNA allowed the Coastal Sediments, Hydrodynamics, and Engineering Laboratory (CSHEL) at University of Delaware to use and upgrade these SCOUT Kayaks. The first kayak to be overhauled was named Bubbles.

1.1.3 University of Delaware Kayak, Bubbles

Bubbles was repurposed and assembled in University of Delaware's Robotics Discovery Laboratory (RDL) located in Lewes, Delaware. The RDL is shared between three marine science laboratories, including CSHEL.

1.1.3.1 Hardware

Figure 1.1 outlines the major hardware components of Bubbles. Legacy hardware on the SCOUT kayak that remained operational included a Minn Kota electric trolling motor with 25kg of thrust. The stern mounted the trolling motor steers azimuthally (no rudder) with a geared high torque servo. This servo/motor combo provides a turn radius of roughly 10m.

1.1.3.2 Electrical

The center compartment houses the kayak's control box, water cooler chamber, deep cycle marine 12V battery, instrumentation, as well as a through-hull and a 12V DC automatic bilge pump. The control box contains the power distribution board, throttle controller, and throttle emergency stop relay. The power distribution board takes unregulated 12V power delivered from a deep cycle marine battery and redistributes it at various regulated voltages required for operating the vehicle. These systems include an electric speed controller (ESC), a high torque servo, the electric trolling motor, an electric water pump, a bilge pump, a computer fan as well as the autopilot and its GPS unit. The 12V deep cycle marine battery provides up to eight hours of operating time depending on the external temperature and hotel load on the battery.

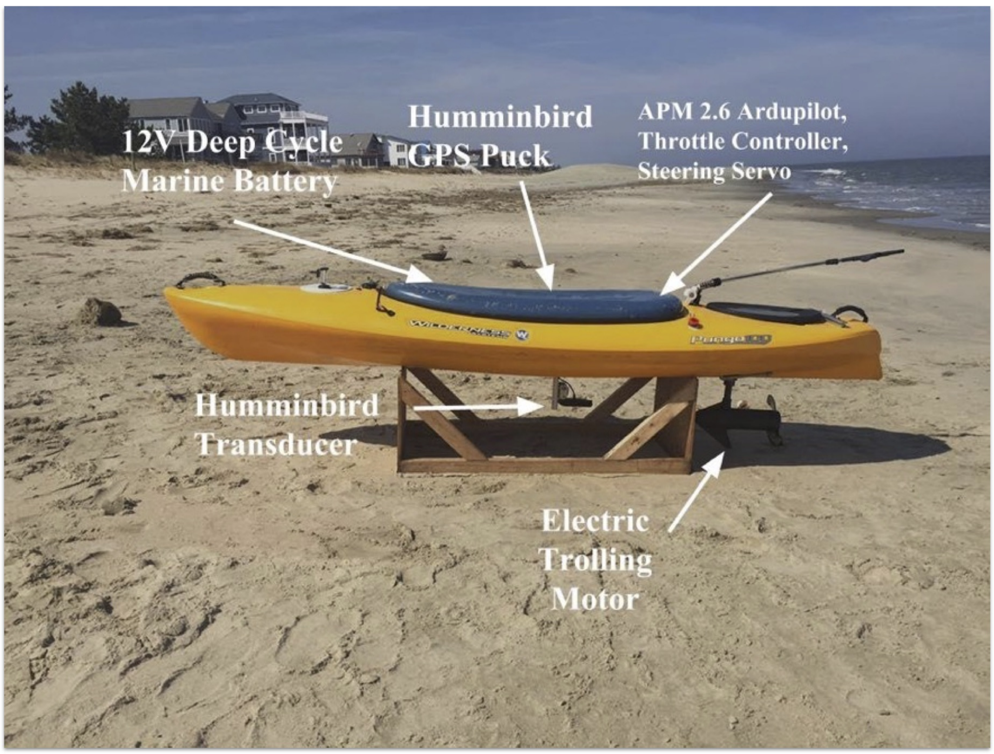

Figure 1.1: Bubbles' hardware configuration

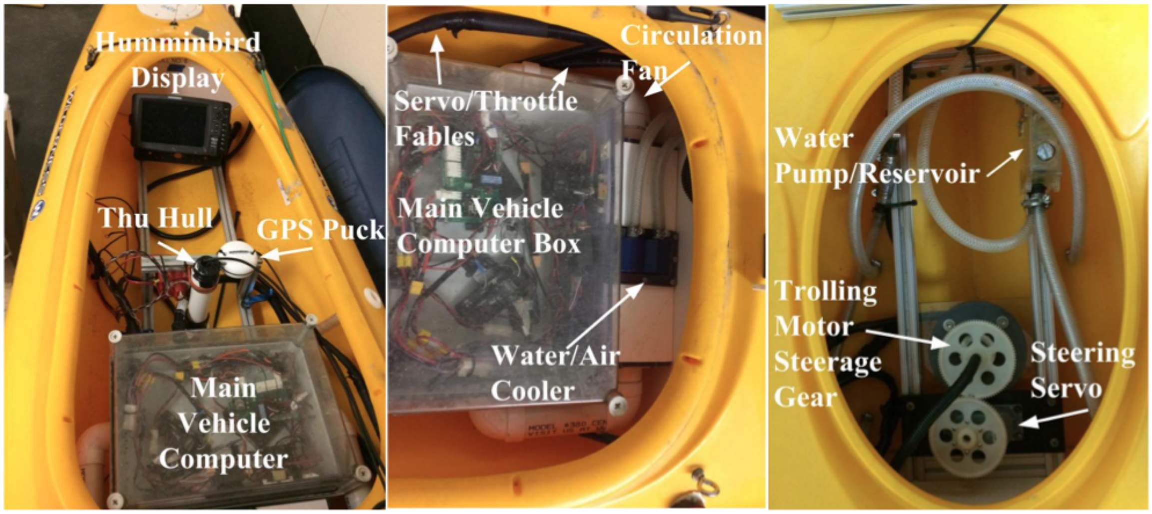

Figure 1.2: Bubbles' hull compartments and components

1.1.3.3 Autopilot

A Turnigy 9x9 Channel 2.4GHz remote control allows the user to remotely operate Bubbles directly or switch over to the. In case of a hobby remote control car or boat, the Turnigy receiver communicates directly to the ESC and steering servo, however, this system has the APM2.6 Ardupilot autopilot inline.

Several hobby autopilots exist on the market; those offered by 3D Robotics are commonly used and have a large online support community. 3D Robotics offers a hobby autopilot, APM2.6 Ardupilot that has been employed on ASVs (Kimball et al., 2014)[15]. The autopilot can be configured for multi-copter, fixed wing plane, or ground rover/boat platforms. It allows the user to control the kayak directly via a Turnigy 9x9 Channel 2.4GHz remote control or behaves as an autopilot outputting two channels of signal: a steering servo, a throttle controller (Kimball et al., 2014)[15]. A 3D Robotics Global Positioning System (GPS) feeds the APM2.6 position information, an internal compass feeds heading, and an internal gyro measures the attitude of the unit. Due to the limited memory of the APM2.6, this motion data cannot be recorded for an extended period. A 9.5GHz radio telemetry kit allows the user to interface with

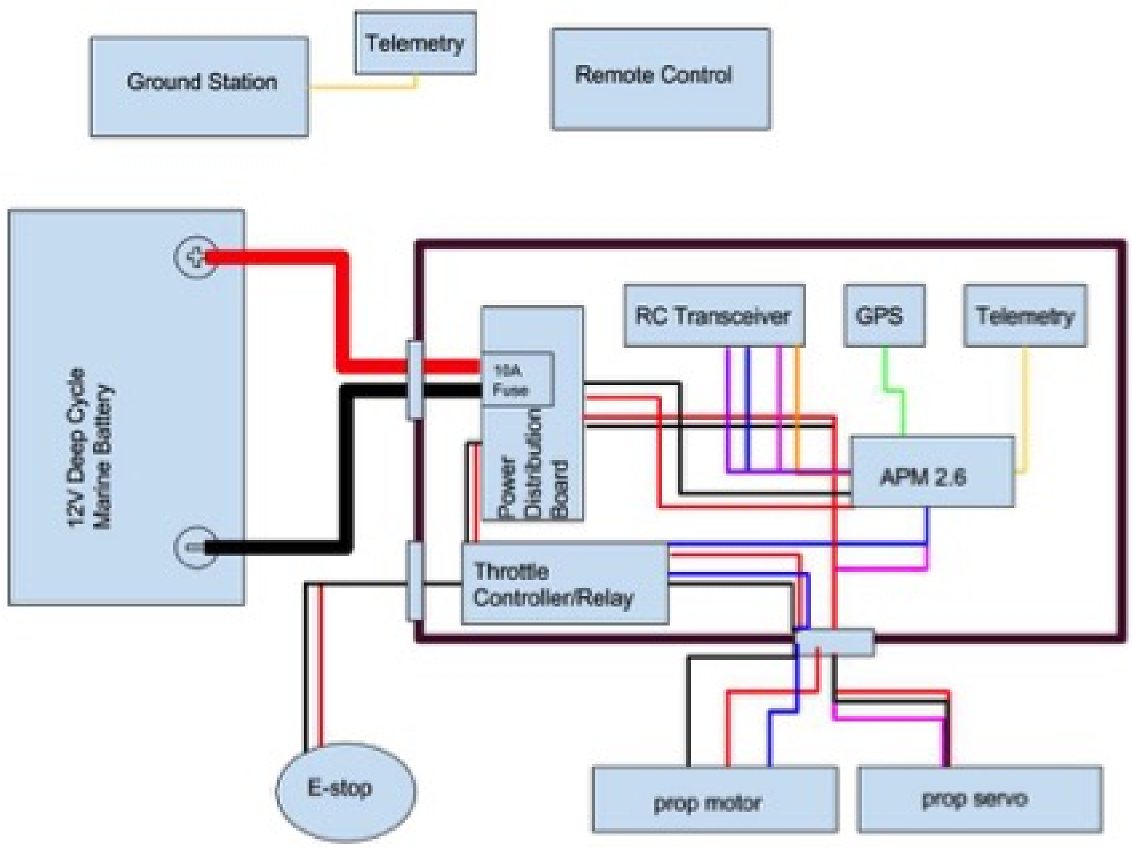

Figure 1.3: Bubbles' wiring diagram

the APM2.6 via free, open source software, Mission Planner. The radio telemetry kit transmits position, flight mode, speed, motion data, mission plans, and mission status information to the ground station computer, however the roughly 50m range of the telemetry limits this data stream. The range of 50m depends on the height of the transmitter and the antenna gain.

A shore station consists of a Windows laptop with Mission Planner software that communicates with the autopilot via a radio telemetry unit. Up to a range of about 50m, the shore station can communicate with the APM2.6 in the form of uploading/downloading missions, autopilot statuses, location, attitude, and controls. Telemetry data is recorded locally onto the laptop as long as the platform is within communication range, however the local storage capacity is limited, and if the mission extends beyond the telemetry range, the motion data is not recorded and therefore cannot be used in the post processing of data.

Major Component Costs (2016 Pricing,$US)	
APM2.6 Autopilot	$159.99
3DR GPS with Compass	$89.99
Telemetry Kit	$49.81
Controller	$199.98
Bilge Pump	$17.00
Bilge Pump wire Connectors	$7.79
Transducer/Pick Point PVC Pipe/Carabines	$34.59
Tone PS-050 Servos	$195.00
Water proof box	$20.00
Marine Cable Connections	$10.00
Marine 12V Deep Cycle Battery	$100.00
Salt Water Trolling Motor	$239.99
Pungo 100 Kayak	$699.99
Total	$1774.12

Table 1.1: Cost of major components of Bubbles, prices as of 2016.

1.2 Methods: Bubbles and Instrument Performance

1.2.1 Platform

1.2.1.1 Environmental Performance

Kayaks are stable and relatively inexpensive platforms with large payloads that make good candidates for research platforms. Because the platform is a kayak designed for a person to sit in it, it resists roll, however it has environmental limits both due to the hull itself and the limits of the electric trolling motor. The University of Delaware Boat Basin in Roosevelt Inlet provided a controlled, low traffic body of water with a range of depths and was the primary testing location for Bubbles.

On February 19, 2016, the wind in the boat basin the wind came out of the north east at 11 knots. In these conditions, the trolling motor did not provide enough thrust to bring the bow of the vessel through the eye of the wind. Therefore a 10 knot wind limit was set for field operations.

A sea-state greater that 1m presented the danger of flooding the kayak. Despite having a cover, the hull is not completely water tight and despite having a bilge pump, this is not ideal for the control box or instrumentation. For this reason, operating conditions were limited to less than 1m of swell.

Because the average speed of the kayak is 1.5m/s, more than 1m/s of current causes steerage and headway issues.

1.2.2 Autopilot Performance

One of the virtues of autonomous platforms is the repeatability of a survey. A manned vessel, particularly a manned kayak, would have a difficult time repeating the same exact survey lines for several surveys. In theory, an autopilot should be able to guide a vessel on a desired path multiple time very closely. For this test I will refer to "along track error" as the distance off course and measure the along track error of the autopilot on the kayak.

The AMP2.6 autopilot utilizes waypoint-to-waypoint mission planning. The user creates waypoint in the open source Mission Planner software and then downloaded to the APM2.6 via radio telemetry.

The user can tune the autopilot using Proportional, Integral, and Derivative (PID) tuning parameters to decrease the along track difference between the travelled and intended paths. The proportional correction is a linear response course correction. If the vessel deviates from the course to the next waypoint by a certain amount, the autopilot applies a proportional linear response to acquire the correct heading. The integral response is calculated by integrating over the past corrections. The derivative parameter is calculated by taking a derivate of the previous responses to predict what the future response will be (Araki, 2009)[3].

The 3D Robotics GPS feeding position data to the autopilot has an accuracy of $\pm$1m. The autopilot does not have a vessel file containing the dimensions of the vessel

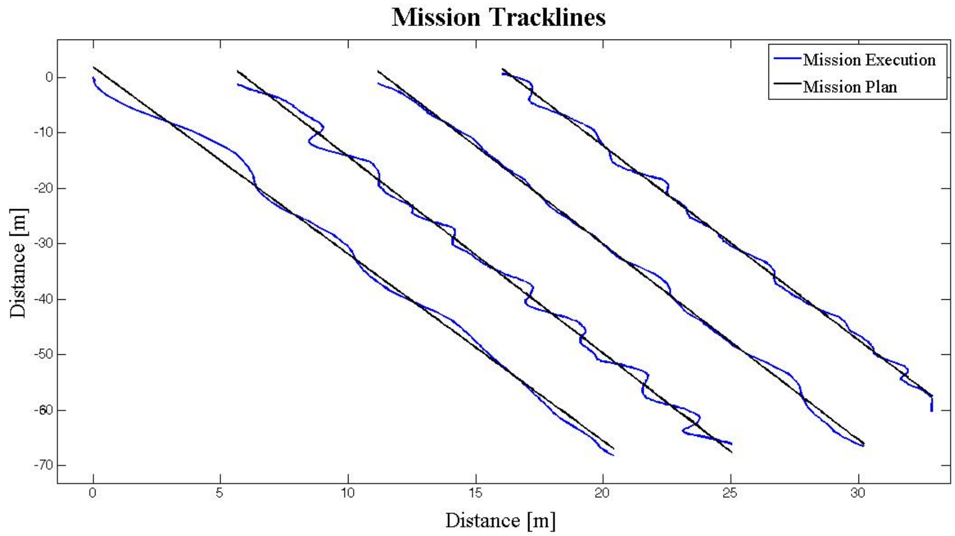

Figure 1.4: Figure 4: Average along track uncertainty of ± 1.02m.

or the speed/thrust capabilities and therefore relies on PID tuning to apply the correct thrust and directional response to steer the vessel to the next waypoint. The user can tune all three PID parameters, however the Proportional parameter was the only parameter that was adjusted for the AMP2.6 on the kayak. Tuning the proportional term via trial and error resulted in along track error of ± 1.02m. This is within 2% of the GPS accuracy without having to tune the integral or derivative parameters therefore only the Proportional parameter was adjusted.

1.2.3 Sonar

At $1000, (2016 pricing) a Humminbird 998c HD SI Combo served as the instrument package for this project. Designed as a consumer level fish finder, the Humminbird unit records side-scan imaging, depth to every 0.1m, and position to a removable SD card. The unit uses a single beam echo sounder (SBES) to measure depth, and dual-frequency side-scan sonar to record the side-scan imaging. The sonar system offers 20°, 60° or 180° coverage at 10db and sonar frequencies of 83, 200, 455, 800, and 50kHz.

Platform Performance	
Draft	0.5 m
Turn Radius	10 m
Top Speed	1.5 m/s
Payload	110 kg
GPS	±1 m
Along Track Error	±1.02 m
Condition Limits	
Wind Limit	10 knots
Wave Limit	1 m

Table 1.2: Summary of Bubbles' performance.

It assumes a fixed speed of sound in water of 1500m/s to perform the depth calculation. Correcting this calculation requires taking conductivity, temperature, depth casts with a Castaway CTD. The Castaway uses the conductivity, temperature, and depth measurements to calculate the sound velocity profile through the water column. The purpose of the project is to operate the ASV in shallow water; because surveys occur in less than 5m of water, the water column is well mixed. Therefore an average sound velocity is calculated from the sound velocity profile. This value is then used in the post processing to correct the sound velocity.

$$depth = d_{recorded} * \frac{u_{CTD}}{u_{sonar}} \tag{1.1}$$

The Humminbird unit has several different settings for the both the side-scan and the echo sounder. Vince Capone, Black Laser Learning, has extensive experience with recreational grade sonar systems in science, military, and law enforcement applications, and recommended the following settings for optimal performance: echo sounder frequency at 200kHz, the side-scan 455kHz. Surveys and the experiments were carried out with these settings.

Also included with the Humminbird sonar package was a Humminbird puck GPS system with a horizontal accuracy of ±1m. This was the GPS used for the following experiments and surveys.

I evaluated the Humminbird 998c HD SI Combo for four parameters: accuracy compared to a lead line, resolution, motion degradation, and side-scan quality.

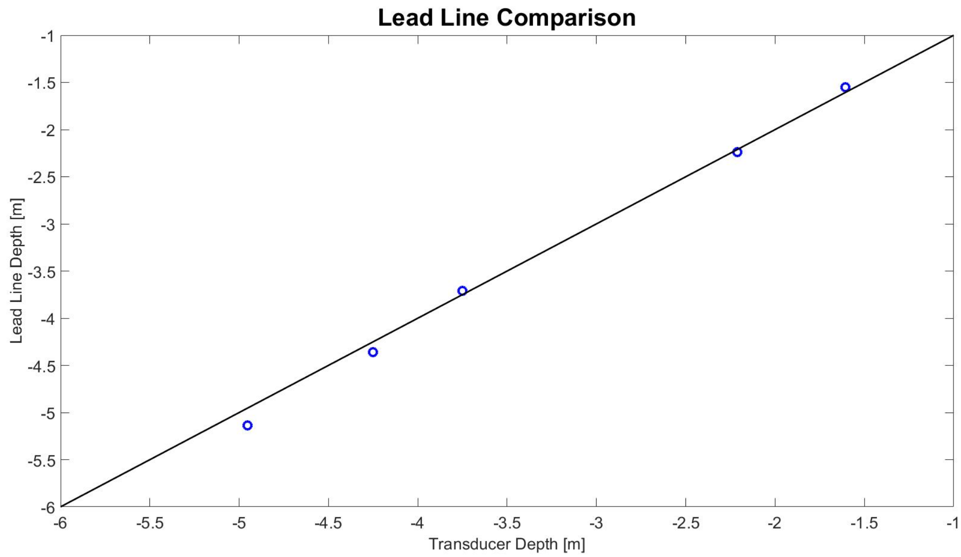

Figure 1.5: Lead Line Comparison: the average percent error comparing the transducer depth to lead line depth is 2.4%. The black line represents unity. Lead line is accurate to 0.5cm.

1.2.3.1 SBES Accuracy

The SBES recorded depth was compared to depth recorded with a weighted line (lead line) to determine the accuracy of the Humminbird system. The University of Delaware Boat Basin provided a range of depths to compare the lead line to the Humminbird unit. The Humminbird was mounted 0.3m below the waterline of the kayak (Figure 1.1). The Humminbird recorded the depth continuously for two minutes at five different depths. During each two minute interval, the depth was recorded with a lead line. This process was repeated at 1.5m, 2.25m, 3.75m, 4.25m, and 5m water depths. CTD casts recorded sound speed profiles to correct the Humminbird sound velocity. The recorded Humminbird depths were sound velocity corrected, corrected to the water level, then averaged over the two minutes. This average depth was compared to the weighted line measurements. There was an average of 2.4% difference between the two measurement methods. In Figure 1.5, the black line represents unity, or perfect 1:1 matching between the lead line measurements and the transducer measurements. The depths are sound velocity corrected: the unit assumes 1500m/s, the measure sound velocity in the boat basin was 1516m/s. Lead line is accurate to 0.5cm.

Weighted Line [m]	SBES [m] (2 min. avg.)	% Difference
5.137	4.95	3.54
4.362	4.25	2.56
3.708	3.75	1.14
2.241	2.21	1.33
1.552	1.60	3.53

Table 1.3: Weighted Line Comparison Results.

1.2.3.2 Tide Station Comparison

To test the resolution of Humminbird system, it was deployed in the boat basin over a tidal cycle and then compared to data recorded from the Lewes tide station. Located in Lewes, Delaware, NOAA maintains a water level station. The tidal station provides a reference point for comparing the SBES as well as to examine the behavior of the SBES in shallow water. The Humminbird recorded over the course of a high to low tide and vice versa in a fixed location with the ability to freely move up and down.

The kayak was fixed in horizontally, free to move vertically and recorded depth data over a high to low tide (Figure 1.6). The tidal station collects a measurement every six minutes with an accuracy of 0.02m. The Humminbird collects data on average at 12Hz, however records every 0.1m. While the Humminbird has a better temporal resolution, the tide station has a better vertical resolution.

Because there are four kilometers between the tide station and the test location, a lag in tidal signal was expected: a late high tide signal from the kayak and an early low tide signal from the kayak. A vertical offset between the tide station data and the kayak data was also expected as the tide station outputs the water level referenced to a given tidal datum (in this case Mean Low Low Water) and the Humminbird measures depth below the transducer.

The 0.1m resolution appears in the SBES data (Figures 7, 8). As depth decreased, reflections and noise became more prevalent. At a depth below the transducer 1m, the unit records multiple reflections off the bottom making the data unreliable without a filter or smoother. In the second experiment, the time lag and vertical offset between the tidal signal captured by the tide station and the Humminbird appears. The time offset was removed, and the mean was removed from both data sets to compare the signals (Figure 9). The 0.1m resolution and noise in water depths less than 1m significantly contribute to the uncertainty of the system.

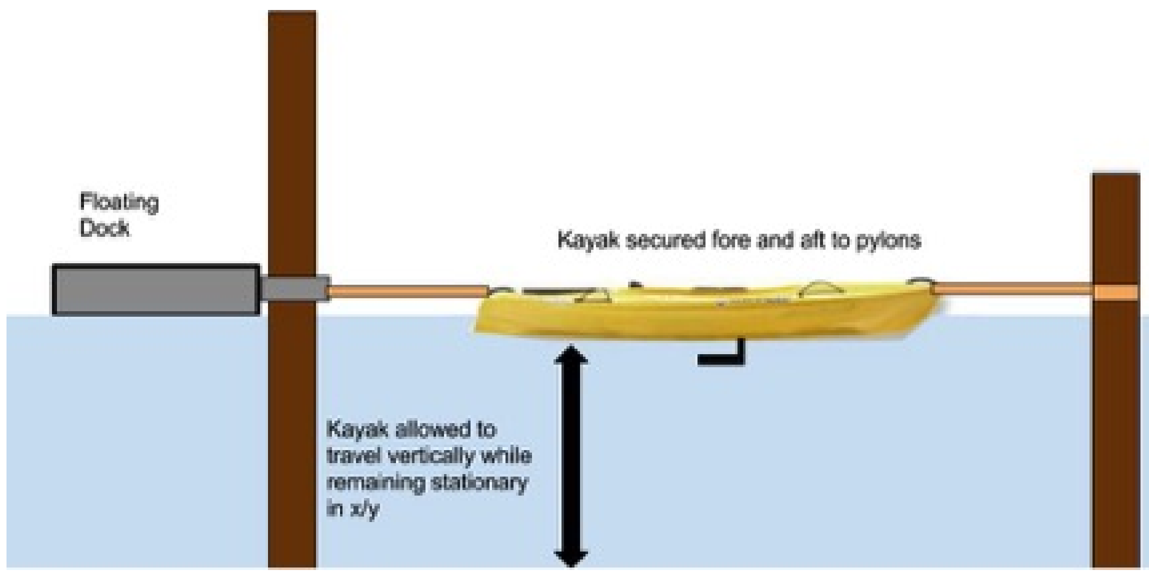

Figure 1.6: Tide test experimental set up.

1.2.3.3 Sonar and Motion

Because the Humminbird uses a single beam echo sounder, the quality of the data is can be affected by the motion of the vessel. However, because Bubbles is a low-cost platform, there is external inertial measurement unit (IMU) on board. The APM2.6 Ardupilot records motion locally but does not have the storage capacity to

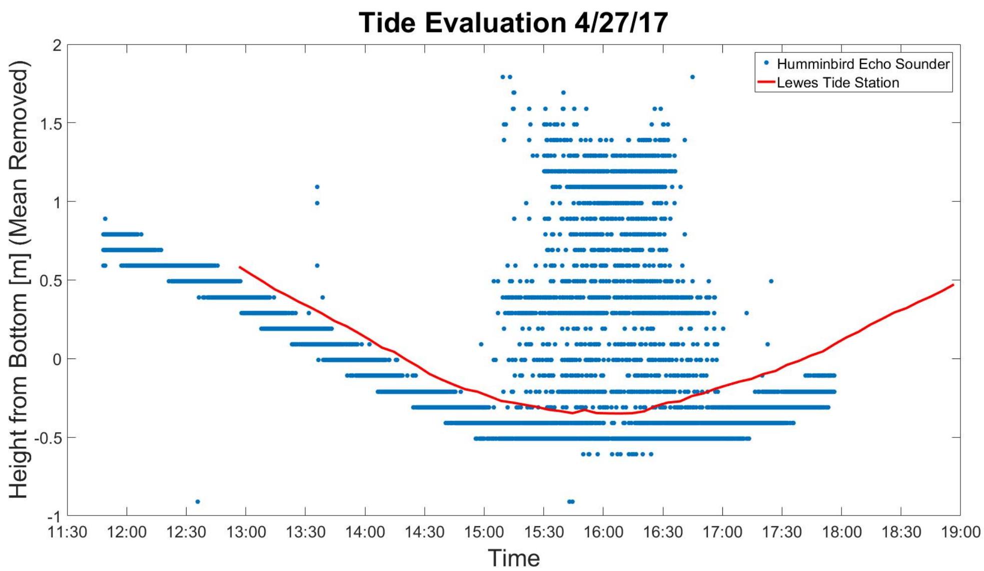

Figure 1.7: The time offset between the tide station and kayak was removed. The mean was removed from both data sets.

record the motion of the vessel for multiple hour missions. The telemetry motion data is also recorded to the shore station laptop via radio telemetry, however it does not always have the range to reach the entire mission area. For these reasons, no internal motion data was collected for correcting the motion out of the recorded sonar data. However, it is possible to examine the effect of the motion on the data in a general sense (Giordano, 2016)[20].

The Humminbird SBES has a 20° beam angle at 10dB. Because the transducer faces down, motion, either roll or pitch, will cause the beam to reflect off of the sea floor at an angle, thus increasing the recorded "depth". The resolution is 0.1m, therefore using Equation 1.2, the maximum motion required to affect the quality of the data can theoretically be calculated. Table 1.4 shows examples of the theoretical effect of a 20° roll on the single beam data at various depths. It requires more than a two meter water depth before the Humminbird would theoretically be able to record noise in the data due to roll or pitch. This is important in determining what weather and sea state conditions are no longer favorable for data collection, not only because of the limitations of the vessel, but the effect of the conditions on the data quality.

$$depth = d_{sonar} * cos(\alpha) \tag{1.2}$$

Depth Recorded [m]	Roll Angle (degrees)	Correct Depth [m]	Difference [m]
0.5	20	0.47	0.03
1	20	0.94	0.06
2	20	1.89	0.11
3	20	2.82	0.18
4	20	3.76	0.24

Table 1.4: Theoretical motion effects on SBES data.

Figures 1.9 and 1.10 plot the effect of the motion of the vessel on the data. In Figure 1.9, the Humminbird sonar was mounted onto the kayak and the vessel was still in a single location. The roll (in red) and pitch (in green) are relatively constant. Note the ±0.1m noise that occurs while the kayak remained still. Next (Figure 1.10), the kayak was rolled (motion in degrees in red) and pitched (motion in degrees in green). The depth (in blue) remains largely unaffected by the motion of the vessel. The Humminbird resolution masks the effect of motion on the echo sounder, negating the need for correcting the roll or pitch of the vessel.

1.2.3.4 Side-scan Target Identification

In addition to the SBES, the Humminbird 998c HD SI Combo records side-scan sonar imaging. This data can be useful for habitat mapping and underwater target location/identification. To evaluate the quality of the side-scan sonar, it was deployed over a known feature that had been previously mapped with a high-resolution survey-grade interferometric/side-scan sonar unit. The Edgetech 6205 Combined Bathymetry and Side-scan Sonar provided a high-resolution point of comparison.

A shipwreck, the W.R. Grace, lies a few hundred meters off the Cape Henlopen State Park Beach in Lewes, Delaware. The wreck provides an area just deep enough

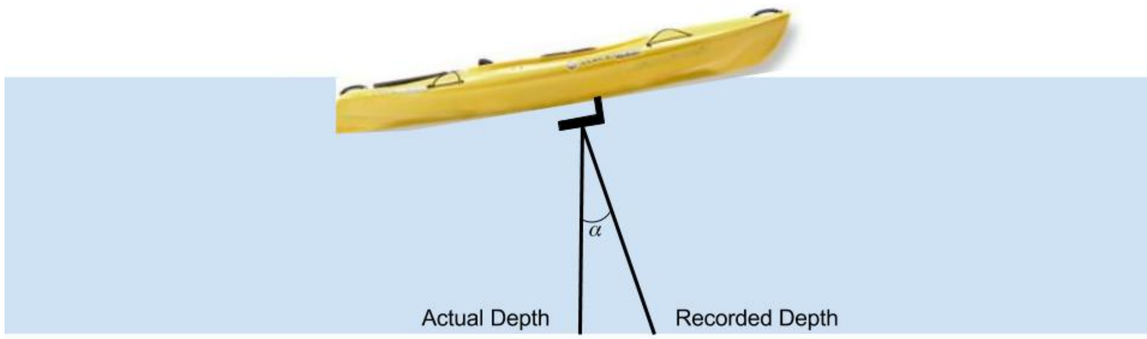

Figure 1.8: The effect of vessel motion on single beam echo sounders (Giordano, 2016)[20].

for an Edgetech 6205 phase differencing bathymetric/side-scan survey unit mounted on a research vessel R/V Joanne Daiber to survey. The wreck is also close enough to shore for the autonomous kayak to be launched from shore and survey.

The W.R. Grace, a 65m shipwreck, lays 170m off the northern beach of Cape Henlopen State Park. The Grace was located from previous surveys done with an Edgetech 6205 sonar unit. Using these previous surveys, GPS coordinates of the bow and stern of the wreck were located. A mission was drafted using these points for reference. Taking into account the limited spatial resolution of Humminbird unit, a 100m^2 polygon with 5m line spacing was chosen in order to resolve the 65m shipwreck which lay diagonally in the polygon. On the survey day conditions were ideal for small

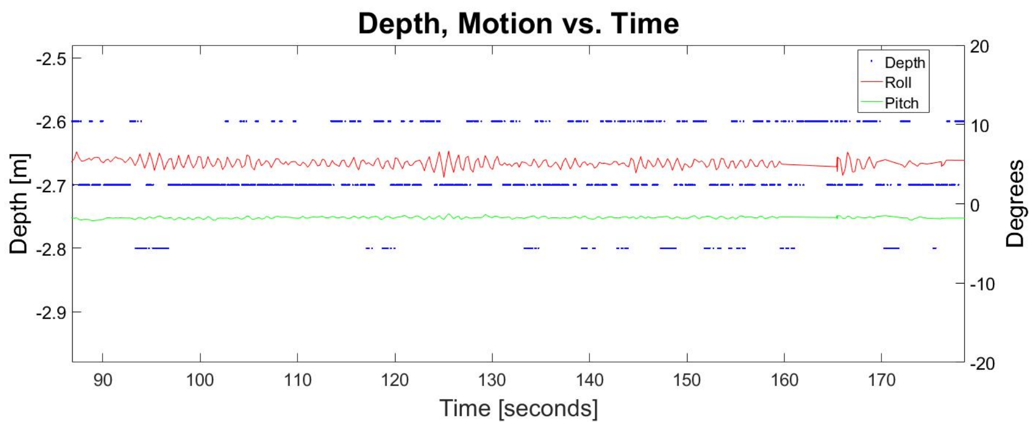

Figure 1.9: No vessel motion: red denotes roll, green denotes pitch, blue denotes the recorded depth.

vessels: the sea state was glassy with less than 0.5m swell and less than 10 knots of wind. There was a 1m/s current flowing from north to south parallel to our mission lines. The kayak was launched from the beach, performed a two hour survey, then was recovered on the beach.

SonarWiz, sonar-processing software by Chesapeake Technologies, was used for post processing of the side-scan sonar data.

Bathymetry and side-scan data collected on October 14, 2015 with the Edgetech 6205. The wreck is very distinguishable in the Edgetech data (Figure 1.11). The Humminbird side-scan resolved the wreck, however the image is distorted, an artifact due to the kayak turning as it passed over the wreck (Figure 1.12). There is a noticeable "swerve" in the Humminbird side-scan data due to the motion of the kayak. Despite the motion, the Humminbird side-scan resolved the wreck, however, the 65m feature was not finely resolved. This indicates that the sides-scan imaging may not produce the resolution required to examine ripple bed forms or other small scale morphological features of interest.

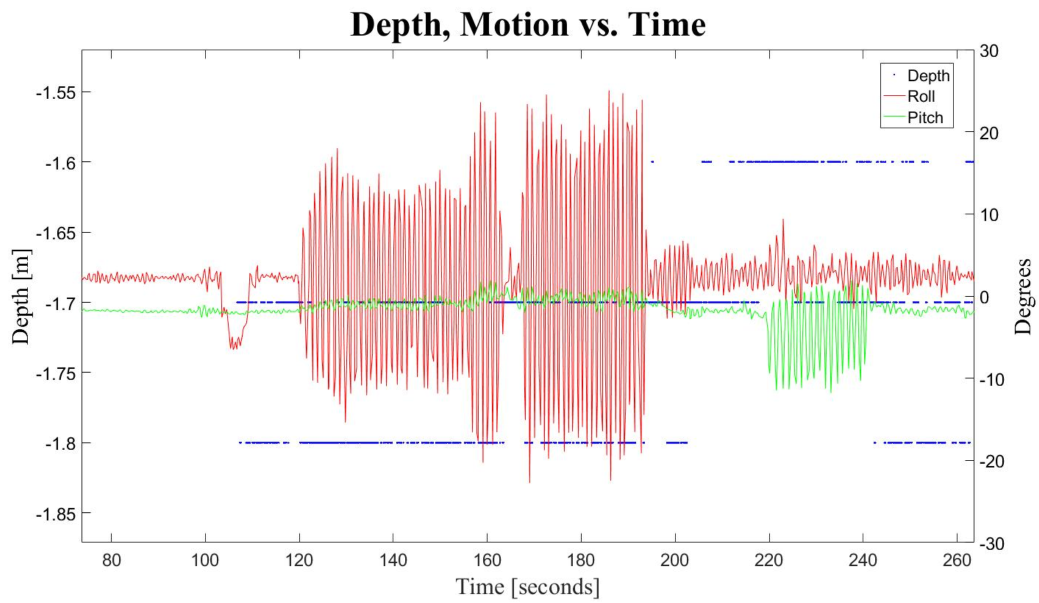

Figure 1.10: Vessel motion's effect on SBES data: red denotes roll, green denotes pitch, blue denotes recorded depth

1.2.3.5 Total Error

When using the Humminbird 998c HD SI combo as a bathymetric survey tool, vertical uncertainty comes from several sources. The first source is the 0.1m vertical resolution of the system. The system has a 2.4%∗water depth accuracy when compared to a lead line test. The Humminbird unit records data at every 0.1m. This means if the average accuracy of the system is 2.4%, it does not exceed the quantization of the system until the measured water depth is greater than four meters. There is a 0.005m uncertainty in the measurement of the vessel/instrument offsets. There is the uncertainty associated with the Castaway CTD's sound velocity profiler of 0.003m and the uncertainty associated with the Lewes tide station of 0.02m. These arise from the sound speed and tidal corrections respectively. Equations 1.3 and 1.4 show the vertical resolution is the main contributor to the vertical uncertainty in the Humminbird SBES.

The Humminbird GPS puck records the horizontal position of the system and has an accuracy ±1m.

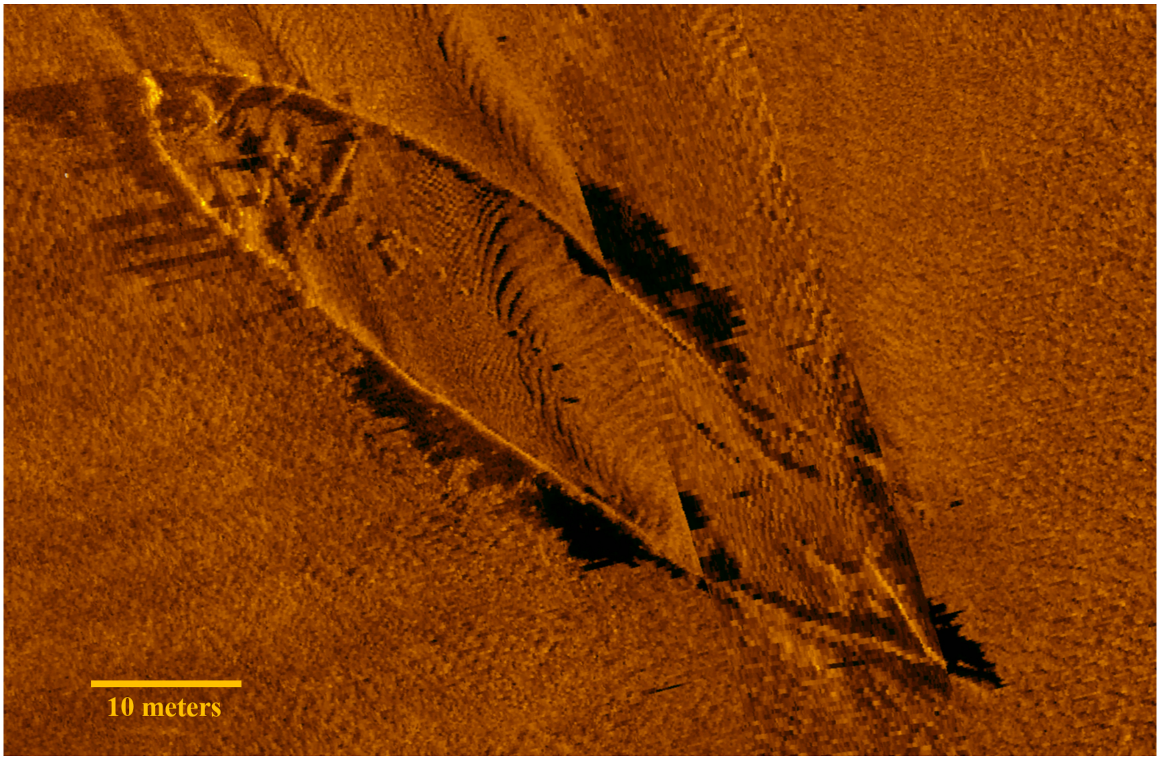

Figure 1.11: Edgetech 6205 side-scan imagery of the W/R Grace

Source	Vertical Error [m]
SBES Resolution	0.1
SBES Accuracy	0.024*depth
Vessel/Instrument Offset Measurement Accuracy	0.005
Lewes Tide Station Accuracy	0.02
Castaway Accuracy	0.003

Table 1.5: Vertical Uncertainty associated with performing bathymetric surveys with the Humminbird 998c HD SI Combo.

$$uncertainty(d) = \sqrt{(}0.1^2 + (0.024 * d)^2 + 0.02^2 + 0.005^2 + 0.003^2) \quad (1.3)$$

$$uncertainty(d = 2m) = \pm 0.11m \quad (1.4)$$

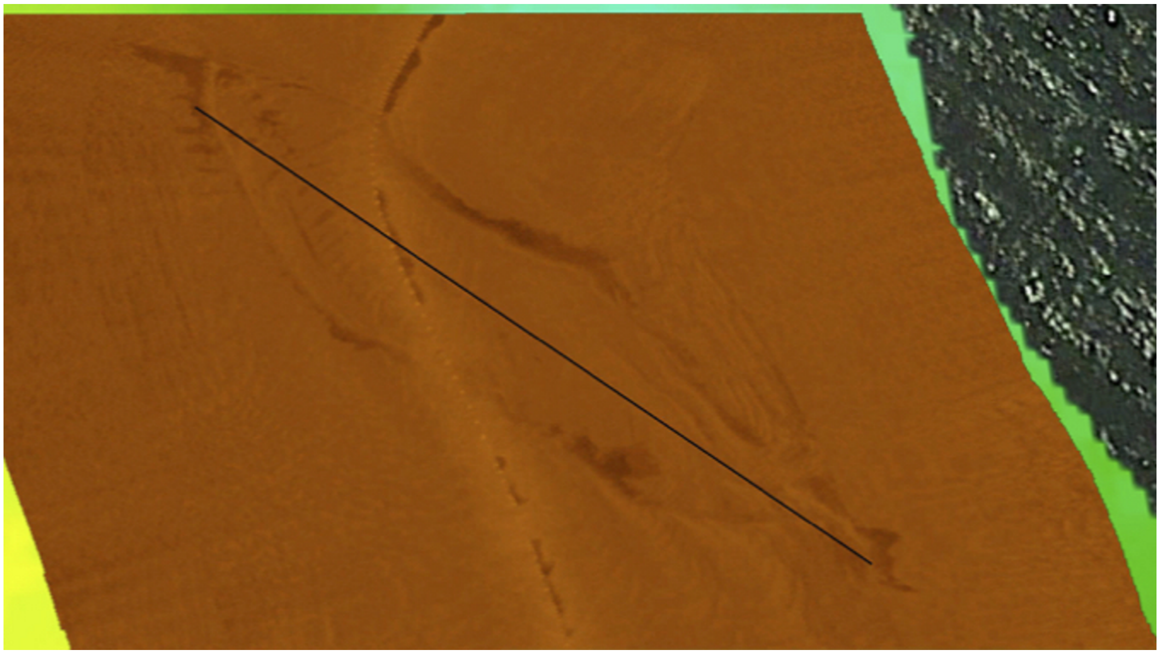

Figure 1.12: Gridded Edgetech 6205 Bathymetric Data shows the outline of the ship wreck and the inset shows the side-scan data collected with the Humminbird 998c HD SI Combo.

1.3 Discussion

1.3.1 Platform

The ability to have an autonomous platform operate with supervision but without direct involvement allows the user to perform other tasks while data is being collected. As a human operated platform, it has been shown that a kayak provides a usable platform for nearshore bathymetric surveying (Hampson, 2008)[22]. However, it requires a significant amount of time and effort to perform a survey in a manned kayak that can be performed efficiently and repeated by this autonomous kayak. This ASV has the ability to repeat surveys over the same lines within ±1m at any time chosen by the user.

Because of the low cost of the components, a side effect in the repurposing an existing ASV was modularity: a separation of the autopilot and vessel functionality from the instrument functionality allows the user to remove or add instrumentation without interfering with the vessel performance. As a “pickup truck” for various oceanographic instruments, this modified SCOUT kayak proved to be a successful platform. With a large payload and extensive operating time, the platform capable of use as an instrument test platform, for example testing a sonar in a shallow environment where a conventional manned vessel would otherwise not be able to go. The drawback to this approach lies in the fact that it restricts the kayak to performing preplanned missions. Because the autopilot is independent of the instrumentation, the kayak is unaware of its environment and therefore cannot deviate from its mission based on data recorded by the instrumentation.

While a kayak provides a very durable platform and the weight in the hull creates a low center of gravity for the platform, sea and wind conditions restrict operations due to the limited thrust provided by the trolling motor. This restricts operational areas to low wave energy environments; high-energy environments such as surf zones are not appropriate for the autonomous kayak.

1.3.2 Autopilot

The limited range of the remote control and telemetry kit require careful mission planning when operating outside of these ranges, as well as monitoring by the user. The limits of the autopilot such as lack of collision avoidance also require previous knowledge of the area of operation, and limited vessel traffic. For the purposes of this project, the kayak operated in areas with little to no boat traffic and never operated beyond line of site of the ground station. Public safety is a concern when operating ASV, particularly platforms that have consumer grade equipment. Prior to every deployment in a public or none-controlled environment, in the local authorities were made aware than autonomous kayak would be operating in the area.

In the future, an upgrade either in the autopilot itself or an external inertial measurement unit that would allow the user to record the motion data of the vessel would be valuable to correct the bathymetry data. It will allow for surveying higher energy areas where the kayak would experience pitch and roll within its operational limits without sacrificing the quality of the data.

1.3.3 Sonar

It was shown in the tide test and in the roll test that the Humminbird echo sounder does not record at a high enough resolution to be considered effective for "high-resolution" profile surveying. However, by the standards set for SBES surveying set forth by the National Oceans and Atmospheric Administration Hydrographic survey manual, the Humminbird meets the minimum requirements for a survey instrument operating in a shallow environment (Umbach, 1976)[40]. The vertical resolution is 0.11m and the horizontal resolution is 1m, therefore this sonar is not suited for surveying fine resolution morphological feature, however large scale features on the order of tens of meters, this sonar may be used. A higher resolution sonar system would be recommended for future use of this platform.

1.4 Conclusion

A SCOUT kayak was repurposed for a low-cost consumer grade modular autonomous surface vehicle. This platform was tested, proving that the autopilot provided repeatable and accurate survey lines. When limited to benign weather and sea-state conditions, the platform performed well. The sonar system was not high-resolution, however because of the lack of resolution, the uncertainty typically associated with vessel motion is less of a concern.

When compared to other autonomous platforms, for example at University of Delaware's Autonomous Systems Bootcamp hosted by University of Delaware during the summer of 2016, the autonomous kayak had the opportunity to operate alongside a variety of autonomous systems. These included a SCOUT kayak repurposed at the University of Rhode Island, a Teledyne Marine Z-Boat, and several autonomous underwater vehicles as well as autonomous aerial vehicles. While all the ASVs experienced issues but performed well over the course of the week, the University of Delaware autonomous kayak stood out for two reasons: its battery life as well as autonomous performance led it to be a key contributor to the boot camp.

A low budget autonomous surface vehicle with a consumer grade sonar opened the doors to many future projects including testing the quality of the sonar data over different sediment types, modifications to the surface vehicle for better maneuverability and robustness in adverse conditions, as well as experimenting with high autonomous functionality such as collision avoidance.

Bubbles, the University of Delaware autonomous kayak, proved to be an excellent proof-of-concept, low budget autonomous surface vehicle that proved to be a valuable stepping stone into the world of autonomous surface vehicles.

The next chapter of this project will discuss deploying this platform as a tool to perform nearshore bathymetric surveys for a rapid storm response study.

Chapter 2

DEPLOYING THE AUTONOMOUS KAYAK TO PERFORM STORM RESPONSE NEARSHORE BATHYMETRIC SURVEYS

2.1 Introduction

In the United States, federal, state, and local government entities are responsible for maintaining and monitoring shorelines. For example, the Delaware Department of Natural Resources (DNREC) is responsible for 613km of coastline in the state of Delaware. The coastal economy of Delaware generates roughly $7 Billion annually (DNREC 2018 Budget Proposal) but is subject to large erosion events such as nor'easter storms and hurricanes as are all coastlines on the Eastern United States Seaboard (Zhang et al., 2001)[43]. Delaware counteracts the shoreline erosion with beach nourishment/replenishment projects. Due to the challenges and expense of surveying a turbid nearshore environment, these projects have been carried out with few or no recent bathymetric surveys of the areas surrounding the nourishment projects (PBS&J, 2010, NOAA, ENC)[32].

As autonomous systems become more commonplace and reliable, private, public, and educational institutions look toward unmanned aerial, surface, and underwater vehicles for both onshore and offshore surveying solutions. However, these systems tend to be expensive and require expertise to operate. Budget constraints and ease of use make consumer/recreational grade autonomous systems attractive alternatives to "turn key" autonomous platforms.

Autonomous surface vehicles (ASVs) are becoming in more common and advantageous tools for bathymetric surveying (Giordano, 2016)[20]. While manned platforms such as kayaks (Hampson, 2008)[22] or jet-skis (van Son et al., 2009)[41] equipped with sonars and GPS systems map the nearshore environment effectively, surveys with these platforms may be time consuming, tiring for the operator, and difficult to repeat with accuracy. Much of Delaware's nearshore coastal zones are shallow and turbid presenting a challenge to other survey techniques such as LiDar systems and traditional survey vessels. ASVs present a solution to surveying such coastal zones that are subject to frequent change, or, for example, studying morphological changes due to storm events.

Storm events occur regularly on the east coast of the continental United States and can have a significant impact on the shorelines (Zhang et al., 2001)[43]. Dr. Arthur Trembanis and Dr. Douglas Miller, University of Delaware, Coastal Imagery for Resiliency (CI4R) Project funded through Delaware SeaGrant. Part of this project is to prove and refine rapid habitat and bathymetric mapping methods in response to storm events. Bubbles, the University of Delaware-United States Naval Academy autonomous kayak is a proof of concept autonomous surface vehicle, adapted to perform bathymetric mapping missions in the shallow environments that conventional vessel mounted sonars would not otherwise be able to operate in. One of the study sites for the CI4R Project is Broadkill Beach, Delaware. This beach provides easy access for surveying the nearshore environment. This portion of the project demonstrates a recreational grade autonomous surface vehicle to be a viable survey system, usable for both scientific and government entities.

This chapter details deploying Bubbles in a storm response bathymetric survey capacity. The first chapter determined the capabilities and limitations of the platform. This chapter will determine the real-world usability of this consumer grade ASV by performing nearshore surveys to measure the effects of storm events on a sandbar feature just off the recently nourished Broadkill Beach in Delaware Bay. The kayak was deployed in response to two storm events to determine if a low-cost autonomous surface vehicle equipped with a consumer grade fish finder can resolve changes in the nearshore morphology caused by storm events.

2.2 Study Location: Broadkill Beach

Located near the mouth of the Delaware Bay, Broadkill Beach experienced many natural and anthropogenic changes for the last century (Maurmeyer, 1978, Jackson, 2001)[28][25]. Most recently, the Beneficial Use of Dredged Materials (BUDM) Project drastically changed Broadkill Beach's shape (DNREC). Material dredged from the Delaware Bay shipping channel extended Broadkill beach from 10m to 100m wide and added a 5m high, 30m wide, 3km long dune. Beach nourishments' affect the nearshore bathymetry varies, depending on location and local influences, requiring bathymetric surveying to understand the change in the nearshore morphology. (Roberts & Wang, 2012)[36].

Understanding the seasonal conditions in the survey area helps understand and interpret the signals caused by short intense storm events. Broadkill Beach is fetch limited and therefore experiences relatively low wave energy. Its location in the bay protects the beach from the direct energy of ocean wave action (Maurmeyer, 1978)[28]. Broadkill Beach experiences primarily tidally driven currents that run parallel to the beach: north east during an incoming tide and south west during an outgoing tide (Stevens & Trembanis, 2012)[39]. Historically, during the summer the current flows from south to north and during the winter the current flows from north to south (Stevens & Trembanis, 2012, Maurmeyer, 1978, PBS&J, 2010)[39][28][32]. While summers typically have milder conditions than winter, the north to south currents dominate on average and longshore transport of sediment from north to south dominates (Maurmeyer, 1978, PBS&J, 2010)[28][32].

A 0.11km^2 survey area between Broadkill Beach and Beach Plum Island Nature Preserve marks the survey area (Figure 2.1, Right). This area contains a sandbar feature, a relic from the Broadkill Inlet believed to be purely a sand feature (Maurmeyer, 1978)[28]. The survey area lies directly south of a *Sabellaria vulgaris* reef, or worm reef, built on a relic groin (Brown & Miller, 2011)[8] and directly north of the Beach Plum Island Nature Preserve. The recently created dune extended on the beach into the northern half of the designated survey area.

Figure 2.1: Pre-nourishment (2015), Post-nourishment(2017), 13.78 km path surveying over a 117,950-square meter area.

2.3 Storm Events

The Delaware Bay historically experiences both tropical and extratropical storm events (Honeycutt et. al. 2001)[23]. The Ash Wednesday Storm in 1962, Mother's Day storm in 2008, and Winter Storm Jonas are some of the most significant and damaging storms to affect the Delaware area. The sandbar contained in the designated survey area has been a marked feature on navigation charts since the 1950s and therefore endured these storms. During winter of 2017, Delaware experienced two extratropical storms known as nor'easters that provided this project's study cases to measure the effect of nor'easter storms on the sandbar and surrounding morphology. A nor'easter tends to be large low-pressure system that affects a large area for several days with a lower intensity than tropical based hurricane systems (Zhang et al., 2001)[43]. To compare the intensity and erosion potential of these storms to each other and previous storms that have affected the area, they will be indexed with a method proposed by Kriebel and Dalryple in 1995 (Zhang et al., 2001)[43].

2.3.1 January Storm

In late January 2017, a nor'easter storm began as a low-pressure system off the coast of Florida, intensified as it travelled north. Between January 23 and January 25, the storm system caused high winds, storm surge, and waves in the Delaware Bay. The storm track moved from south to north but stayed offshore (NWS, 2017). The wind primarily came out of the north west, perpendicular to Broadkill Beach. Figure 2.4 shows the offshore wave height associated with the storm. Buoy 44009 located offshore from Delaware bay was unable to record data during these storms. Buoy 44091 off New Jersey's coast recorded significant wave heights. Because of the broad reach of nor'easter storm systems, this buoy's data suffices for this project. The amount of time that the significant wave height remains above 2m determines the duration of the storm (Armaroli, 2012)[4]. The storm stayed in the Mid-Atlantic region for 56 hours. In Figure 2.3, the water levels referenced to Mean High High Water show the storm tide occurring between January 23rd and 25. The peak wind speeds coincide with the flooding storm tide (Figure 2.5).

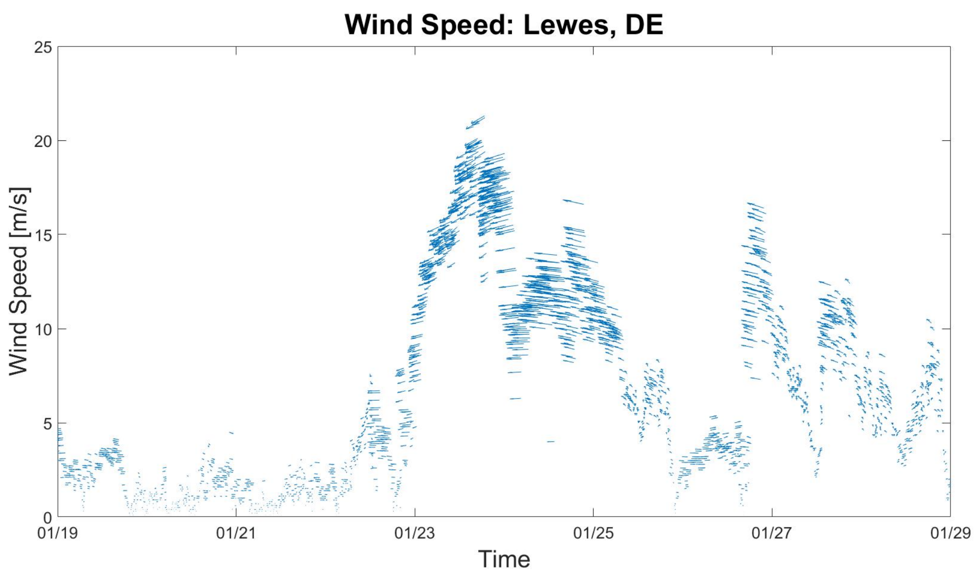

Figure 2.2: January Storm Wind Velocity.

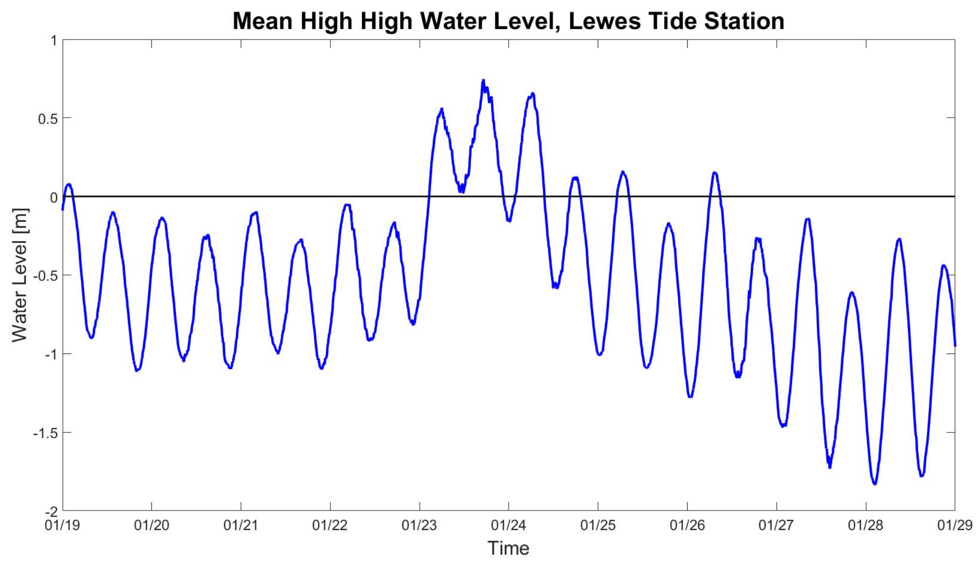

Figure 2.3: January Tides: Mean High High Water Level Reference.

2.3.2 March Storm

The extratropical cyclone originated in the Gulf of Mexico region and combined with a continental low-pressure front to form an intense but short duration storm mid-March 2017. While comparable to the January storm in wind speed and offshore significant wave height, it moved through the Mid-Atlantic region faster than the January storm, remaining for 41 hours. The wind was primarily out of the east and reached a higher magnitude than the January storm (Figure 2.6). Broadkill beach experienced peak wind speeds with an outgoing tide (Figure 2.9. While the magnitude of the storm tide was comparable for both storms, there was one storm tide compared to the three that occurred during the January storm (Figure 2.7).

2.3.3 Storm Index

Comparing these storms to each other and to previous storm events in the area create a context for expected impact from the storms. Using a combination of storm surge based on Mean High High Water levels recorded from tidal stations, offshore

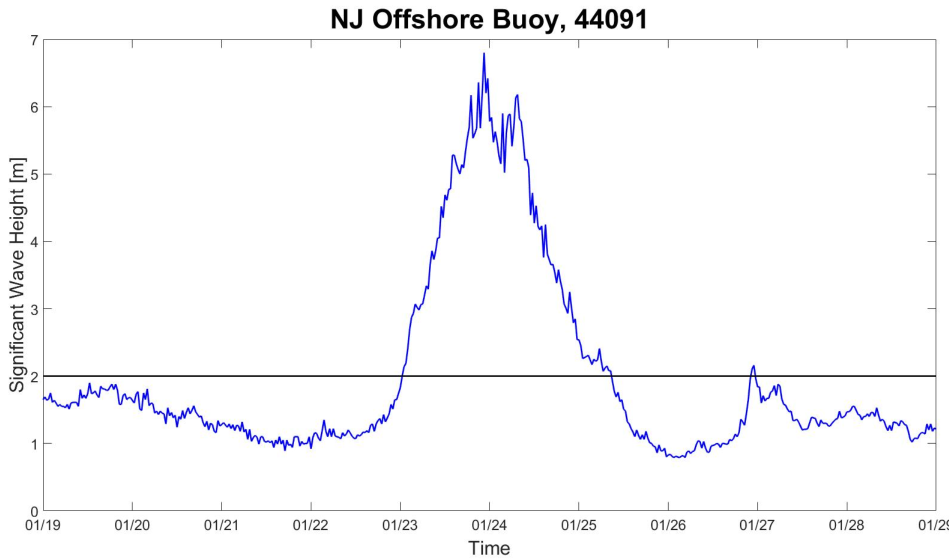

Figure 2.4: NJ Buoy 44091 offshore significant wave height.

significant wave height, and storm duration normalized for tidal cycles, Kriebel and Dalrymple developed a nor'easter storm hind casting index to represent and compare nor'easter storm intensities and erosion potential (Zhang et al., 2001)[43].

$$I = SH(t_D)^{0.3} \tag{2.1}$$

I denotes the index, S represents the maximum storm surge height. The Lewes tide station is located 6.8 km from the study site and the maximum Mean High High Water Level recorded during the storms will serve as the maximum storm surge height parameter. H represents the offshore significant wave height. Delaware's offshore National Data Buoy Center Buoy 44009 was not operational from December 2016 through April 2017, therefore, New Jersey's Buoy 44091 provided the offshore significant wave height. This buoy is 162km from the study site, however nor'easters characteristically cover a very large area and this will do as a proxy (Zhang et al, 2001)[43]. The number of hours that the offshore significant wave height is greater than two meters determines the duration of the storm (Armaroli et al., 2012)[4]. Dividing the duration by 12 hours

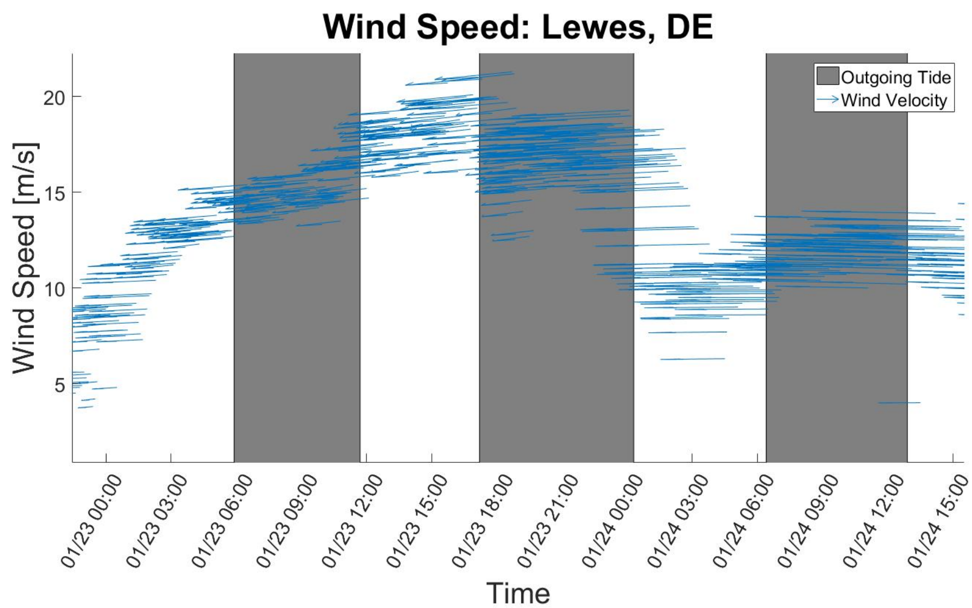

Figure 2.5: January storm winds overlaid on tides.

normalizes the duration by a tidal cycle and yields t_D in the risk index equation cycle (Zhang et al., 2001)[43].

The January nor'easter has a higher risk index than the March nor'easter, however in the context of historic storms that have affected Broadkill Beach and the surrounding Mid-Atlantic region, the are mild storms. Because the sand bar in the survey area is known to be a robust feature, it may move but should remain largely intact through the January and March storms (Elgar et al., 2001)[13].

2.4 Methods

2.4.1 Surveys

The University of Delaware autonomous kayak is a repurposed SCOUT kayak, originally developed at Massachusetts Institute of Technology (Curcio, 2005)[10]. This low-cost autonomous surface was fitted with hobby grade autopilot and a Humminbird 998c HD SI Combo fish-finder. This sonar unit records side-scan imagery as well as

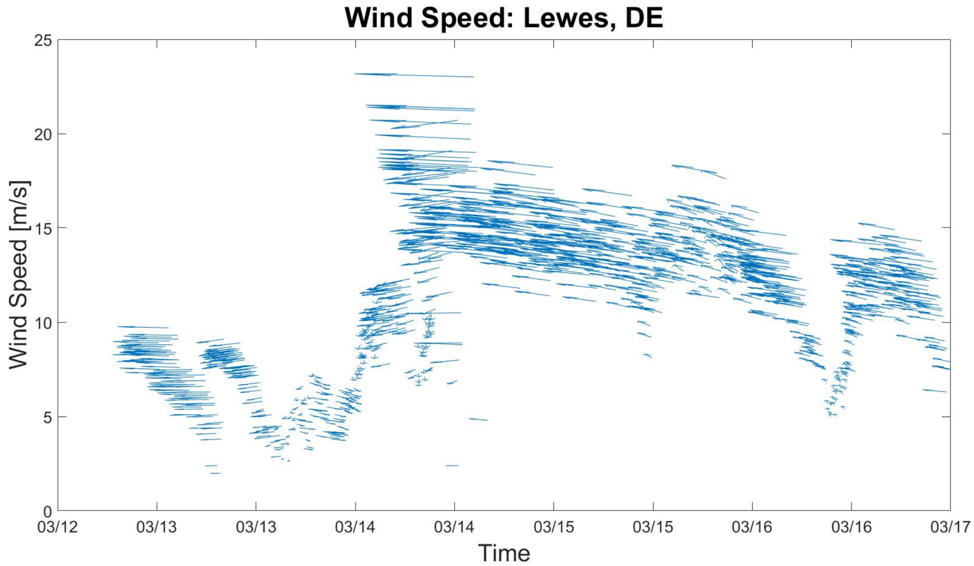

Figure 2.6: March Storm Wind Velocity.

Storm	Storm Surge [m]	Significant Wave Height [m]	Normalized Storm Duration	Nor'easter Risk Index
January 23, 2017	0.746	6.8	4.66	8.05
March 14, 2017	0.708	6.6	3.42	6.76
Hurricane Sandy, 2012	1.235	7.28	7	16.12
Hurricane Joaquin, 2015	0.889	6.11	11.25	11.23

Table 2.1: Kriebel and Dalrymple index storms affecting the Delaware region.

single beam echo sounder depth data and position data with a vertical error of ±0.11m and a horizontal error of ±1m.

The kayak requires two people for preparing and deploying. The equipment for the survey was brought to the south end of the survey area where there is relatively close vehicle access to beach. The ground station consists of a Windows laptop with Mav-link Mission Planner software, a radio telemetry unit, and a remote control. This

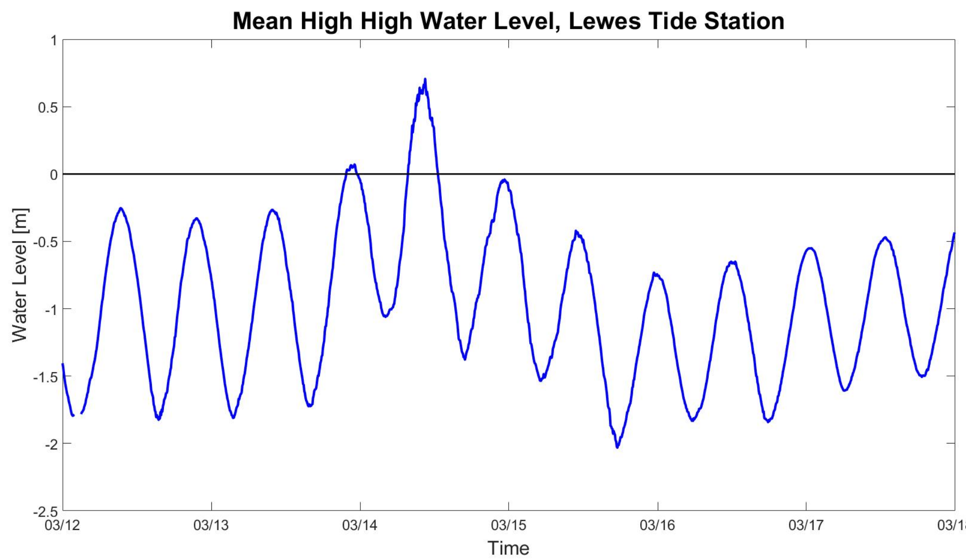

Figure 2.7: March Tides: Mean High High Water Level Reference.

allow the user to monitor the progress and status of the autonomous kayak when it is in range of the telemetry (roughly 50m dependent on antenna gain and height) as well as manually control the kayak if necessary. The Humminbird unit does not have remote access, therefore the user must apply the settings and begin recording data before the kayak executes the mission. For the purposes of correcting the bathymetric data, Conductivity, Temperature, Depth (CTD) casts were performed using a Castaway CTD unit during each of the surveys. This unit calculates and outputs a profile of the speed of sound through the water that is used in post-processing. The 117,950-square meter area surveyed in a 10m grid required 3.5 hours to survey with the kayak surveying at on average 1.5m/s. The same mission was executed three times over the course of the two storms at or near high tide.

The first survey was conducted four days before the January storm on January 19. Because of the direction of the storm and the proximity of the storm to the survey area when the survey was conducted, the winds and sea state were at the operation limit of the autonomous kayak. The wind speed during the survey was 3.5m/s, the air

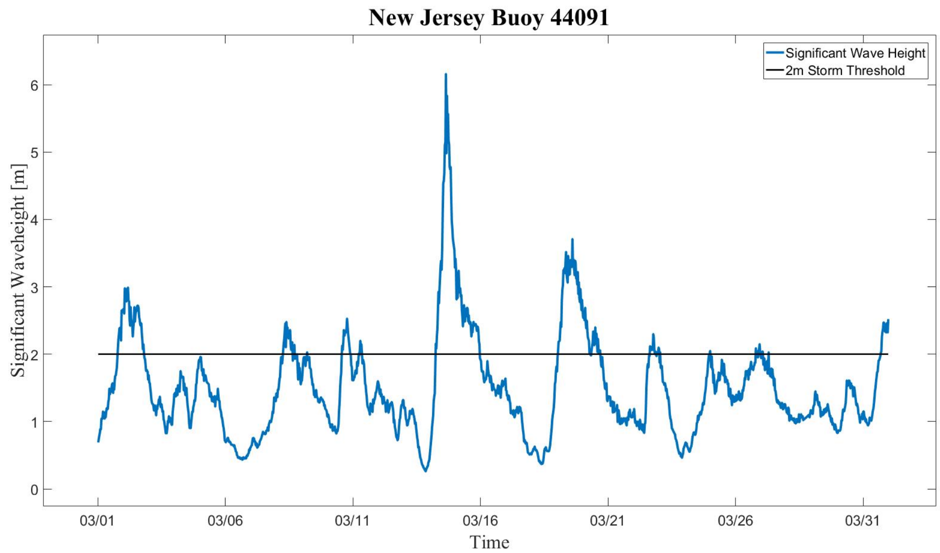

Figure 2.8: NJ Buoy 44091 offshore significant wave height.

temperature was 6.5°C, and the water temperature was 5.3°C.

The second survey was conducted six days after the January storm on January 29. The sea state was much lower during this survey. Glassy sea state with less than 0.25m swell left the autonomous kayak with only the tidally driven current to contend with. The wind speed during the survey was 3.5m/s, the air temperature was 2°C and the water temperature was 5.4°C. The third and final survey was conducted three days after the second storm on March 17. March 13 was the intended pre- storm survey date, however equipment malfunction and conditions did not allow for a survey. The sea state and wind conditions for the March 17 survey were at the operational limits of the kayak platform. The wind speed was 5 to 6m/s (the limiting wind speed for the kayak is 5m/s), the air temperature was 0°C, and the water temperature was 4.7°C.

2.4.2 Data Processing

The Humminbird's bathymetry and side-scan data record locally to an SD card. The single beam echo sounder (SBES), Global Positioning System (GPS), and time

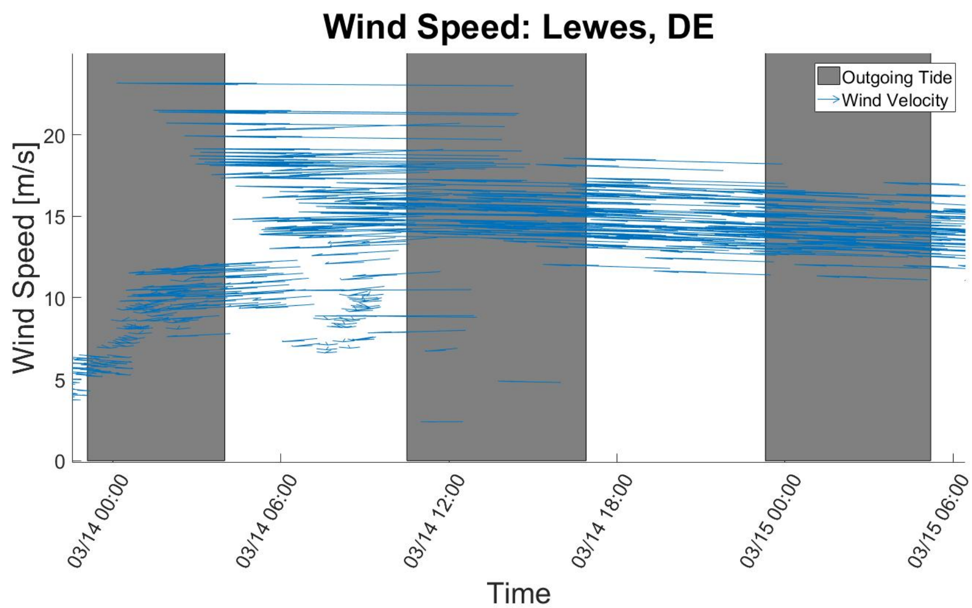

Figure 2.9: March storm winds overlaid on tides.

data are converted from the proprietary Humminbird file format to an XYZT.csv file via Humviewer software. This file contains the longitude, latitude, altitude (height of the transducer above the sea floor), and time. The vessel offset of 0.3m is applied to the depth data. The transducer is mounted below the kayak, 0.3m below the waterline of the vessel, therefore 0.3m is added to the altitude data.

Using a Matlab script, the Humminbird SBES data is corrected for sound speed. When the Humminbird collects data, it assumes that the sound speed is fixed at 1500m/s. Because the survey environment is shallow and well mixed, the average sound speed calculated by the Castaway CTD is used to replace this assumed sound velocity value.

Once sound velocity corrected, the data is then tide corrected with Mean Low Low Water Level referenced tide data from the Lewes Tide Station. There are different tidal datums that can be used to correct bathymetry data and Mean Lower Low Water was chosen for this project. Mean Low Low Water is defined by NOAA: "The average of the lower low water height of each tidal day observed over the National Tidal Datum

Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch" (NOAA, 2013)[1]. The tide station collects data every six minutes and therefore the tide data set must be interpolated to match the number of data points collected by the Humminbird unit which collects depth data at an average of 12Hz. A MATLAB script trims the tide data to match the initial and final times of the survey. Once trimmed, the script performs a linear interpolation of the tidal data, then removes the tidal signal from the bathymetric data.

Once the data set is sound speed, vessel offset, and tide corrected, it is exported as an XYZ.csv file that contains longitude, latitude, and depth data (negative values) to be gridded and analyzed.

Fledermaus (QPS) is a gridding software that allows the user to import XYZ data and grid the data using a variety of settings and methods. For these surveys, the data were gridded at 5m with a three-point moving average. Five-meter gridding was the minimum grid necessary to create a solid surface over the survey area. The three-point moving average smooths the 0.11m uncertainty associated the Humminbird 998c HD SI Combo. The ridges that appear in the surface are artifacts from the interpolation (Figure 2.10).

A MATLAB script examined the details of the survey transects more closely. The script extracted individual alongshore and cross shore transects from the surveys. The sonar acquires depth data at a higher frequency than the GPS acquires position data. Therefore, multiple depth values are recorded with the same GPS value. The script averaged the depths associated with each GPS point then assuming the transect was a straight line (plus or minus 1 meter), took the difference between each GPS point, yielding the distance between each value. The resulting transect data was in the form of distance along transect vs. depth (Figure 2.11). This was linearly interpolated to evenly distribute the data points along the transect. A spatial fast Fourier transform (FFT) determined which signals the bathymetry produced and the noise produced (Figure 2.12). A spatial instead of temporal FFT was performed because spatial resolution and

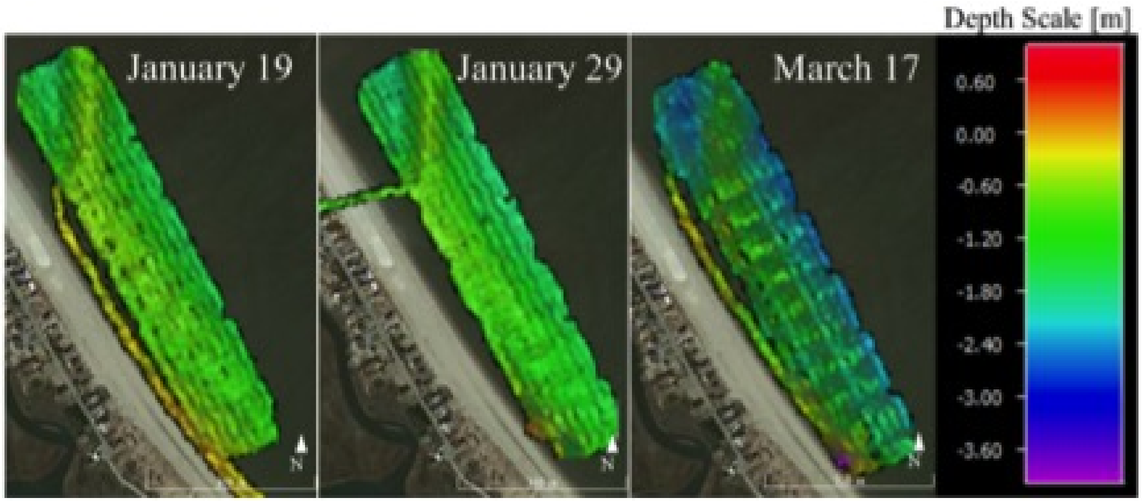

Figure 2.10: Survey data gridded at 5m with a 3 point moving average in Fledermaus.

noise is more relevant than temporal resolution and noise in the context of this study. Once the noise level determined, a low pass smoother was applied to the transect in the form of a centered 50-point moving window average. The smoothed data was removed from the original data and the standard deviation of the noise bounds the smoothed data in Figure 2.13. This smoother removed the low power, high wave number noise while maintaining the high-power signals (Figure 2.14).

2.5 Results

2.5.1 Survey Results

The first survey exposed the sandbar's location and dimensions in the northern section of the survey area south of the worm reef groin. It sits one meter above the surrounding sea-floor with a depression between the beach and the sandbar (Figure 2.10, left panel). The sandbar appears welded to the beach, tapering south and onshore. The sandbar angles north from the beach roughly 220m long and roughly 45m wide. Every transect was analyzed, however only the fifth longshore transect and the fifth cross-shore transect are discussed. These transects pass through the middle of the sandbar (alongshore and cross-shore) and display the sandbar's general behavior in

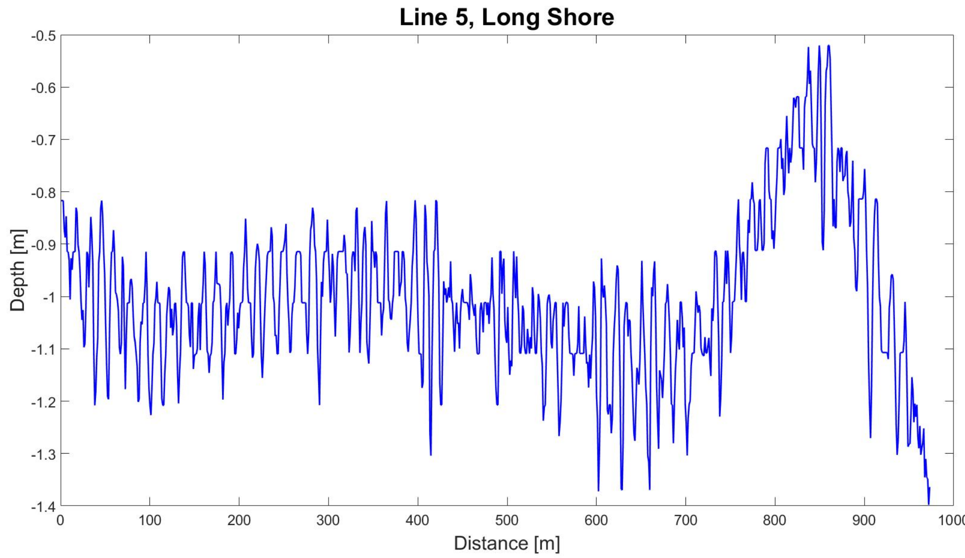

Figure 2.11: Unfiltered depth data, alongshore transect (north is right).

response to the storm events.

In the January 29 post-storm survey, the sandbar dimensions remain roughly the same, however the depression deepened (Figure 2.10, center panel). The entire survey area deepened roughly 0.2m. The alongshore transect shows the sandbar feature's peak moving north 12m (Figure 9). The cross-shore transect shows the sandbar peak moving onshore 63m. The noise associated with the second survey in the alongshore transects is significantly less than the noise in the alongshore transect in the first survey (Figure 2.15). The cross-shore transects from both surveys have comparable noise levels (Figure 2.16). Forty-seven days passed between the second and third surveys. Because Broadkill beach is in a protected, fetch-limited bay, the nearshore morphology retains the impact from storm events and does not change drastically due to normal conditions (Jackson et al., 2002)[25]. Therefore, the post-storm survey on January 29 serves as the pre-storm survey for the March storm as no storm events occurred in the 47-day interval between the storms. The March 17 survey shows an average of 0.5m depth increase over most of the survey area. Again, the dimensions of the sandbar remain

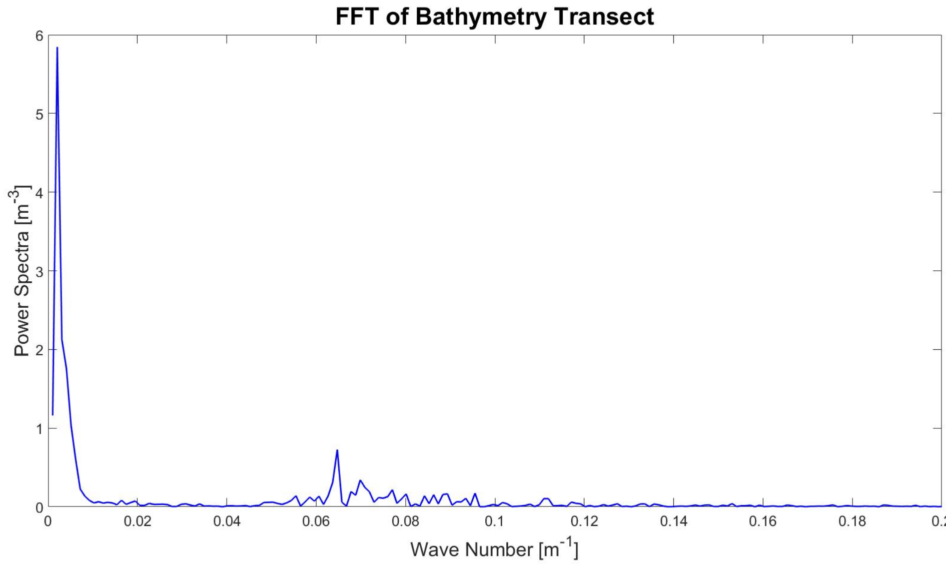

Figure 2.12: Spatial FFT of unfiltered depth data.

comparable to the first two surveys, however there is a more distinct deepening of the in depression shoreward of the sandbar (Figure 2.10, right panel). The alongshore transect shows the sandbar peak moving south 31m. The cross-shore transect show the sandbar peak moving 65m offshore. The standard deviation of the noise in this third survey is comparable to the first survey in both the alongshore and cross-shore transects (Figures 2.15, 2.16).

The Humminbird unit collected side-scan data for the three surveys. The side-scan, processed in Chesapeake Technologies' SonarWiz, show no significant features and did not resolve noticeable bed forms. Change in sediment type (for example, mud to sand) did not appear in the side-scan data as the backscatter intensity remained constant through the survey area. Figure 2.17 shows the side-scan data recorded during the March 17 survey and is representative of the side-scan data collected in January.

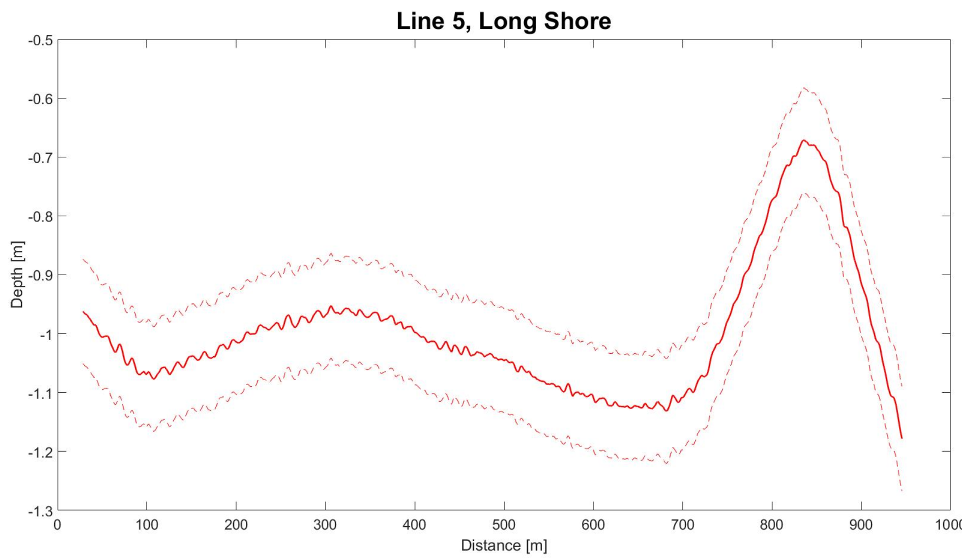

Figure 2.13: Low pass 50 point average moving window smoother applied to the bathymetry data.

2.5.2 Platform Performance

The average along track error of the kayak was ±0.11m between all three surveys. The noise due to the conditions is evident in the error bars in Figure 13. Because the resolution of the echo sounder is 0.1m and the survey area has maximum depth of 4m, roll and pitch of the kayak does not affect the data. However, if the heave cause by chop and swell is greater than 0.1m, it will be recorded in the data, causing noise in the signal.

2.6 Discussion

2.6.1 Nearshore Storm Response

Sediment moved out of the survey area, a result from the storm events, evident by the survey area deepening with each of the two storms. The vertical uncertainty of the Humminbird sonar system (±0.11m) was up to within 50% of the vertical change measured between the storms. This uncertainty was pushed down with smoothing the raw signal. The sandbar feature shifted horizontally onshore and north during the first

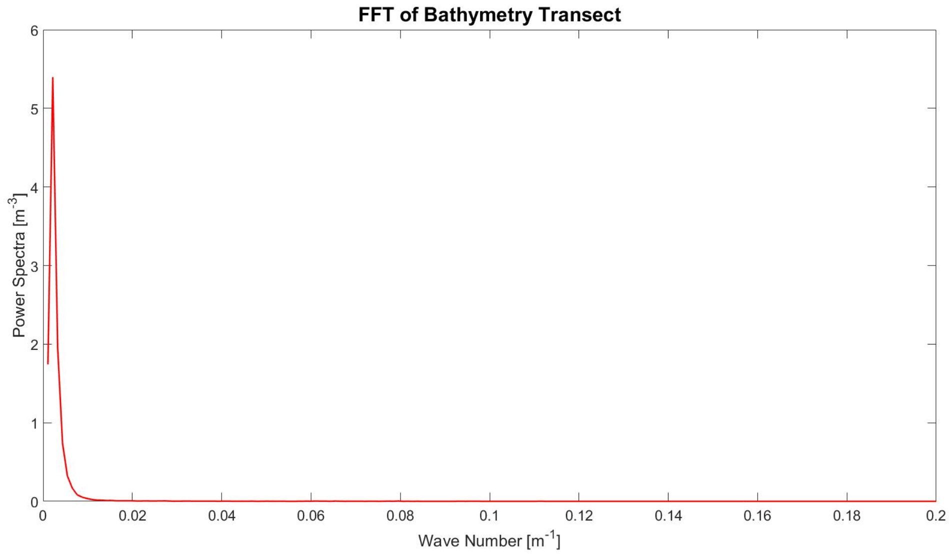

Figure 2.14: Spatial FFT of smoothd data shows the noise is removed

storm then offshore and south during the second storm orders of magnitude greater than the horizontal uncertainty of the Humminbird system (±1m). These horizontal movements were seen not only in the discussed transects, but all transects.

Neither storm in the study had local wave height data or local nearshore current data during the storms. Without this information, it is difficult to understand the exact mechanisms driving the sandbar movement during these storms. In general, sandbars move offshore during high energy storm events from undertow currents driven by wave breaking in a positive feedback with the changing bathymetry (Elgar et al., 2001)[13]. This follows with the observations during the March storm. However, in the case of the January storm, the sandbar migrates onshore. In the Delaware Bay, currents are primarily tidally, and wind driven (French, 1990)[17]. The peak wind velocities during the January storm occurred during a peak flooding tide. This means the tidal and wind driven currents flowed north and west, the same directions the sandbar migrated according to the discussed transects (Figures 2.15, 2.16). During the March storm, the peak winds occurred during an outgoing tide. The outgoing tide drove the currents

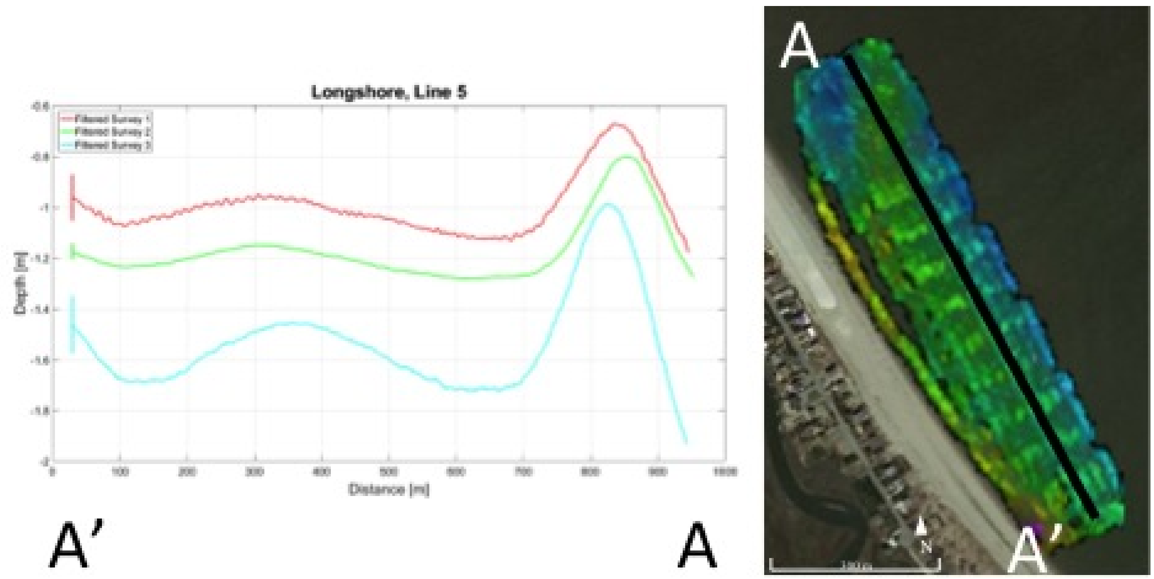

Figure 2.15: Smoothed alongshore transects.

south and east, against the wind creating more wave action, potentially allowing for the positive feedback undertow-bathymetry movement forcing described by Elgar (Elgar et al., 2001)[13].

The sandbar is robust feature. It has been noted in navigation charts dating to the 1970s. Since that time, many seasonal storms and hurricanes occurred in the Delaware Bay. The few mentioned in Table 1 demonstrate the relatively low intensity of the storms used in this study compared to significant nor'easter and hurricane events. It should be expected that the sandbar feature migrated during previous storms but given that it survived those events, it moved but did not dissipate, as expected with these two low Kriebel and Dalrymple index storms.

2.6.2 ASV Platform Performance

The autonomous kayak efficiently repeated the same survey three times. This allowed for direct comparison between transects as well as direct comparison between

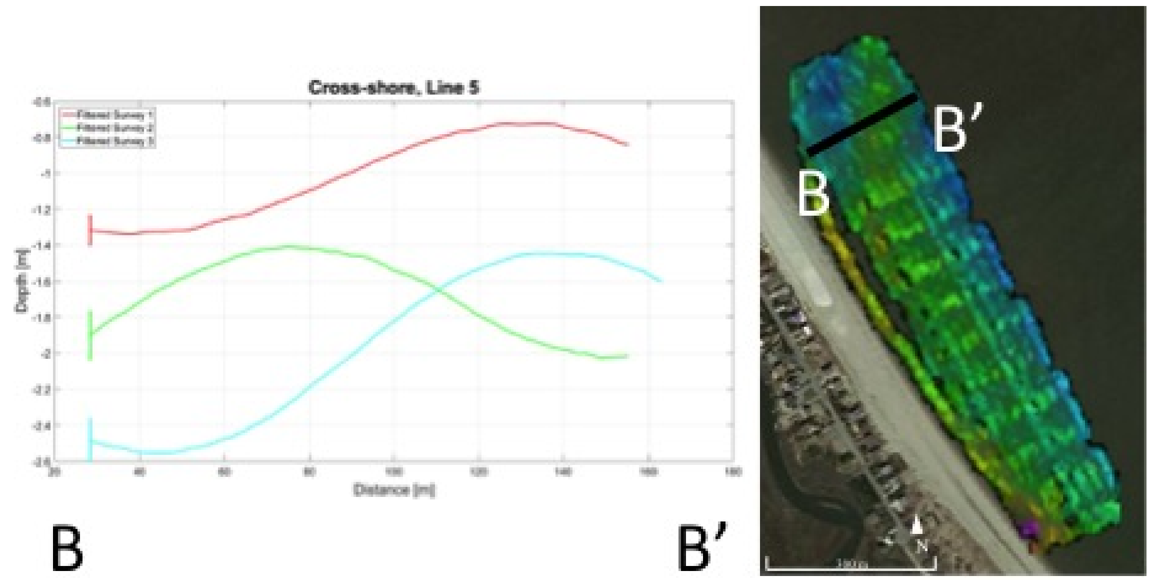

Figure 2.16: Smoothed cross-shore transects.

gridded data sets. Performing the surveys in a manned kayak, while possible (Hampson, 2008)[22], would not result in lines repeated between surveys within ±1m and would be very uncomfortable to perform during January and March air and water temperatures. While the autonomous kayak requires human supervision while surveying, this can be done comfortably from the beach. As a rapidly deployable system, the weather and sea state are the limiting factor in using the autonomous kayak as a storm response survey platform. Storms inherently bring adverse conditions with them and it is not guaranteed that there will be favorable conditions prior to a storm. In low energy environments such as Broadkill Beach, morphology changed by storms tends to remain unchanged for extended periods of time (Jackson et al., 2002)[25], and this allows more time before and after the storm for surveying, however in high energy areas, this is not necessarily the case. In addition, the kayak is limited to relatively protected environments with limited wave action. Broadkill beach provides a low wave energy environment, however an ocean facing beach would limit the kayak's nearshore operation to beyond the surf zone.

The Humminbird 998c HD SI Combo, despite limited vertical resolution and high vertical and horizontal uncertainty, resolved vertical and horizontal changes in the morphology between surveys. Single beam echo sounders are limited in spatial coverage, which requires dense transect lines in the mission planning. In the cold weather, the battery life decreases, limiting the survey time and thereby limiting the resolution that can be achieved with tighter line spacing. In terms of vertical resolution, the maximum vertical uncertainty in the Humminbird depth readings after correcting for tidal variations and sound speed is ± 0.14m. Smoothing the data extracted a cleaner bathymetric single, however the system is not ideal for shallow water environments when vertical changes in the morphology can occur on the centimeter scale.

2.7 Conclusion

This project demonstrates that autonomous surface vehicles have a place in the solution to better understand nearshore morphology. The storms that occur in the Delaware Bay affect the shoreline, both the beach and the nearshore environment (French, 1990, Jackson et al., 2002)[17][25] and there is a need to understand the effect these storms have on shorelines and the University of Delaware autonomous kayak was useful toward that end. It surveyed a sandbar feature that was robust to storm events, measured the sandbar's response to storms which was predicted by previous research on sandbar behavior and Broadkill Beach's environment. This provides the beginning of future work studying nearshore sandbar dynamics in low energy environments, both in storm events and in nominal condition.

In terms of storm response studies, the autonomous kayak platform is easily prepared, transported, and deployed by two people with as little as 24 hours of notice making it a viable storm response platform. The limiting factors are the environment that is can operate in is required to be low energy and the limited spatial resolution of the sonar unit. An upgraded sonar unit and more robust platform would address both problems, however and increase in cost is associated with such upgrades. This project opened the door to applying autonomous surface vehicles to address the challenges of bathymetric surveying in the nearshore environment.

The University of Delaware kayak proved to be a viable platform for nearshore storm response surveys. Because consumer grade parts and instrumentation comprise it, there are resolution limits. However, two nor'easter storms created morphological changes greater than the resolution and uncertainty limits of the sonar system. A solution to both the resolution and spatial coverage limitations of an autonomous kayak outfitted with a consumer grade sonar would be to deploy multiple platforms or upgrade the sonar system on the platform. As a proof of concept low-cost autonomous surface vehicle used to survey the nearshore environment, the University of Delaware autonomous kayak proved that it is a viable platform and researcher and environmental management agencies should pursue autonomous surface vehicles as nearshore bathymetric survey platforms.

Figure 2.17: Humminbird side-scan data, March 17

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