OERA Research Project
Final Report

ADAAM
Acoustic Doppler Aquatic Animal Monitoring

Project start date - March 1, 2018

Luna Sea Solutions Inc.
Memorial University of Newfoundland
Dalhousie Ocean Acoustics Laboratory

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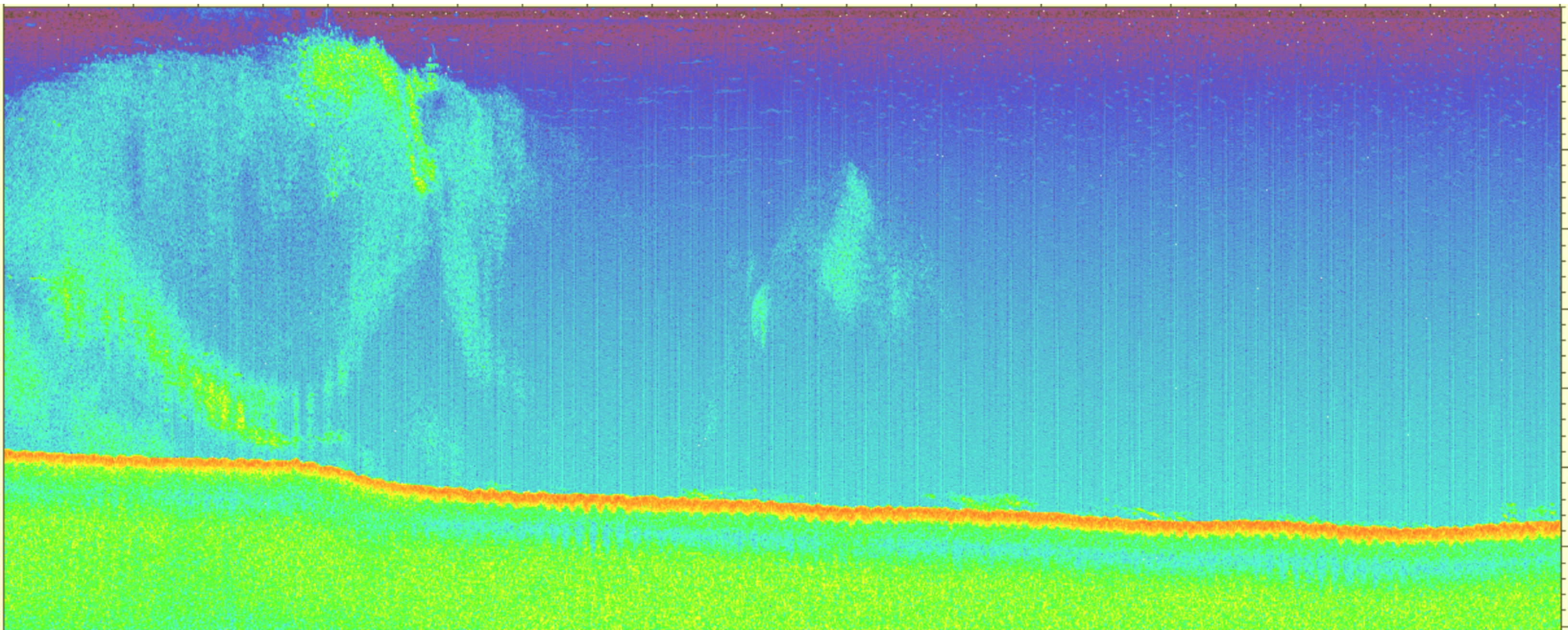

Executive Summary

The tidal energy industry requires effective marine life monitoring systems for characterising pre-deployment conditions and evaluating the environmental response to deployment, operation, and recovery of turbines. There is concensus that the continued development of in-stream tidal energy installations must go hand-in-hand with improved knowledge of the avoidance and evasion behaviours, strike detection, and species distribution of marine animals. Significant work focused on imaging sonars (active acoustics) and hydrophones (passive acoustics) is underway. However, active acoustic data that is regularly collected for measuring tidal flows is not currently utilised for marine life monitoring.

Acoustic Doppler current profilers (ADCPs) are the standard tool for monitoring ocean currents, and they are widely used by the tidal energy industry for physical site characterisations and monitoring. ADCPs also detect signals scattered by fish, marine mammals, and other discrete targets in the water column, however typical approaches to ADCP data processing require that such signals are rejected as noise. The rejected signals contain valuable information on marine life movement and hold the potential for a valuable new approach to fisheries acoustics. An alternative ADCP data processing method presented by *Zedel and Cyr-Racine* (2009) uses a least-squares based algorithm to compute both current velocities and velocities of fish and other discrete water column targets, even when fish are intermittently present. Even with a suitable processing algorithm, the challenge remains to verify the accuracy of fish detections in ADCP data.

A standard tool for detecting fish is the split-beam echosounder, which under ideal conditions has the ability to provide information on the speed and direction of discrete targets in the water column as well as backscattered signal amplitude. The ability to estimate both numbers and velocities of discrete targets in the water column using split-beam echosounders, combined with their established utility for biological surveying, makes them a sound choice for validating ADCP fish detection and velocity data.

This project advances research conducted by Dr. Len Zedel (Memorial University Newfoundland), with a focus on testing and validating the use of ADCPs for marine life detection. In this study, we make use of data collected using a co-located BioSonics DTX split-beam echosounder, ADCPs, and optical imaging systems to validate fish counts and velocities derived from ADCP data. The study area consists of Grand and Petit Passages in Digby County, Nova Scotia, as well as the surrounding areas of St. Mary's Bay and the outer Bay of Fundy. Grand and Petit Passages are characterised by strong tidal currents, and are sites of interest for the development of in-stream tidal energy technology. The project objectives include: (1) validate the application of ADCPs to marine life monitoring; (2) gain information on marine life (swim velocity, counts, and identification) utilizing the split-beam sonar, optical images, and ADCP data; (3) advance methods for ocean bottom-mount and vessel-based data collection; and (4) develop algorithms for marine life detection from ADCP data, for academic use and commercial application.

The study consisted of multiple instrument deployments spanning from 2018 to 2020, using both fixed (sebead-mounted, with upward-oriented instruments) and mobile platforms (vessel-mounted, downward-oriented instruments). The mobile platforms included the ‘Jetyak’, an inboard jet-powered autonomous surface vessel developed at Woods Hole Oceanographic Institution, and two research vessels operated by Luna Sea Solutions Inc. (Luna): the ‘Puffin’, an outboard-powered Rosborough RF-18; and the ‘Grand Adventure’, a Rosborough 28 with inboard diesel. The vessel-mount infrastructure developed for use aboard the RV Puffin and the RV Grand Adventure has been demonstrated to be highly functional and robust for data collection in the high tidal flow environments of Grand and Petit Passages. The pole-mount systems employed on both vessels allowed us to rapidly deploy the co-located instruments. The vessel-based deployment platforms benefit from lower operational costs and complexity than autonomous bottom deployments. However, the shorter-term vessel deployments came with associated challenges of collecting sufficient and suitable validation data.

The Jetyak has been shown to be a uniquely capable deployment platform. Given its utility in shallow coastal waters, along with the decreased risk to survey operators, the Jetyak provides potential to address needs both for long term monitoring and for increased capacity for responsive (reactive) monitoring capability at the local level. Though data collected using the Jetyak was not suitable for use in the ADCP validation analyses, we were able to use data from a Jetyak-mounted sidescan sonar to visualise fish schools in some cases.

Fish detections in ADCP data were highly correlated to those from the BioSonics split-beam echosounder. The strong linear relationship is very encouraging and certainly met the expectations of the research team. Use of the ADCP for discrete target detection also provides an alternative processing approach for dealing with frequently-observed near surface bubble-plumes, eliminating the need for the more operator-intensive process of determining an exclusion line – required when using the split-beam echosounder in an upward-orientation in high energy tidal environments. The validated fish detection method gives us a basis to reanalyse earlier data sets to explore any biological signals of significance.

Validating ADCP-based fish swimming velocities remains a challenging task that is sensitive to properties of fish behaviour; namely, fish must be present, and in schools with sufficiently low density to (a) allow the computation of meaningful echosounder track data and (b) avoid oversaturation of the ADCP data by discrete targets. Data passing our selection criteria were not sufficient for a robust statistical validation of the ADCP-derived fish swimming velocities. However, the comparisons associated with the schools that met our selection criteria are favourable. We consider the sensitivity of the analysis to the fish swimming and schooling behaviour we observed an important result, and recommend that it be considered carefully in the event of similar future studies.

On the choice of instrumentation and processing software: The use of Sonar5-Pro versus Visual Aquatic for the echosounder data analysis represents a notable difference between the bottom-mount and vessel-mount experiments. The extraction of tracks from the echosounder data contains steps that are inherently subjective, though the quality of the fish track data were likely much more dependent on the properties of the fish schools. The fish tracking software packages known to us (i.e., Sonar5-Pro, Visual Aquatic, or Echoview) appear flexible enough to achieve comparable results that are sufficient for the analyses described in this report. Though direct comparisons to the echosounder data were only made with RDI ADCP data, we would expect comparable performance using a different ADCP (i.e., Nortek). Differences in sampling rates between instruments may have implications for the number of fish identified by the algorithm, due to differences in repeat counts of individual fish.

The data processing pipeline used to analyse the ADCP data presented in this document has been organized as a toolbox currently known as ADCPFish, which processes raw ADCP data into depth and time-averaged fish and water velocities. The toolbox is based on code written by Dr. Len Zedel, and was adapted for use as a toolbox by Muriel Dunn. The application has since been refactored and extended by Luna to encompass a broader range of instrument types, orientations, and functionality.

Contents

List of Figures

1 Introduction and Objectives

The tidal energy industry requires effective marine life monitoring systems for characterizing pre-deployment conditions and evaluating the environmental response to deployment, operation, and recovery of turbines. This includes evaluating avoidance and evasion behaviours, improving strike detection, and gaining a better understanding of species distributions for fish and marine mammals. Significant work focused on imaging sonars (active acoustics) and hydrophones (passive acoustics) is underway, including integrating these systems to implement a "look, listen, and learn" approach to environmental monitoring. However, active acoustic data that is regularly collected for measuring tidal flows is not currently utilized for marine life monitoring.

Acoustic Doppler current profiler systems (ADCPs) provide profiles of ocean currents and are a standard tool for characterising and monitoring ocean currents. ADCPs also detect signals scattered by fish and marine mammals, but these signals are normally treated as noise and are rejected by signal processing algorithms. These rejected signals contain valuable information on marine life movement and hold the potential for a valuable new approach to fisheries acoustics. *Zedel and Cyr-Racine* (2009)[1] presented an alternative approach to analysing Doppler sonar data using a least-squares based algorithm which analyzes each acoustic beam individually to extract both fish and water velocities, even when fish are intermittently present. Even with a suitable processing algorithm, the challenge remains to verify the accuracy of fish detections in ADCP data.

Split-beam echosounders form a fundamental tool for fisheries research and surveys, having the ability to provide information on the speed and direction of discrete targets in the water column as well as backscattered signal amplitude. The ability to estimate both numbers and velocities of discrete targets in the water column using split-beam echosounders, combined with their established utility for biological surveying, makes them a sound choice for validating ADCP-derived data. Some modern ADCPs are equipped with a fifth vertically-oriented beam capable of functioning as an echosounder. Such systems have the potential to allow a validation-type comparison of fish counting estimates made using the least-squares algorithm on data from the four slanted beams to estimates from the echosounder beam using a single instrument. However, it is not possible to validate observations of discrete target velocities using such an instrument.

This project advances research conducted by Dr. Len Zedel (Memorial University Newfoundland), with a focus on testing and validating the use of ADCPs for marine life detection. In this study, we make use of data collected using a co-located BioSonics DTX split-beam echosounder, ADCPs, and optical imaging systems to validate fish counts and velocities derived from ADCP data. The study area consists of Grand and Petit Passages in Digby County, Nova Scotia, as well as the surrounding areas of St. Mary's Bay and the outer Bay of Fundy. Grand and Petit Passages are characterised by strong tidal currents, and are sites of interest for the development of in-stream tidal energy technology.

Key research questions addressed in this report formed the basis of an M.Sc. thesis project (*Dunn*, 2019)[2]. The results of the thesis project have led to important contributions to this report, in

[1] https://academic.oup.com/icesjms/article/66/9/1846/725323

[2] https://research.library.mun.ca/14340/1/thesis.pdf

particular, the validation of ADCP fish count data and the development of an ADCP data processing toolbox.

The project objectives include:

- Validate the application of ADCPs to marine life monitoring;
- Gain information on marine life (swim velocity, counts, and identification) utilizing the split-beam sonar, optical images, and ADCP data, including comparison of results;
- Advance methods for ocean bottom-mount and vessel-based data collection; and
- Develop algorithms for marine life detection from ADCP data, for academic use and commercial application by incorporating into Luna Ocean Data Analysis Software (LODAS) for processing new and existing ADCP data.

The tidal energy sector benefit focuses on expanding use of a standard tool for flow characterization for contributing to marine life monitoring, with applications to ocean research beyond tidal energy applications.

This document adresses the following work items following the original statement of work:

1. Community Engagement

   Ensure that community engagement is a key part of the ADAAM project. Use local knowledge of marine life presence to aid in experiment planning and involve community members in data analysis through crowdsourced review of video data, to be hosted online. Share information on the project using social media and through the local newspaper (Passages). Following data collection, make initial results accessible to the community for informal one-on-one or small group discussion.

2. System Testing

   Initial field testing of the instruments and systems will take place in a calm environment prior to deployments in the more energetic tidal passages. Operational methodology should be tested, including the simultaneous use of: ADCP, split-beam sonar, and an optical camera system. The instruments will be tested aboard mobile platforms, including (1) the Reseach Vessel Puffin, an outboard-powered Rosborough RF18, and (2) the Jetyak, an inboard jet-powered autonomous surface vessel developed by Woods Hole Oceanographic Institution. The Jetyak is an Unmanned Surface Vehicle (USV) that can operate under user remote control and also as an Autonomous Surface Vehicle (ASV).

   The initial testing will foster confidence and further experience in system integration, which will increase readiness for use in more challenging and higher cost environments. It will also provide initial data sets for advancing software development and validation of ADCP marine life detection.

3. Bottom Mount Deployment

   Minimum one-month deployment of the ADCP, split-beam sonar, and optical image system on a bottom-mounted frame in Grand Passage. Grand Passage has been well-studied by the project team and has high abundance and diversity of marine life. The Grand Passage environment is ideal for a cost-effective bottom-mounted deployment, with ease of access, highly capable and readily available local vessels, significant existing research, and good water clarity for use of optical imaging. The instruments, batteries, and data storage will be mounted to a bottom frame, then deployed and recovered using a local vessel. The bottom-mount deployment will yield data suitable for the purpose of validating ADCP-based estimates of fish numbers and velocities.

4. Mobile Data Collection Platforms

   Demonstrate data collection using the Jetyak in Grand and Petit Passages. These environments are easily accessible, resulting in cost-effective research and increased safety, and are appropriate for demonstrating technical viability for several tidal energy sites, including the Minas Passage, which is slightly more energetic than Petit Passage during flood tides. The RV Puffin and the Jetyak are being developed by the project team for specialized services required for tidal energy site assessment, turbine performance monitoring, and marine operations support.

   The mobile platform deployments will yield short-term data sets in several areas of interest, and demonstrate the operational capabilities of the Jetyak in high-energy tidal environments.

5. Data Analysis/Research

   Validate fish counting and velocity data from ADCP using data from a split-beam sonar and optical imaging systems. The comparison will follow a rigorous scientific approach led by Dr. Zedel. The ADCP and the split-beam sonar will be configured to collect data as near to coincidently as possible. Explore system thresholds and detection criteria in ADCP data that allow that instrument to best reproduce the data standard of the BioSonics split-beam sonar. The optical camera system will be used for validation of acoustics results where possible, including relative abundance and direction of movement. Image review will be conducted manually, focusing on times of interest identified by the acoustic time series.

   Software development is planned for the MATLAB environment, which is standard software used by Luna, Dal, MUN, and others for oceanographic research and commercial applications.

   The analysis will serve to validate the use of ADCP data for marine life detection and measuring swim speeds, and will help advance software for analysis of existing and future ADCP data sets. A conference (or journal) paper will be produced to disseminate the results of the proposed testing and validation.

2 Methods and Results/Deliverables

This section provides a full overview of the ADAAM project by work item.

2.1 Community Engagement

The field work conducted in Grand Passage during summer 2018 was streamlined with several other research and demonstration projects, including deployment of the Sustainable Marine Energy PLAT-I tidal power system, passive acoustic studies by Jasco and Dalhousie (OERA funded), and the STREEM project (OERA funded). Specifically, we (a) planned our deployment location to meet criteria required for our objectives (depth, flow speed, and likelihood of fish presence) while minimizing interference with other experiments, and (b) shared vessel time for Huntley Sub-Aqua's barge 'Kipawo' with other bottom mount deployments for cost savings. The ADAAM project was discussed in four public open-house meetings (held primarily for PLAT-I), as well as in informal converstations with local residents in Freeport, NS, and the surrounding communities. Public notifications of mooring locations and functions were shared on social media. Local knowledge was used in site selection based on matching fish presence, fishing activity, depth, flow speed, shelter, etc. to data collection needs.

Optical camera imagery from a 2019 bottom-mount deployment that also included an ADCP and echosounder was reviewed in collaboration with Digby Neck and Islands community members. During the deployment, still photographs were captured by the camera in bursts of three photos per minute. The images were compiled and converted to a video format which was shared with the community through social media platforms. Reviewers were asked to identify and timestamp any fish schools apparent in the video. The video is hosted on Vimeo, and can be found at https://vimeo.com/347772899.

During 2019 and 2020, Luna employed Gavin Feiel as an intern and First Mate aboard research vessels Puffin and Grand Adventure. Gavin is a resident of Freeport, a fisherman, and a marine biology student at Dalhousie University. His local knowledge of fish was used for the vessel-based data collection with Puffin and Grand Adventure, resulting in fish rich data sets.

2.2 System Testing

Initial system testing was conducted during Spring 2018 in Shad Bay, Nova Scotia, and Holyrood, Newfoundland (Marine Institute, Holyrood Marine Base). Further vessel-based testing was conducted alongside 2018 and 2019 bottom-mount experiments.

The work in Shad Bay focused on testing the vessel mount configuration on the Research Vessel "Puffin", including mounts, electrical supply, and electronics. The existing pole mount on the Puffin was found to be sufficiently robust for data collection at speeds up to at least 8 knots (no need to exceed), with a simple mounting plate to accommodate concurrent data collection with an RDI Workhorse Sentinel ADCP and a BioSonics DTX transducer. Troubleshooting was required to resolve component issues with two DTX topside units, including initial issues with power supply (electrical noise from a high-end "pure sine wave" inverter) and cable connections. The Shad Bay test environment is shown in Figure 1, with pole-mounted co-located ADCP (under yellow protective cover) and a single BioSonics DTX transducer (under bubble wrap).

Figure 1: Initial System Testing - Shad Bay

The work in Holyrood focused on gaining a thorough understanding of the BioSonics DTX split-beam, including a trial calibration and testing for crosstalk (acoustic interference) with an ADCP. Both the 200 kHz BioSonics split-beam system and a 600 kHz RDI ADCP were operated in close proximity on the dock at Memorial University's Holyrood marine base. These tests showed some evidence of cross talk but interference showing up on the BioSonics system was infrequent. The intermittent nature of the interference is statistical since the ADCP, in this case, operated at 1 ping (acoustic transmission) per second compared to the BioSonics which was pinging at 4 times per second. Both instruments only acquire data for about 100 ms. In order for interference to show up, the ADCP would need to transmit at a time when the BioSonics was actively receiving. At no time was interference from the BioSonics seen in the ADCP data.

Vessel-mount data were collected alongside instrument bottom-mount campaigns conducted in fall 2018 and summer 2019 to test the functionality of the systems and to provide supplementary data. Field testing of the ADCP and echosounder was carried out in fall 2018 in Grand Passage. Data were collected along transects using a 600 kHz RDI Workhorse Sentinel ADCP and three BioSonics DTX transducers (38 kHz, 120 kHz and 200 kHz). The instrument configuration on the Puffin pole mount is shown in Figures 2 and 3. Weather conditions limited our work, however we were able to confirm the presence of fish schools in the water column, as well as verify that the bottom-mounted 120 kHz BioSonics DTX transducer was sampling by detecting pings while operating the vessel-mounted echosounder in listening mode.

Figure 2: Vessel pole-mount installation aboard the RV Puffin.

Vessel-mount data were collected from the RV Puffin immediately following the 2019 bottom-mount campaign, using a Nortek Signature500 ADCP, Raymarine echosounder, and Sub-aqua HD optical camera. Given that the BioSonics DTX echosounder was not on board, the data are not suitable for a statistical validation of the ADCP fish counting and velocity data. Fish schools that were observed using the acoustic instruments were generally at depths beyond the effective range of the optical camera.

Initial testing of the Jetyak was carried out in Freeport Harbour in October 2019, following the second of two bottom-mount instrument deployments. Mission planning and Jetyak auto-navigation trials were conducted. During testing, the Jetyak carried a Ping DSP sidescan sonar. The Ping DSP mount point was modified to decrease the protrusion of the instrument from the underside of the Jetyak in anticipation of high flow speeds. The Ping sonar operated from the Jetyak demonstrated the ability to resolve known water column objects (i.e., seaweed) in shallow waters that are generally inaccessible to larger operating platforms.

Further testing of the Jetyak was conducted in high flow areas of Grand Passage, and included both human-controlled and autonomous missions. The deployment area roughly corresponded to the location of the bottom-mounted instrument frame. In same high flow areas, pre-programmed autonomous missions of grid patterns were successfully completed in flows of up to 2.5 m/s.

Figure 3: Vessel-mount configuration aboard the RV Puffin in Grand Passage. The four instruments on the pole mount (left of image) from left to right are the 600 kHz RDI ADCP and the 38 kHz, 120 kHz, and 200 kHz BioSonics DTX transducer heads. The post on the right is a GPS receiver.

2.3 Bottom Mount Deployment

2.3.1 2018 Bottom Deployment

For bottom mounted data collection we co-located a 600 kHz RDI Workhorse Sentinel ADCP with a 120 kHz BioSonics DTX split-beam echosounder. The deployment took place in Grand Passage, Nova Scotia, at a depth of 25 m. The nominal tide range in Grand Pasage is ca. 5 m and the current speeds as much as 2.5 m/s. We chose this site because it is located in a tidal channel that is identified as having the potential for in-stream tidal generation. From preliminary tests we had identified the potential for interference of the BioSonics data from the ADCP transmissions. In order to eliminate risk to the data, we selected different sonar operating frequencies and regulated the duty cycles to overlap for half of the total sampling time to assure the collection of uncontaminated data. The bottom-mounted self-contained frame is shown in Figure 4, and was deployed at the location shown in Figure 5; note that the location was selected to avoid any intersection with the nearby ferry route.

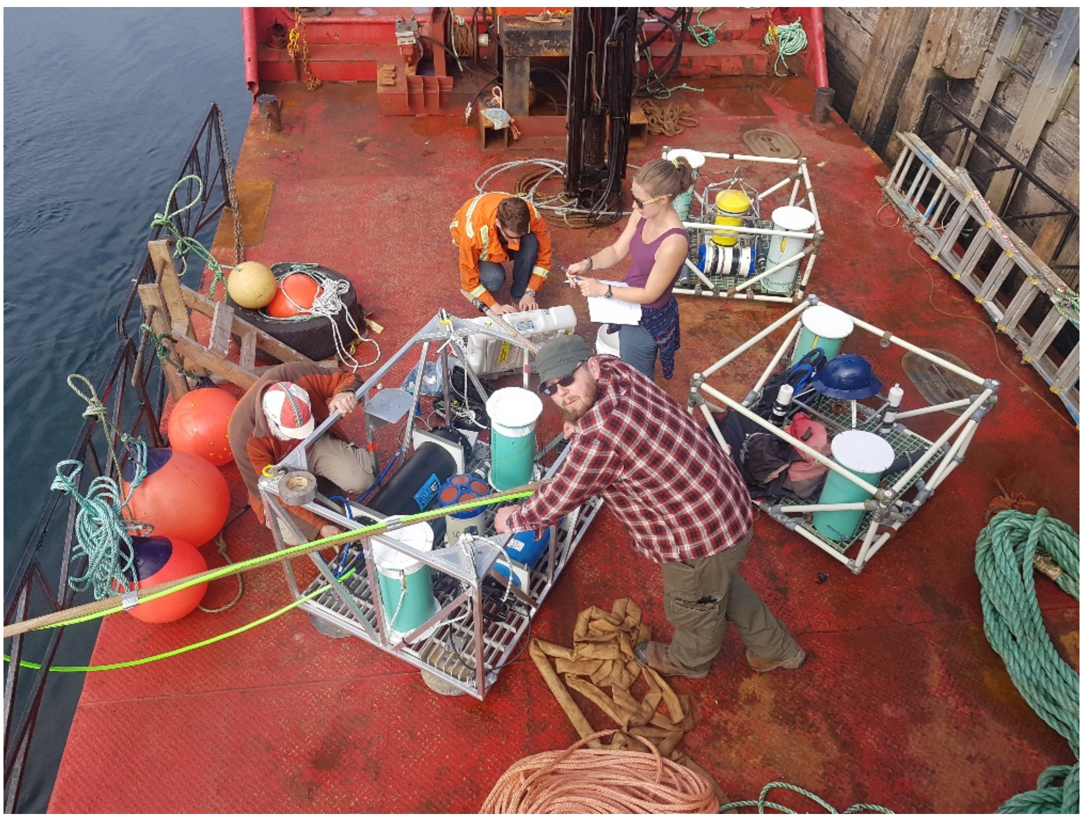

Figure 4: Bottom frame being prepared for deployment in Grand Passage, 2018.

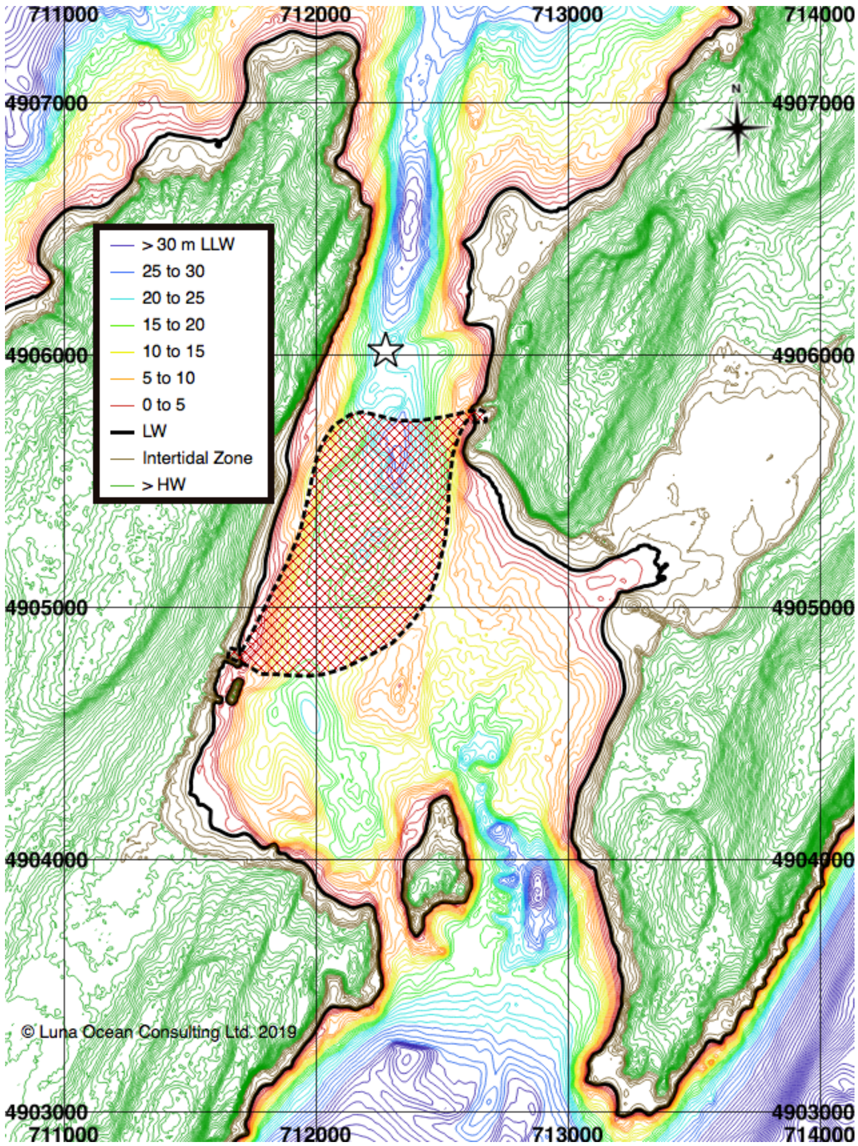

Figure 5: Map of Grand Passage. ADAAM 2018 bottom frame deployment location indicated by the white star. The bounds of the ferry route are shown by red cross-hatched region and dotted black outline.

The equipment was deployed for 37 days, from September 21, 2018, to October 29, 2018, however – unfortunately – a battery manufacturer fault coupled with battery de-rating associated with lower operating temperatures limited the BioSonics DTX sampling period to approximately 9 days. The ADCP logged data for the full 37 days.

A common problem when operating two nearby acoustic instruments is interference between the two instruments. We chose widely separated frequencies to mitigate this problem (120 kHz for split-beam and 600 kHz for the ADCP). Nevertheless, we observed contamination in the split-beam sonar data during lab tests. Therefore, in addition to the separate frequencies, we staggered the duty cycle to ensure the collection of both individual uncontaminated data as well as simultaneous measurements. The ADCP was set to collect at one ping per second with 1 m bins with no averaging of the profile data; the sampling duty cycle was 20 minutes on and 20 minutes off. The split-beam sonar was configured to transmit four pings per second at a 0.1 ms pulse duration. The staggered duty cycle was set up by an initial 10 minute lag relative to the ADCP and a 20 minutes on and 40 minutes off duty cycle. With the sample schedules offset by 10 minutes in this way, there were 10 minutes per hour during which both instruments operated simultaneously (37 hours in total) and 10 minutes with each instrument operating independently. Review of the collected data demonstrates that simultaneous operation results in some interference but is of a nature that does not preclude fully recovering the data. Future data collection will focus on simultaneous operation.

The ADCP compass was calibrated the day before the deployment using the conventional rotation of the mounted frame. Calibration of the (magnetic) compass corrects for the presence of any iron (or other ferromagnetic) materials that distort the earth's magnetic field. In order to recover accurate instrument orientation information, the calibration removes these deviations from the compass data. The ADCP backscatter calibration coefficients were taken from a January 2018 laboratory calibration. The split-beam was calibrated with a 33.2 mm diameter tungsten carbide sphere in the days immediately following the retrieval of the frame; the calculated offset of 1.1 dB was applied to the BioSonics dataset.

The data sets contain several instances of fish detections, and the experiment in this regard was highly successful, with limitations. In addition to shortened battery life in the BioSonics system, a fault in the ADCP configuration allowed only for fish detection, not calculation of their swim speeds. For this reason, a repeat of this experiment was planned for 2019, including implementation of lessons learned with regard to power management and a change in ADCP configuration options that was available in newer ADCP models but unfortunately not on the instrument used during the first deployment.

Sub-sea optical video was not collected in 2018 for the vessel mount or bottom mount experiments.

Fish count results from the comparative analysis are described in Section 2.5.1.

2.3.2 2019 Bottom Deployment

A second bottom deployment was carried out from June 11 to July 9, 2019 (28 day duration) with a co-located 600 kHz RDI Sentinel Workhouse ADCP, 120 kHz BioSonics DTX split-beam echosounder, and Sub-aqua HD optical camera. The ADCP provided data for the entire 28 day deployment while the BioSonics DTX successfully collected data for 24 days. The extended deployment duration from the BioSonics system was achieved by correcting a significant battery power leak and adjusting the sampling duty cycle.

The deployment time was chosen to meet academic constraints while deferring as long as possible in order to capture fish migrations. Both the ADCP and BioSonics data were of good quality for evaluating fish presence in Grand Passage. Unfortunately, we saw very few fish during this deployment, making the dataset unsuitable for pursuing the ADAAM project objective of validating ADCP use for fish detection.

The Sub-aqua HD optical camera operated as expected, with a logging duration of 2 days. Fish were observed in some instances, though not coinciding with data collection by the duty-cycling acoustic instruments. The optical camera imagery was compiled and converted to a video format to be reviewed by community members for the presence of fish schools, as described in Section 2.1

2.4 Mobile Data Collection Platforms

Data were collected from vessel-based platforms in September-October 2018, August 2019, and August-September 2020. The 2018 and 2019 deployents were carried out alongside bottom-mount deployments, and served to supplement the data collected from the bottom pod and field-test the instruments on a vessel-based platform. The 2018 and 2019 vessel-based deployments are described in Section 2.2. These data were not used for statistical validation of ADCP-based fish counting and velocity observation, though the 2019 vessel deployment with a Nortek Signature500 did provide useful data for extending the capability of the ADCP data processing software package. The 2020 vessel-mount deployments were specifically tailored to collect data for validating ADCP-based fish swimming velocity measurements.

2.4.1 2020 Vessel Deployment

During August and September of 2020, data were collected using the 120 kHz BioSonics DTX split-beam echosounder and a 600 kHz RDI Workhorse Sentinel ADCP mounted aboard the RV Grand Adventure. Both instruments were mounted on a pole which could be lowered over the vessel's port side and fixed in position, as shown in Figure 6. In the deployed position, the instruments were submerged to a depth of approximately 1 m. Data collection days were determined by weather and the availability of the vessel and crew. Days characterised by wind and waves (wind speeds greater than ca. 10 kts) were avoided based on adverse effects on data quality. The regional scope of the sampling included Grand and Petit Passages, St. Mary's Bay, and the outer Bay of Fundy, between Petit Passage and Brier Island (Figure 7).

The ADCP was powered by the Grand Adventure's 12 V power supply with a DC-AC inverter, and data were recorded on a Panasonic Toughbook laptop. The BioSonics DTX was powered from a dedicated 12 V DC Deep Sea Power & Light battery. Data were live-viewed and recorded on a Toughbook laptop. The same ADCP backscatter calibration data obtained prior to the 2018 bottom-mount deployment were applied to the 2020 ADCP data.

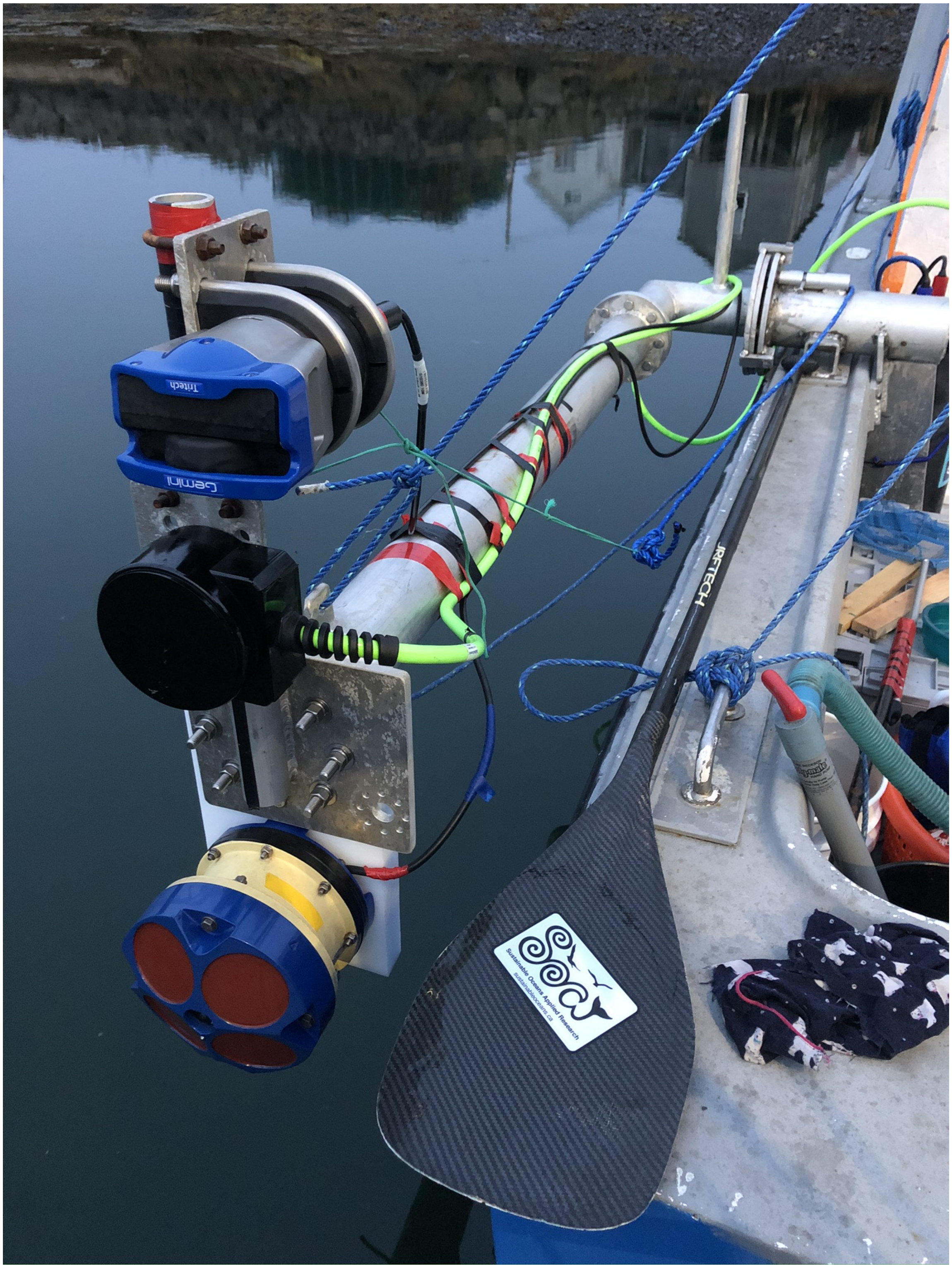

Figure 6: Instrument mounting pole in the undeployed position aboard the RV Grand Adventure. The 600 kHz RDI Workhorse Sentinel ADCP and 120 kHz BioSonics DTX split-beam echosounder are the bottom and middle instruments, respectively. The third instrument (highest in the photo) is a Tritech Gemini multibeam sonar which was not used for the purposes of this report.

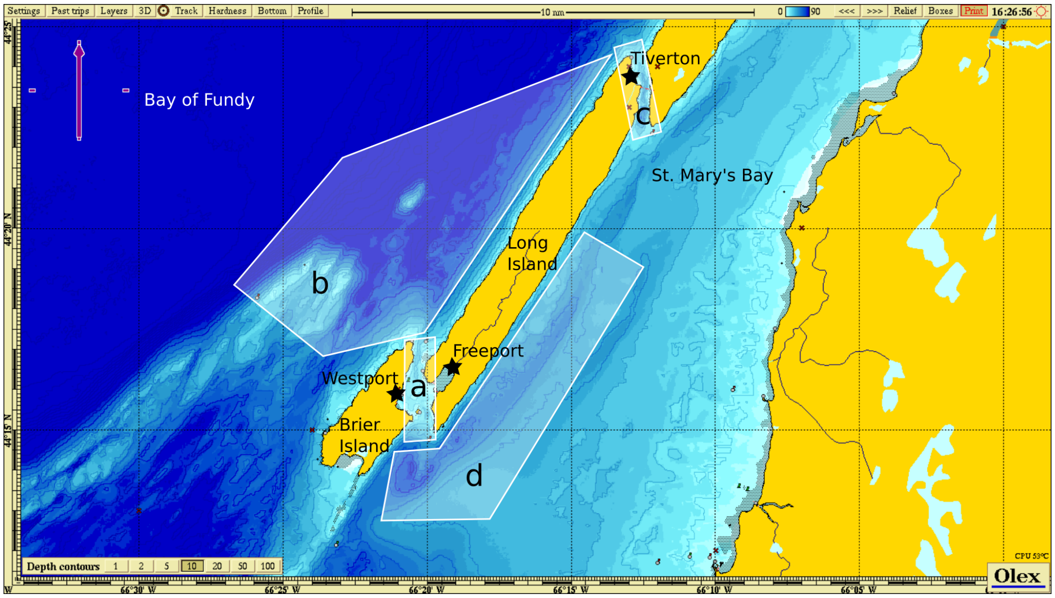

Figure 7: Map of vessel-based survey region, including (a) Grand Passage, (b) the outer Bay of Fundy, (c) Petit Passage, and (d) St. Mary's Bay.

The Grand Adventure typically travelled at a reduced speed of ca. 2 m/s while sampling, relative to a more typical 3.5-4 m/s transit speed. In some cases where fish schools were visible on the BioSonics real-time display, the vessel was slowed and allowed to passively drift.

We observed many – often large – fish schools during our data collection. We were able to visually identify fish species (herring, mackerel, and pollock) in select cases where fish could be observed from the surface. One particularly large sequence of schools is shown in Figure 8. Visual observations from the surface indicated that herring were present. Unfortunately, large dense schools such as the ones shown in Figure 8 are not suitable for camparative analyses between the ADCP and split-beam echosounder because of target saturation effects. The details of this limitation are discussed in Section 2.5.2.

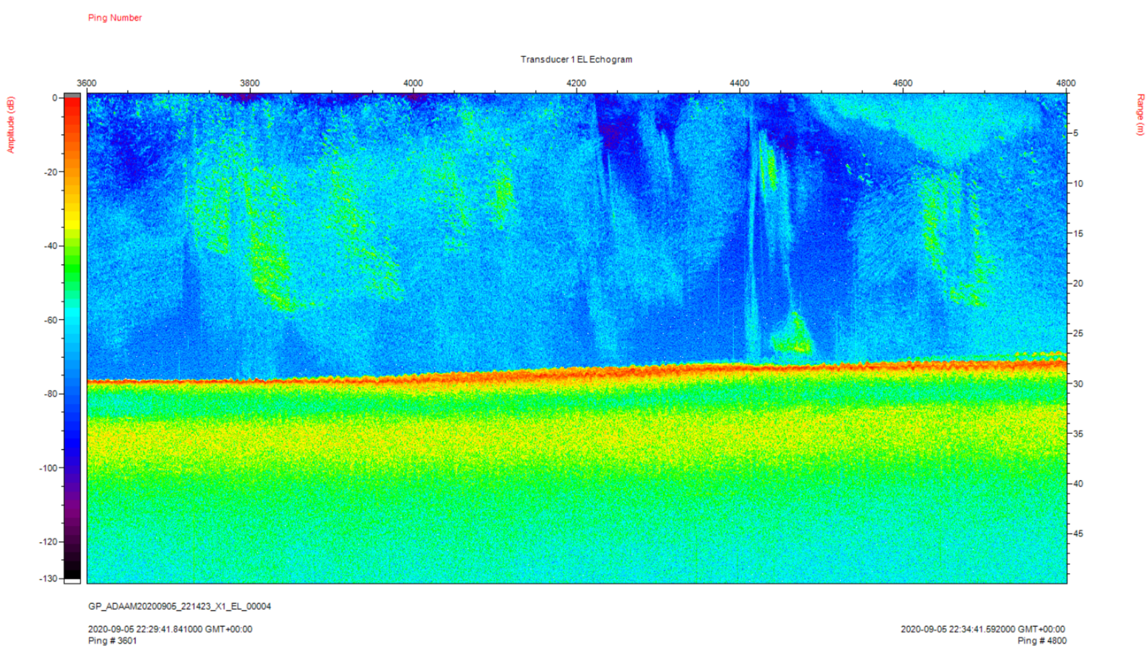

Figure 8: BioSonics DTX echogram of large fish schools observed on 5 September 2020. Herring were observed at the sea surface.

2.4.2 Jetyak Deployment

Figure 9: The Jetyak on September 1, 2020, in transit northward out of Petit Passage.

The Jetyak (Figure 9) was deployed on August 31 and September 1, 2020, and was operated in tandem with the RV Grand Adventure. The Jetyak carried a Nortek Signature500 ADCP and Ping DSP sidescan sonar. The survey area included Grand and Petit Passages, St. Mary's Bay, and the outer Bay of Fundy.

The Jetyak demonstrated a high level of capability as a deployment platform; it was collectively operated for approximately 8 hours during the two deployment days, and was exposed to currents up to 2.5 m/s, as well as the relatively exposed waters of the outer Bay of Fundy and St. Mary's Bay. Unfortunately, an unresolved technical issue with the Signature500 ADCP meant that data were not recorded for the majority of the deployment, and acoustic interference with the Ping sonar was a major issue during periods when data were collected. Fish schools are observable in the data collected using the Ping DSP. Some examples are shown in Figure 10. In select cases, fish schools visible to the RDI ADCP and BioSonics DTX echosounder on board the RV Grand Adventure are also visible using the the Jetyak-mounted Ping DSP, though spatial referencing is difficult given that the instruments were not co-located.

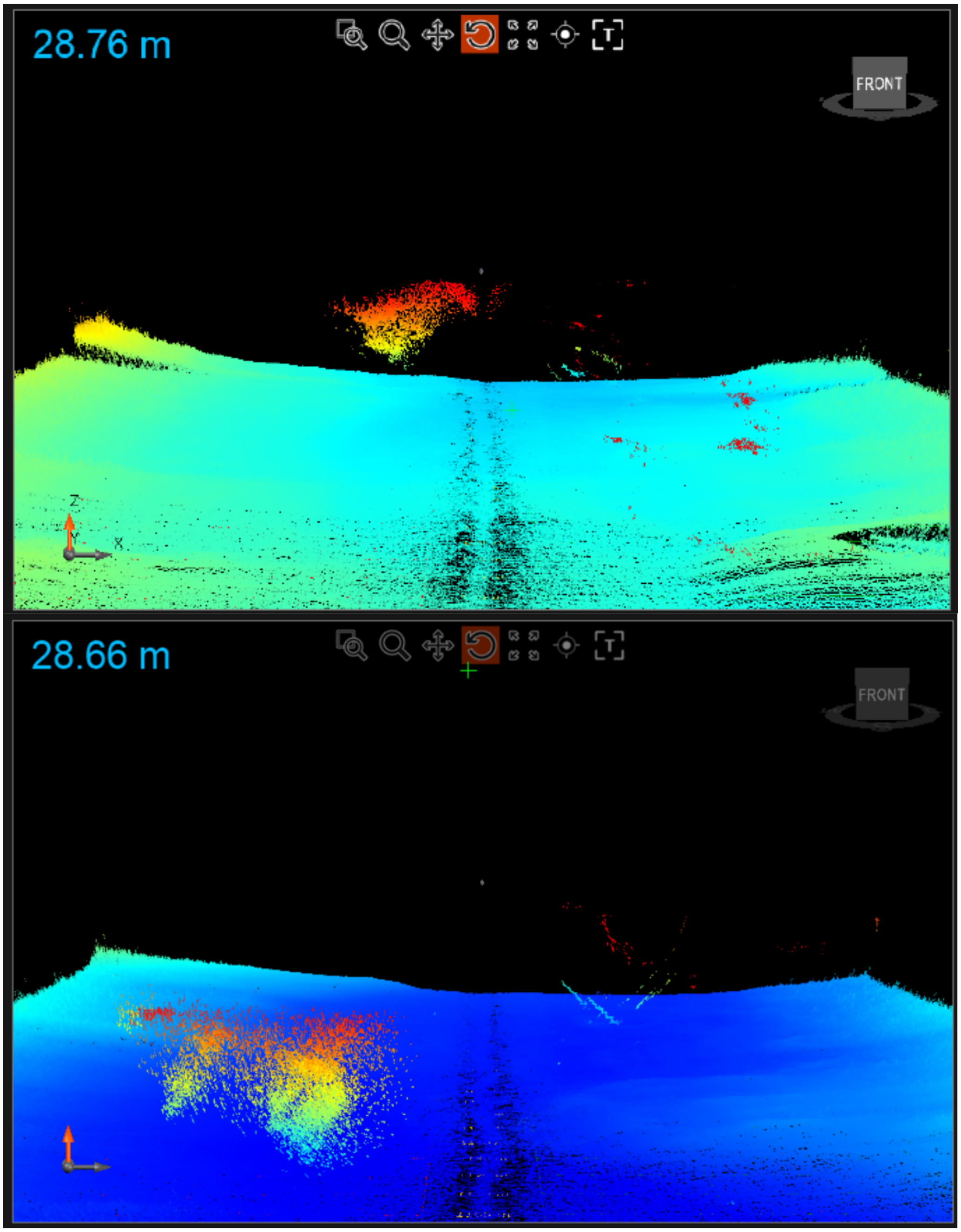

Figure 10: Sidescan sonar images from the Jetyak-mounted Ping DSP sonar, September 1, 2020. Returns from a fish school are visible (red-yellow-green). The water depths at times of recording were 28.76 m and 28.66 m.

2.5 Data Analysis

In this section we present results from the quantitaive fish counting and velocity comparisons between data from the BioSonics DTX split-beam echosounder and ADCP data processed using the novel least-squares processing method. Section 2.5.1 follows directly from discussion in M. Dunn's thesis (*Dunn*, 2019). The data used in the analyses are principally drawn from the 2018 bottom-mount deployment and the 2020 vessel-mount deployments. The 2018 bottom deployment yielded data of the highest quality for fish counting comparisons, though velocity data were not retrievable. Data from the 2020 vessel deployments were used for the velocity comparison.

2.5.1 Fish Count Comparisons

Backscatter data were converted to volume backscatter coefficients using the procedure outlined by *Deines* (1999). The presence of fish in the Doppler sonar data can be indicated by volume backscatter levels exceeding a specified threshold, but properties unique to the broadband Doppler system allow discrimination of discrete targets as opposed to volume backscatter. Broadband Doppler systems transmit pulse pairs and the magnitude of the autocorrelation of the received signal is a measure of the quality of the received signal and the phase of the autocorrelation is used to extract velocity. When coincident with a high volume backscatter signal, a strong correlation suggests an acoustically discrete target like a fish or the surface, as distinct from median value correlation characteristic of a cloud of bubbles or a more extensive school of fish (*Tollefsen and Zedel*, 2003).

The volume backscatter and correlation thresholds are applied to each beam individually for fish detection. An example is shown in Figure 11. Threshold value of -45 dB and 153 counts were used for volume backscatter and correlation respectively. To place the correlation threshold into context, normal volume backscatter data would have an average correlation of about 128 counts. Conversely, water targets are identified as signals below either the intensity or correlation thresholds. Note in particular the clear agreement in backscatter structure when comparing the Doppler sonar data (Figure 11a) with the split-beam data (Figure 11c).

Sonar5-Pro, a post-processing tool for echosounder data, was used to extract fish detections from the BioSonics data for count comparisons. Fish were identified in the split-beam sonar data based on target strength alone. Strong returns from the surface and also strong returns from near-surface bubble plumes by the echosounder had to be removed from the data as an analysis step. A surface exclusion line could be defined automatically within the software by using the bottom detection algorithm, however manual adjustment for areas of combined fish and bubble signals was generally required. The Cross-Filter Detector algorithm (*Balk and Lindem*, 2002) was used to identify single echo detections (SEDs) and to combine them into fish tracks. This algorithm is composed of two filters: a foreground filter that smooths over the stronger signal with a running mean and a background filter that smooths the weaker signal and adds an offset to minimize the intensity of the weaker signal even further. The combination of these filters isolates the targets into SEDs. These targets are then combined into fish tracks based on proximity, and accepted or rejected depending on length, speed, and path. Both SEDs and fish tracks (combined sequences of SEDs) are useful

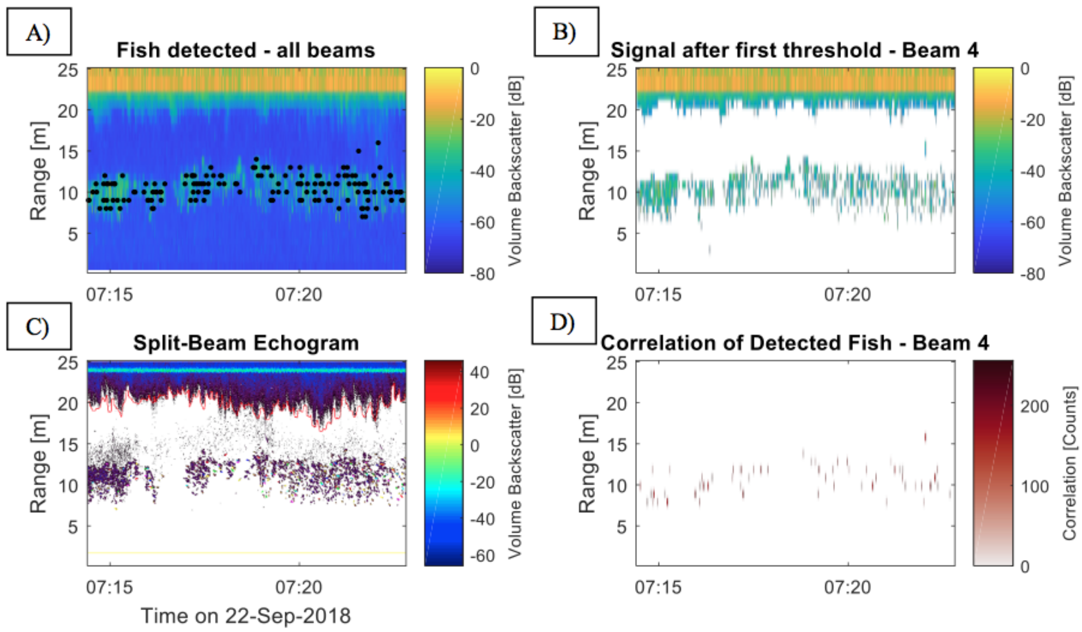

Figure 11: A) A volume backscatter echogram from the ADCP of a fish school, with the identified fish targets (.) from all four beams. B) The remaining data after the backscatter threshold is applied. C) The corresponding split-beam echosounder signal. D) Return signals that met or surpassed the intensity and correlation thresholds. Figure from *Dunn* (2019).

for comparisons to target counts from an ADCP, with the knowledge that a given target may be counted multiple times in the SED case. Only the SEDs included in tracks and the whole tracks themselves were used to compare with the fish targets identified in the ADCP data. In other words, isolated SEDs that were not grouped into tracks by the Sonar5-Pro algorithm were omitted from any analyses.

A total of 37 hours of simultaneous data were collected between September 21 and October 1, 2018, in 10-minute intervals. The accepted fish detections for both instruments were averaged over 2-hour time bins and 1 m depth bins in order to make a comparison. A particular challenge in strong tidal flows is the occurrence of near surface bubble plumes (*Melvin and Cochrane*, 2013) which are often hard to distinguish from fish (or plankton) targets. With the Doppler sonar, we used the requirement of high signal correlations to distinguish discrete targets from bubble clouds. The filtering process is demonstrated through the data present in Figure 11. Note the difference between Figure 11b and 11d, where the correlation threshold effectively removes the bubble plumes. For split-beam sonar data, most bubbles were avoided by using the surface exclusion line algorithm. That algorithm is not always correct and it requires a user to review areas of spread bubble plumes or regions where fish and bubbles are mixed. In these areas, it becomes a somewhat arbitrary judgment call to distinguish desirable data from bubble clouds. This process is irreproducible and time-consuming.

The ADCP and the split-beam sonar were evaluated by comparing counts with overlapping 2 m depth and 2 h time intervals. A linear regression model (Figure 12) between the two instrument detections has a slope of 1.47 for the fish tracks and 9.87 for the SEDs. The single echo detection and fish track comparison show that there are an average of seven single echo detections per track. The fish tracks are a slightly better representation of fish counts when compared to ADCP-derived counts. Overall, the datasets indicate a strong agreement between instruments, with a cross-correlation coefficient of 0.91. Due to differences in sampling volumes, operating frequency, and measured product (fish track counts or SEDs within fish tracks for the split-beam versus fish targets alone for the ADCP) differences in counts between the instruments are expected.

A time series comparison of fish target and fish track counts from the ADCP and echosounder spanning the full period over which both instruments were sampling is shown in Figure 13. There is a clear qualitative agreement between the target distributions, though the ADCP appears to detect targets in some instances where the echosounder detects fewer, or none.

The linear relationship between fish target and SED/fish-track counts from the ADCP and echosounder is very encouraging and certainly meets our expectations. This result gives us a basis to reanalyse earlier data sets to explore any biological signals of significance. For example, data collected for monitoring turbulence in Grand Passage in 2012 were suitable for reprocessing for fish detections. Examples of such reanalysed data, from September 4-7, are shown in Figures 14 and 15. In Figure 14, the size of fish schools and their mean vertical position are plotted relative to the position of the mean sea surface, and mean school velocities plotted alongside components of current velocity, together allowing an analysis of school dynamics relative to tidal phase. In Figure 15, time series of acoustic backscatter intensity, fish counts and concentrations, and flow speeds reveal periodic signals of fish presence. The availability of such data sets invites opportunity to

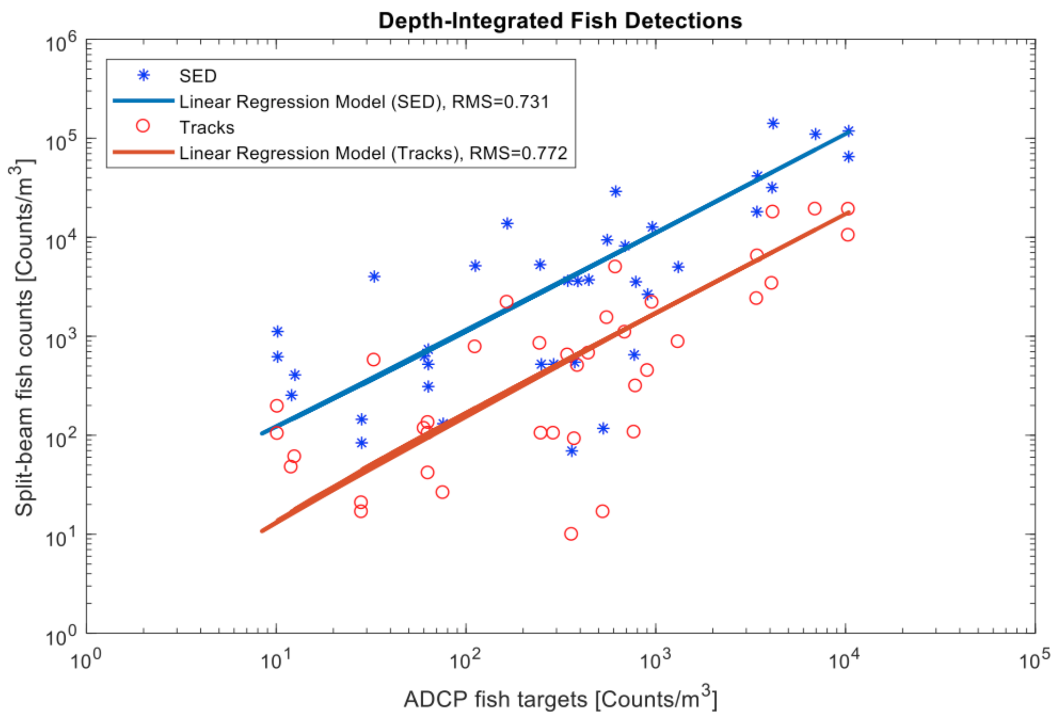

Figure 12: Linear regression analysis for comparison of ADCP fish targets dataset to split-beam fish track counts and SED within fish tracks count. Figure from *Dunn* (2019).

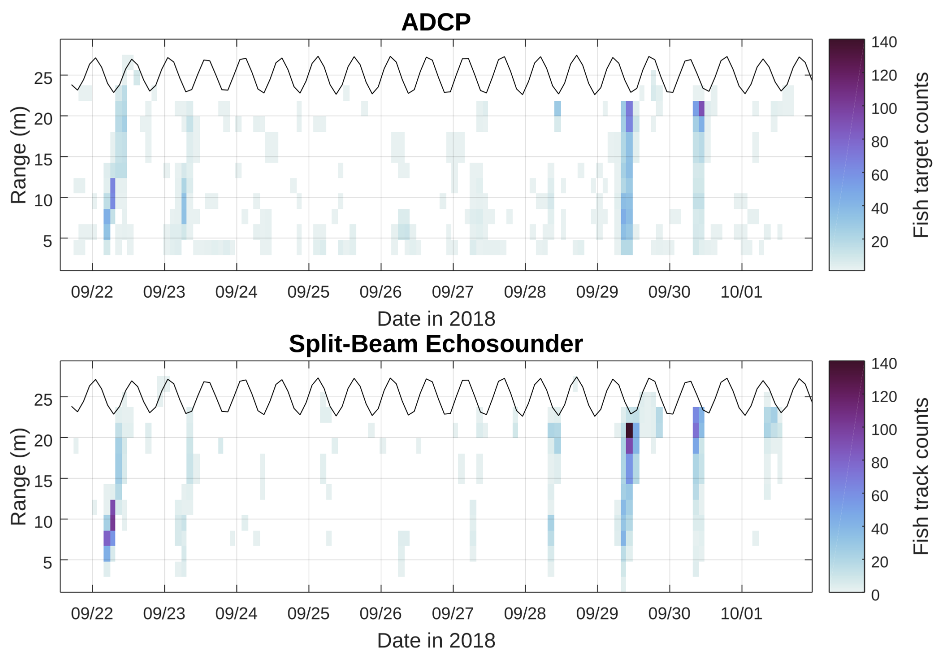

Figure 13: Time series of fish target counts from the ADCP (upper) and sigle echo detection track counts from the split-beam echosounder (lower). Figure from *Dunn* (2019).

partner with biology researchers to explore fish behaviour and fish usage of Grand Passage.

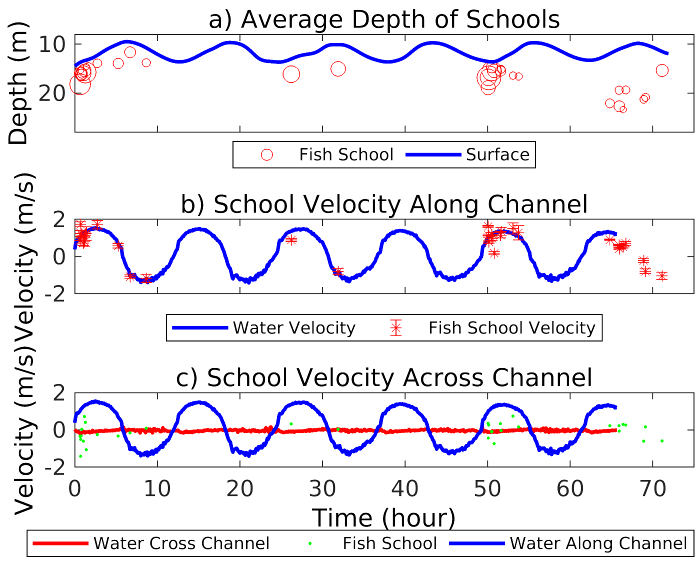

Figure 14: ACDP time series data of fish and fish school properties relative to currents from a 2018 bottom-mount deployment in Grand Passage, NS. (a) Depth of schools relative to the sea surface. Larger red markers correspond to larger schools. (b) Along-channel velocities of fish schools relative to the along-channel component of current velocity. (c) Across-channel velocities of fish schools relative to both the along- and across-channel components of current velocity. Figure from *Zedel* (2014).

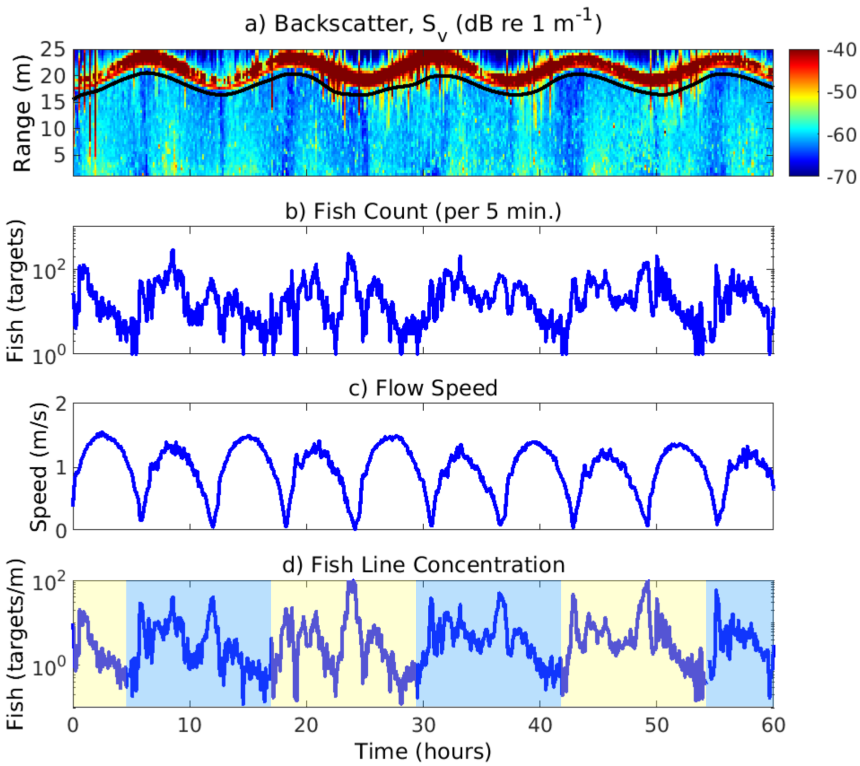

Figure 15: ADCP data from a 2018 bottom-mount deployment in Grand Passage, NS. (a) Acoustic volume backscatter strength: indicates relative amount of acoustic backscatter. Possible suggestion of lower backscatter at times of high water. (b) Fish Count: direct count of total fish detected in water column. The volume of water sampled changes with time as tidal velocity changes. Fewer fish when the water isn't moving. (c) Flow speed: mean water speeds. (d) Line Fish Concentration: fish counts scaled by distance water has travelled in sample interval (fish detections per m). The value is proportional to fish concentration and shows relative variations. The alternating yellow and blue background panels highlight a semidiurnal period in fish concentration. Figure from *Zedel* (2014).

2.5.2 Fish Velocity Comparisons

Echosounder data collected during the 2020 vessel-mount campaign were processed using Visual Aquatic – the BioSonics proprietary processing software. Note that this software is different from the software used for the fish-count comparison (Sonar5-Pro). The change in software was a matter of availability due to licensing. Both softwares satisfied the same SED and fish track extraction requirements for our analyses.

Velocity is not a direct data product provided by the echosounder; as for the fish counting case, echogram data are processed to identify single echo detections (SEDs, which may be fish or other nekton, bubbles, (in)organic debris, etc.) using intensity thresholding. The software then combines contiguous, or nearly contiguous, SEDs based on a set of track selection criteria, allowing sequences of target ranges and angles within the echosounder beam – which are direct data products – to be used to compute along-track velocities. The implication of this process for retrieving meaningful velocity data is that individual targets (e.g., fish within a school) must be resolvable, so that the extracted tracks correspond to true target velocities, and not to erroneously combined SED sequences. Furthermore, the velocities of fish must be consistent within a school, since the comparison with ADCP-derived velocities requires averaging over time and depth.

We observed many, and often large, schools of fish or other scatterers during each of our vessel-based surveys. However, the schools were generally of a high enough density that neither we nor the software we used could identify individual scatterers within the schools. This was particularly problematic when computing velocities using data from the echosounder, which relies upon echogram image processing to infer the velocities of detected scatterers from one timestep to the next (that is, a computation that is less direct than the approach used for the ADCP). ADCP technology is able to extract fish school velocities under such circumstances (*Demer et al.*, 2000; *Zedel et al.*, 2003), though “saturation” of the data by discrete targets may occur when the number of fish per unit volume approaches the sampling resolution of the instrument; in other words, only one target detection is possible per sampled unit in time and space (0.25 s $\times$ 0.5 m, in the case of this deployment), leading the number of targets in dense schools to be underestimated.

In order to satisfy the considerations of fish school density and swimming behaviour, data analysts reviewed all the available data from the August and September 2020 vessel-mount deployments to identify instances where constituent targets within a school were resolvable by eye. The high-graded data were then processed using the Visual Aquatic software to evaluate whether the constituent targets in the schools were characterized by a consistent direction of travel. Two schools met the selection criteria (see Figures 16 and 17), both recorded on September 1, 2020, near the northern mouth of Petit Passage. The locations of the schools relative to Petit Passage, along with vessel trajectory data, are shown in Figures 18 and 19.

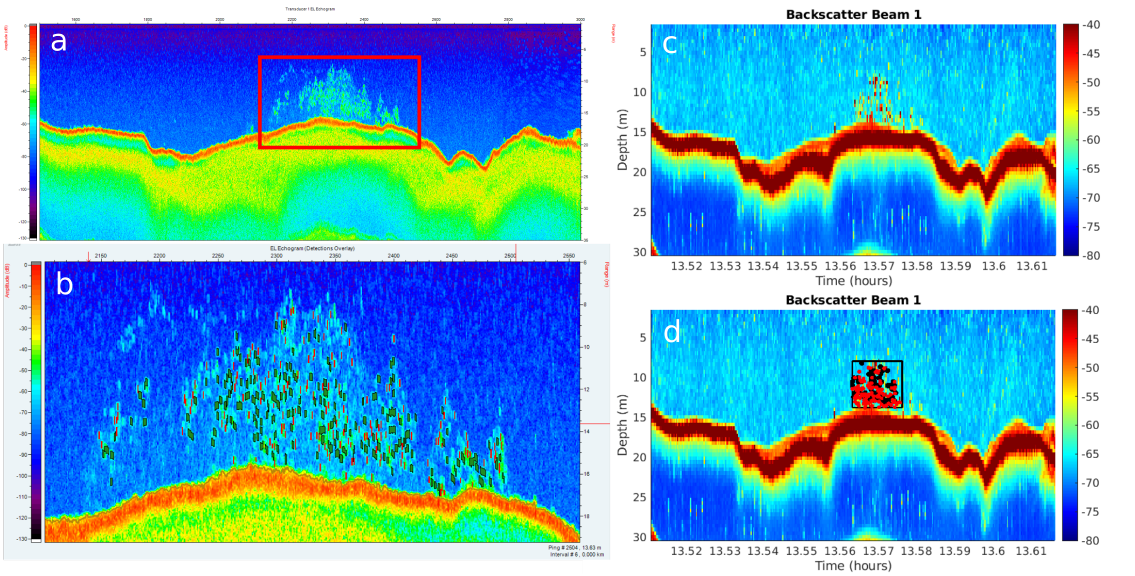

Figure 16: (a) Echogram image from the BioSonics DTX split-beam echosounder, as viewed in the Visual Aquatic software. The red box contains one fish school used for a comparison of velocity estimates from the ADCP. (b) Magnified echogram of the fish school, with single echo detections (red) and tracks (green) overlaid. (c) ADCP volume backscatter amplitudes (dB re 1 m^{-1}) associated with the same school shown in (a) and (b). (d) Target velocities were averaged over the time and depth intervals indicated by the black box. Red and black dots indicate the detected positions of targets by the echosounder and ADCP, respectively. The lower image resolution for the ADCP data relative to data from the echosounder is a function of the lower sampling resolution in time and space.

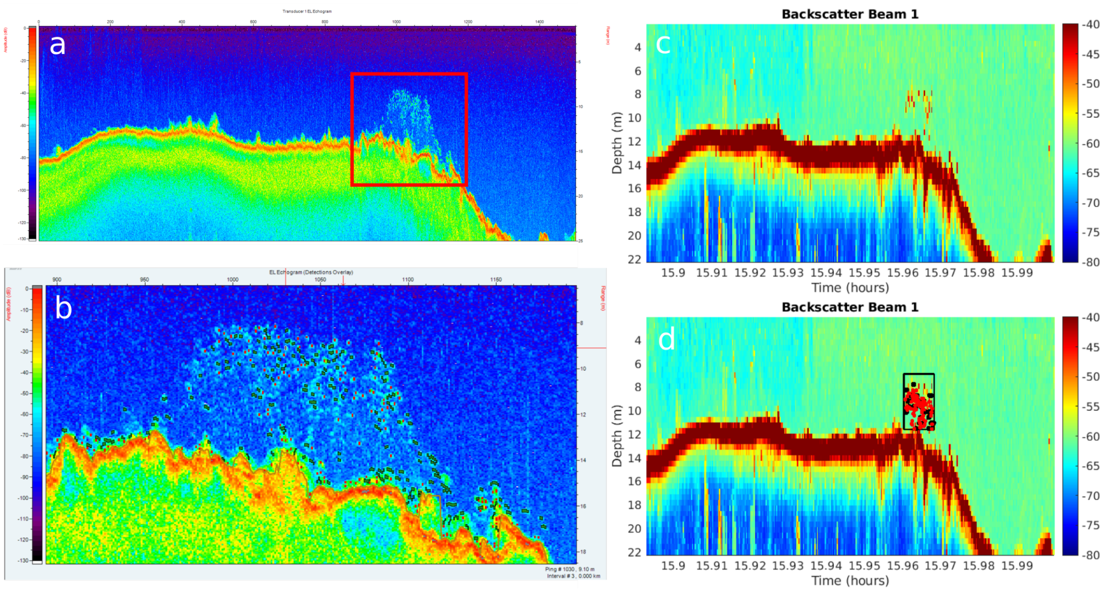

Figure 17: (a) Echogram image from the BioSonics DTX split-beam echosounder, as viewed in the Visual Aquatic software. The red box contains one fish school used for a comparison of velocity estimates from the ADCP. (b) Magnified echogram of the fish school, with single echo detections (red) and tracks (green) overlaid. (c) ADCP volume backscatter amplitudes (dB re 1 m^{-1}) associated with the same school shown in (a) and (b). (d) Target velocities were averaged over the time and depth intervals indicated by the black box. Red and black dots indicate the detected positions of targets by the echosounder and ADCP, respectively.

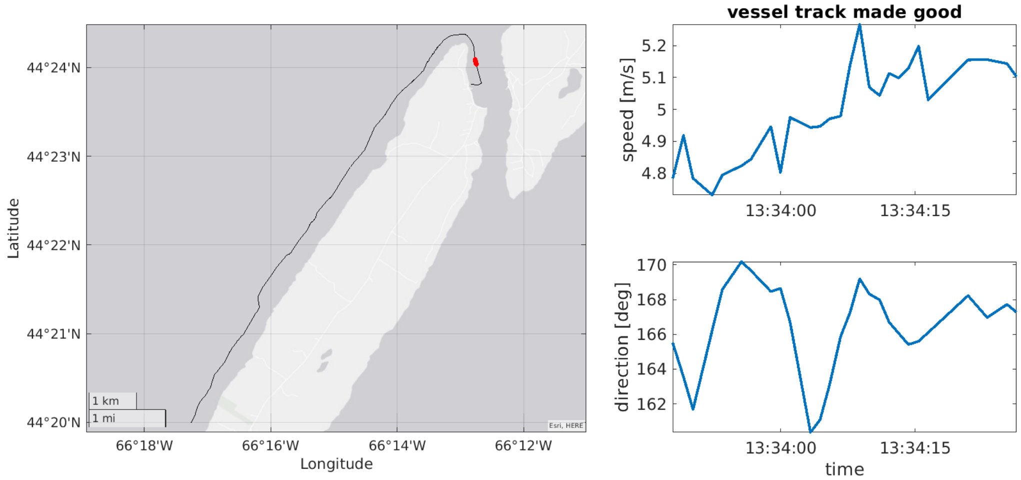

Figure 18: Left: Map indicating the location of the first of two schools selected for the comparative velocity analysis. The channel is Petit Passage, separating the Digby Neck from Long Island. Right: Speed and direction of vessel movement (over ground) during the averaging window (i.e. the red marks on left panel).

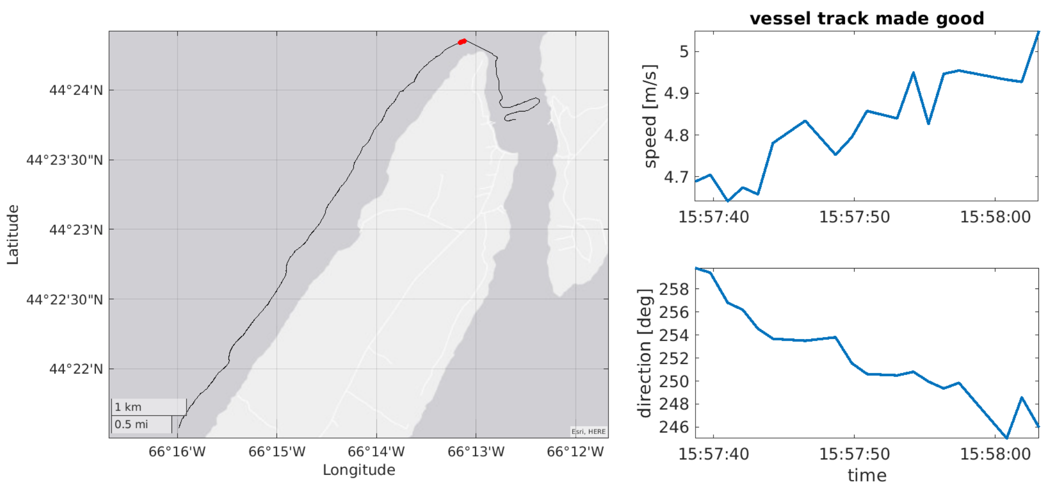

Figure 19: Map indicating the location of the second of two schools selected for the comparative velocity analysis.

Mean current velocity profiles and fish school velocity estimates are shown in Figures 20 and 21. Velocity estimates from the echosounder and the ADCP, averaged over the depth and duration that the schools were observed (ca. 5 m and 30 s, respectively), were of comparable magnitude and direction. The coordinate system is defined relative to the along- (fore-aft) and across-vessel (port-starboard) axes of the RV Grand Adventure. In the cases of both schools, the principal velocity component was along the fore-aft axis of the Grand Adventure, which was in transit while the schools were observed. The port-starboard velocity component was near zero, and neither component differed notably from the background current velocity. This suggests that the fish were being transported passively by the current, and that their swimming velocities were small relative to the vessel speed. Given that the Grand Adventure was not holding station while both schools were observed, it is expected that the current velocities in Figures 20 and 21 do not approach zero near the bed.

The consistent underestimate of the principal (fore-aft) velocity component by the echosounder relative to the ADCP is unsurprising, since any differences in fish swimming direction within the averaging area would tend to bias the estimate toward zero.

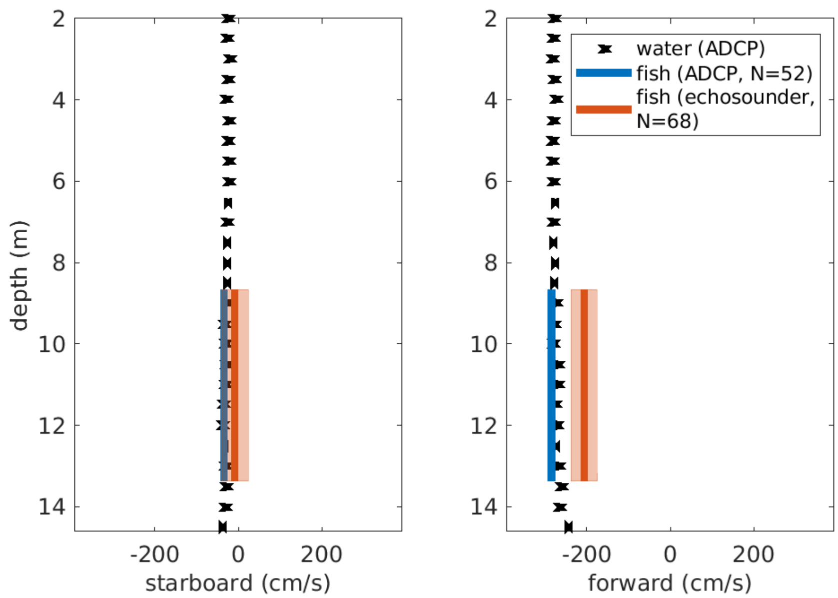

Figure 20: Selected fish school 1: Current velocity profiles for the the across-vessel (left) and along-vessel (right) components of velocity. The mean fish school velocities from the ADCP and echosounder, with 95% confidence intervals, are indicated by the coloured vertical lines and shaded boxes.

Based on the encouraging school velocity comparisons from the 2020 data, we applied the least-squares velocity computation method to data collected in Grand Passage during the 2019 vessel

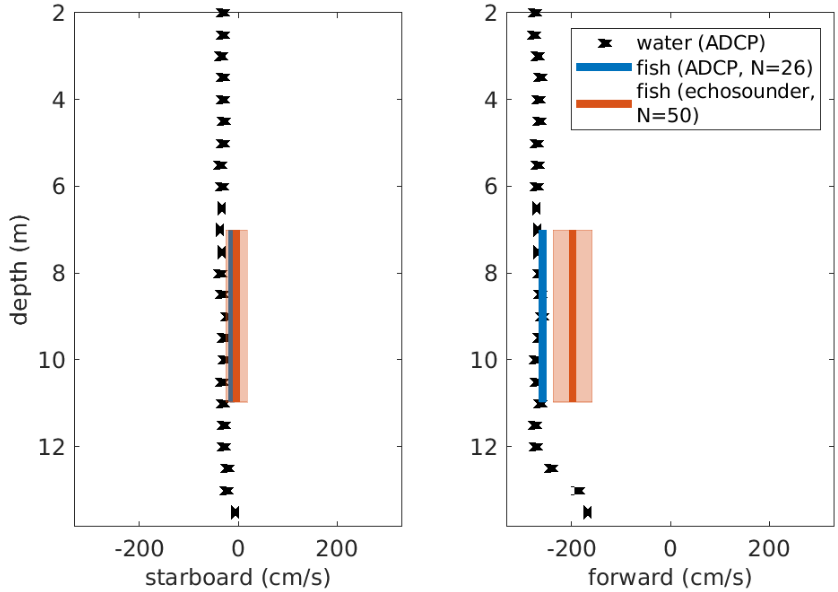

Figure 21: Selected fish school 2: Current velocity profiles for the the across-vessel (left) and along-vessel (right) components of velocity. The mean fish school velocities from the ADCP and echosounder, with 95% confidence intervals, are indicated by the coloured vertical lines and shaded boxes.

deployment aboard the RV Puffin. A split-beam echosounder was not on board, so the data are not suitable for use in the validation analysis; however, the deployed ADCP was a Nortek Signature500 rather than the 600 kHz RDI Workhorse Sentinel which collected the data used for the rest of the analyses in this report. Well-defined fish schools were visible during the deployment using the Puffin's Raymarine echosounder. A fish school visible using both the Raymarine echosounder and Signature500 ADCP is shown in Figure 22. Velocity estimates computed using a subset of the fish school data in Figure 22 are shown in Figure 23. Notable, in this case, is the clear difference between the velocity components of the fish school relative to the background current components, indicating active swimming behaviour. This is in contrast to the passive fish swimming behaviour observed during the 2020 campaign (see Figures 20 and 21).

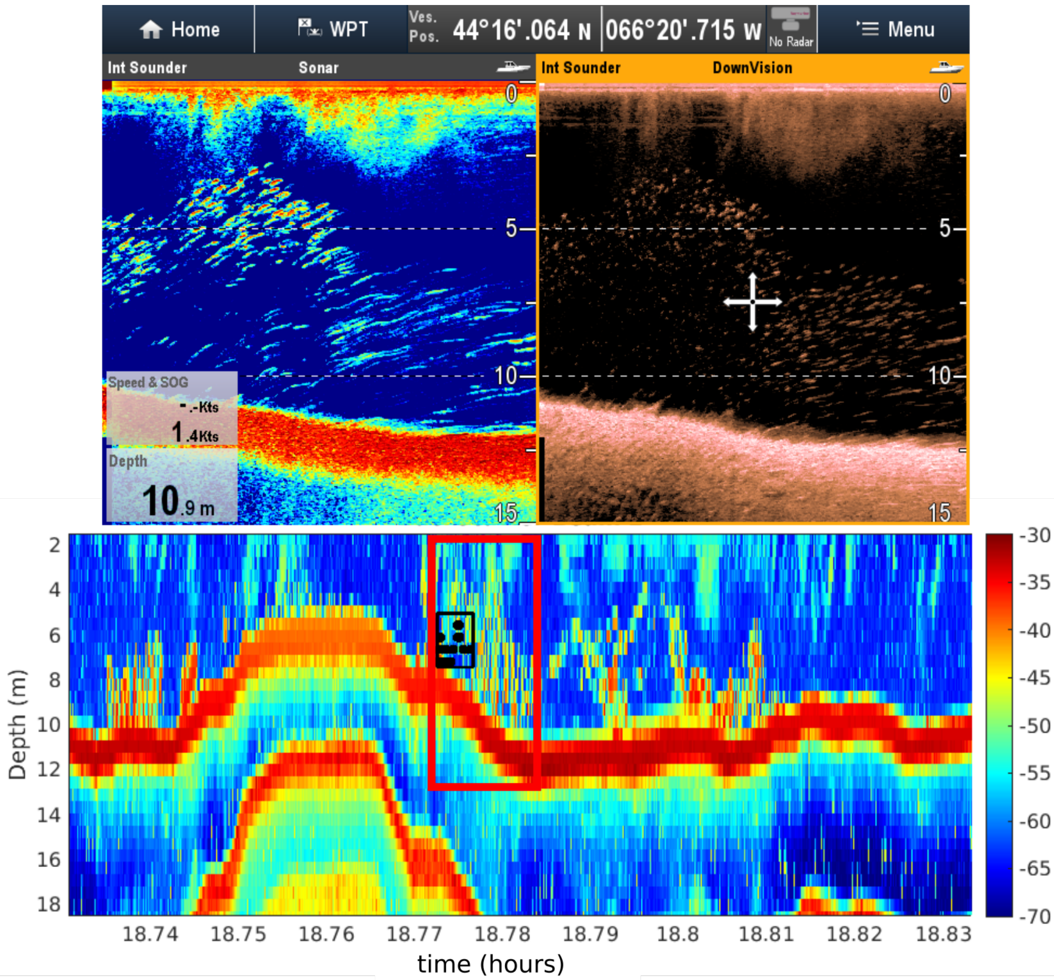

Figure 22: (Top) Fish school observed using the Puffin's Raymarine echosounder in Grand Passage, August 26, 2019. (Bottom) Backscatter intensity data, in dB re 1 m^{-1}, from beam 1 of the Nortek Signature500 ADCP deployed aboard the Puffin. The red box corresponds to the time and space intervals shown in the Raymarine echogram. Fish velocity estimates were computed using a subset of the fish school, shown by the black box. Detected fish are indicated by black dots.

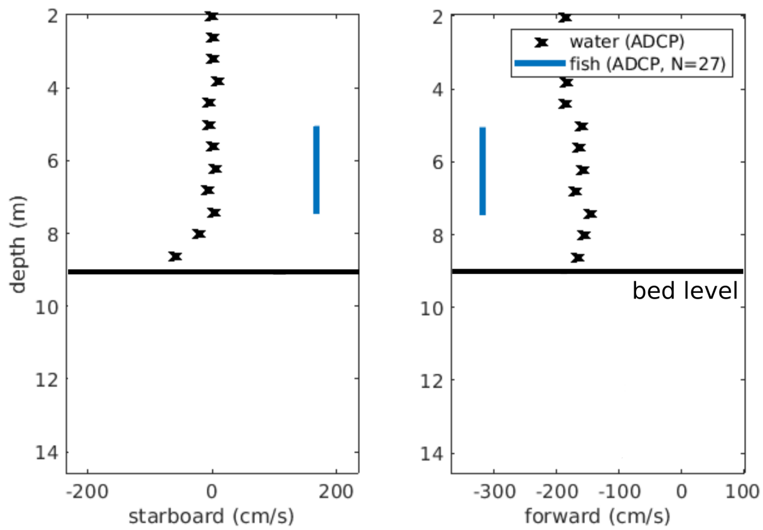

Figure 23: Current velocity profiles for the the across-vessel (left) and along-vessel (right) components of velocity, computed using data from a Nortek Signature500 ADCP (no corresponding split-beam echosounder data). The mean fish school velocities from the ADCP are indicated by the blue vertical lines.

2.5.3 Software

Software development is advancing with a package currently known as ADCPFish: A MATLAB toolbox that processes raw ADCP data into depth and time-averaged fish and water velocities. The original toolbox was developed by M. Dunn, based on code from Dr. Len Zedel. Development of the software package has been carried forward by Luna. The toolbox converts unprocessed data files from RDI or Nortek ADCPs, oriented either upward (bottom-mounted) or downward (vessel-mounted) into standardized MATLAB data structures, then it calibrates and corrects for spherical spreading and absorption. Using a combination of correlation and volume backscatter thresholds, the toolbox determines whether signals are from fish or water targets in each beam individually. The targets for all the beams are binned to calculate the average fish velocity and count. It also bins the non-fish targets to extract the water velocity profiles. The code is kept in an online repository and is maintained under version control. Documentation for each user-facing function and parameter is available, and additinal plotting and data visualization functions have been written.

2.5.4 Presentations

Content in this report has been presented at multiple conferences and seminars, including *Dunn et al.* (2019), *Zedel et al.* (2019), *Dunn et al.* (2020), and *Zedel and Trowse* (2020). The objectives of this report also provided a basis for M. Dunn's graduate thesis project (*Dunn*, 2019).

3 Conclusions

Our conclusions associated with each of the stated project objectives are as follows:

1. Validate the application of ADCPs to marine life monitoring:

We demonstrated that detections in ADCP data were proportional to those from the BioSonics split-beam echosounder. While exact agreement in detections would be exceptional and unexpected given the differences in sampling domain and ping interval, the linear relationship provides a level of validation that certainly meets our expectations.

The ADCP provides an alternative processing approach for dealing with near surface bubbles that eliminates the need for the more operator-intensive process of determining an exclusion line. Some of this processing advantage can be attributed to the use of correlation to distinguish discrete targets, but the higher frequency (600 kHz versus 120 kHz) was likely a factor as well.

The ability to extract fish velocity from ADCP data is to some extent an established capability (*Holliday*, 1974; *Demer et al.*, 2000; *Zedel et al.*, 2003; *Zedel and Cyr-Racine*, 2009). Validating the swimming velocities, however, remains a challenging task that is sensitive to properties of fish behaviour; namely, fish must be present, and in schools with sufficiently low density to (a) allow the computation of meaningful echosounder track data and (b) avoid oversaturation of the ADCP data by discrete targets. We did not collect data of sufficient quality for a robust statistical validation of the ADCD-derived fish swimming velocities. However, the comparisons associated with the schools that met our selection criteria are favourable. We consider the sensitivity of the analysis to the fish swimming and schooling behaviour we observed an important result, and recommend that it be considered carefully in the event of similar future studies. Long-term, fixed deployments are likely to be most fruitful, based on the infrequent and transient nature of suitable fish schools in the data.

On the choice of instrumentation and processing software: The use of Sonar5-Pro versus Visual Aquatic for the echosounder data analysis represents a notable difference between the bottom-mount and vessel-mount experiments. The extraction of tracks from the echosounder data contains steps that are inherently subjective, though the quality of the fish track data were likely much more dependent on the properties of the fish schools. The fish tracking software packages known to us (i.e., Sonar5-Pro, Visual Aquatic, or Echoview) appear flexible enough to achieve comparable results that are sufficient for the analyses described in this report. Though direct comparisons to the echosounder data were only made with RDI ADCP data, we would expect comparable performance using a different ADCP (i.e., Nortek). Differences in sampling rates between instruments may have implications for the number of fish identified by the algorithm, due to differences in repeat counts of individual fish.

2. Provide information on marine life (swim velocity, counts, and identification) utilizing the split-beam sonar, optical video, and ADCP data, including comparison of results:

The ADCP fish count data reveal interesting variations of fish presence in time and space. The fish count validation results provide a basis to reanalyse earlier data sets to explore any biological signals of significance.

The fish velocity data obtained using both ADCPs and the echosounder indicates that the fish schools we observed were not actively swimming, or at least had velocities that were small relative to the principal current velocity component (ca. 2 m/s)

The optical camera was used during one bottom-mount deployment (2019) and multiple vessel deployments (2018, 2019). In general, targets that were visible to the acoustic instruments were not visible to the camera due to the limited optical range. In this regard, the camera was not generally useful as a validation tool for species identification, counting, or velocity estimation. However, the camera data were used as a community engagement tool, and public involvement did help to identify instances where fish schools were visible in the data.

We were able to identify fish species in some instances where the schools could be seen near the surface (e.g., herring, mackerel, pollock). In select cases, we were able to associate the visually identified schools with schools visible to the ADCP and echosounder.

3. Advance methods for ocean bottom-mount and vessel-based data collection:

We have demonstrated the vessel-mount infrastructure developed for use aboard the RV Puffin and the RV Grand Adventure to be highly functional and robust for data collection in the high tidal flow environments of Grand and Petit Passages. The pole-mount systems employed on both vessels allowed us to rapidly deploy the co-located instruments. The vessel-based deployment platforms benefit from lower operational costs and complexity than autonomous bottom deployments. However, the shorter-term vessel deployments came with associated challenges of collecting sufficient and suitable validation data.

The Jetyak has been shown to be a uniquely capable deployment platform. Though data collected using the Jetyak was not suitable for use in the ADCP validation analyses, we were able to use data from the the Ping DSP sidescan sonar to visualize fish schools in some cases. The utility of the Jetyak in shallow coastal waters coupled with the decreased risk to survey operators makes the Jetyak a promising tool for future deployments.

4. Develop algorithms for marine life detection from ADCP data for academic use and commercial application:

The data processing pipeline used to analyze the ADCP data presented in this document has been organized as a toolbox currently known as ADCPFish, which processes raw ADCP data into depth and time-averaged fish and water velocities. The toolbox is based on code written by Dr. Len Zedel, and was adapted for use as a toolbox by Muriel Dunn. The application has since been refactored and extended to encompass a broader range of instrument types, orientations, and functionality.

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