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Quo Vadimus

Uncrewed surface vehicles (USVs) as platforms for fisheries and plankton acoustics

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Abstract

Uncrewed surface vehicles (USVs) equipped with echosounders have the potential to replace or enhance acoustic observations from conventional research vessels (RVs), increase spatial and temporal coverage, and reduce cost and carbon emission. We discuss the objectives, system requirements, infrastructure, and regulations for using USVs with echosounders to conduct ecological experiments, acoustic-trawl surveys, and long-term monitoring. We present four example applications of USVs with lengths <8 m, and highlight some advantages and disadvantages relative to RV-based data acquisitions. Sail-driven USVs operate continuously for months and are more mature than motorized USVs, but they are slower. To maintain the pace of an RV, multiple sail-powered USVs sample in coordination. In comparison, motorized USVs can travel as fast as RVs and therefore may facilitate a combined survey, interleaving USV and RV transects, with RV-based biological sampling. Important considerations for all USVs include platform design, noise and transducer motion mitigation, communications and operations infrastructure, onboard data processing, biological sampling approach, and legal requirements. This technology is evolving and applied in multiple disciplines, but further development and institutional commitment are needed to allow USVs equipped with echosounders to become ubiquitous and useful components of a worldwide network of autonomous ocean observation platforms.

Keywords: echosounding; trawl; alternative platform; carbon emission; echosounders; autonomous platforms; acoustic survey; ecosystem monitoring

Introduction

Echosounder surveys of marine organisms are traditionally conducted from research vessels (RVs). However, recent developments in uncrewed vehicles and compact low-power instruments (Verfuss et al. 2019) now allow echosounders to be deployed on a range of autonomous platforms, e.g. buoyancy-propelled gliders and floats (Guihen et al. 2014, Benoit-Bird et al. 2018), motorized autonomous underwater vehicles (AUVs) (Fernandes et al. 2000, 2003, Patel et al. 2004, Benoit-Bird et al. 2019), moorings (Brierley et al. 2006), and uncrewed surface vehicles (USVs) (Swart et al. 2016, De Robertis et al. 2019). Consequently, uncrewed sampling platforms are augmenting and replacing RVs for conducting ecological experiments (De Robertis et al. 2019, Kuhn et al. 2020, Totland and Johnsen 2022, Evans et al. 2023), acoustic-trawl surveys of fish and zooplankton (Stierhoff et al. 2019, 2023a, 2023b), and long-term monitoring of marine ecosystems. USVs are of interest because they are mobile, can be equipped with sensors similar to those used on RVs, and operate on the sea surface allowing more options for echosounding, power generation, and satellite communications.

USVs are propelled using wave (Greene et al. 2014), wind (Mordy et al. 2017), solar, battery (Totland and Johnsen 2022), or fossil fuel (Mayer and Schmidt 2023) power. USVs propelled using wave, wind, or solar power generally have longer endurance, typically months; and slower speed, typically <4 kts, or both, relative to those powered by battery or fuel. Some fuel-powered USVs (e.g. Mayer and Schmidt 2023) are capable of speeds rivalling the survey speed (∼10 kts) of RVs and have multi-day operational durations. USV sensors are typically powered by batteries, which may be charged by photovoltaic, hydro, wind, or fuel generators.

Both RVs and USVs are subjected to sea-state, which affects navigation and data quality due to platform motion (Stanton 1982), and bubble noise and attenuation (Bruno and Novarini 1983, De Robertis et al. 2019, Jech et al. 2021). These issues are likely to be more significant for echosounder data collected from small USVs, compared with larger vessels. Although small USVs produce fewer bubbles than larger RVs, signals transmitted and received by shallower transducers are more susceptible to attenuation from wind-generated bubbles (Bruno and Novarini 1983). Also, signal quality may be degraded more by non-coincident transmit and receive beam patterns (Dunford 2005), because transducer pitch and especially roll motions during sound propagation are relatively large on small USVs that lack stabilized transducers.

Irrespective of the data-collection platform, interpretation of the echosounder data generally requires biological information, whether collected coincidentally or separately. However, unlike RVs that can collect both echosounder data and samples of the species and sizes of the animals contributing to the echoes, USVs are generally not equipped to image or capture specimens. Consequently, the interpretation of echosounder data from USVs requires model assumptions and predictions based on prior knowledge (De Robertis et al. 2021), or contextual information collected from other sources (e.g. Bolser et al. 2023), e.g. fishery catches, if they are representative of the surveyed population (Berge 2023). For use in fisheries management processes, it is generally required that the resulting information is comparable to that in the existing assessment time series. Other applications may have less strict requirements; like detecting the absence of scattering organisms. In addition to these technical and logistical considerations, laws and regulations can also constrain the use of USVs. USV governance is a developing field, currently the progress is locally driven, and the practice differs between nations.

Despite these challenges, USVs are increasingly available to augment or replace RV-based echosounder measurements or to conduct experiments or monitoring missions—and their capabilities are expanding. For example, some small USVs can also collect ancillary data on atmospheric, oceanographic, and seabed habitats such as: air temperature, barometric pressure, and wind speed and direction; sea surface temperature, salinity, and chlorophyll concentration; current speed and direction; and seabed depth and type (Mordy et al. 2017, Verfuss et al. 2019). These data are useful for contextualizing echosounder observations, validating models, and understanding ecological processes (Moline and Benoit-Bird 2016).

Relative to RVs, USVs provide echosounder data at lower risk for personnel and at a lower cost and carbon emission per sampling distance. For example, an RV can cost roughly 35 000 US$/day to survey at ~10 kt, or 146 US$/nmi, compared to a sail-powered, emission-free USV that may cost ~3000 US$/day to survey at ~2 kt, or 63 US$/nmi. Certainly, the relative costs and emissions, and the associated support systems, features, and capabilities of each platform will vary. For example, some USV providers include data collections, telemetry, integration, and curation in their daily rates, and RV operators do not. Additionally, USVs provide new opportunities for sampling with increased spatial and temporal resolutions and in areas inaccessible to RVs, whereas RVs have other capabilities, notably specimen sampling, that a USV generally does not possess.

Here, primarily because they are commercially available, we focus on small USVs, typically <8 m length, that are equipped with echosounders. We outline a vision for widespread, routine use of small USVs in fisheries research, surveys, and monitoring and identify considerations for this technological evolution.

A strategy for using USVs

The process leading to successful use of USVs is complex, and a systems engineering approach (NASA 2023) is a useful framework. It first defines the objectives, then the approach and requirements, and concludes with implementation. The objectives are defined by stakeholders from science, industry, or resource management. The approach defines how the mission will be accomplished, including consideration of the target species or assemblage; the sampling area, time of year, duration and design; and data acquisition, processing, archiving, and use. The requirements define the features and performance specifications of the USV, instrumentation, support infrastructure, and regulation compliance. Lastly, implementation is the action to achieve the objectives, judged by the performance metrics, and requires adherence to applicable laws and regulations. In the following sections, we identify considerations in each step and highlight those that differ from RV-based operations.

Objectives of USV operations

The objectives are defined by the information requirement. Typical objectives for small USVs equipped with echosounders may be grouped into ecological experiments, acoustic-trawl surveys of managed resources, and ecosystem monitoring.

Experiments

Experiments are typically single, data-gathering deployments to answer specific research questions. For example, these may be related to an evaluation of the USV performance or to an ecological interest. The objective of the USV application may be to test hypotheses such as whether data collected from a USV and a RV are significantly different (De Robertis et al. 2019, Totland and Johnsen 2022, Evans et al. 2023, Pedersen et al. 2024); to study animal behaviour (Kuhn et al. 2020, Bandara et al. 2022), detect gas seeps (Scoulding et al. 2020), or examine environmental drivers of fish distributions (Levine et al. 2021, Lawrence et al. 2024).

Surveys

Acoustic-trawl surveys are used to provide indices of fish abundance to support fisheries management (MacLennan and Simmonds 2005). Small USVs equipped with echosounders are used in a variety of ways to potentially improve the accuracy, precision, or efficiency of these surveys. USVs can increase the spatial and temporal sampling domains of RV-based surveys or replace RVs, e.g. when they are unavailable (e.g. De Robertis et al. 2019, 2021). USVs can sample a subset of survey transects while the RV collects echosounder and trawl data along the other transects and at target locations (Stierhoff et al. 2023a, 2023b). USVs can survey otherwise unsampled seasons or areas (De Robertis et al. 2021, Levine et al. 2021), farther offshore and closer to the coast (Stierhoff et al. 2019, 2020a, 2023a), or in areas closed to RVs such as offshore wind-energy areas. Although USVs can collect echosounder data that is comparable to that from RVs (e.g. De Robertis et al. 2019, 2021), the data must be interpreted using biological information from another source. This requirement is especially critical for applications in which USVs are used to continue existing survey time series that provide inputs to stock assessments.

Monitoring

Small USVs equipped with echosounders may be used to monitor the distribution patterns of acoustic backscatter, which can be split into general taxonomic groups (e.g. fishes, zooplankton) using, e.g. scattering model predictions and multi-frequency analysis techniques (e.g. Korneliussen 2018). The objectives of monitoring include, e.g. tracking the timing, extent, or inter-annual variability of fish migrations (Stierhoff et al. 2019, Komiyama 2021, Levine et al. 2021); studying areas prior to a survey, providing information for optimal allocation of RV-based sampling (instead of using vessels for scouting as in, e.g. Skaret et al. 2020); reconnoitring to inform RV-based fishing operations, or mapping changes in prey-distribution patterns (Kuhn et al. 2020). More generally, USVs can be used to monitor acoustic backscatter over an area and time with decreased cost and carbon emission.

USV approach and requirements

The approach to using USVs involves numerous considerations such as: the operational area and period; obstacles such as shoals, RVs, icebergs, fishing gear, logs, sea ice, kelp, and recreational boaters; and environmental conditions, e.g. temperature, current, waves, and wind. Furthermore, USVs may become damaged and inoperable and require recovery. Critically, USVs must be tested in the maximum sea-state that they will be exposed to during their missions.

USV size, speed, and deployment duration

In addition to the sea state in which it can operate, USV size is directly related to the amount of space and power available for the echosounder system but also to the purchase, operation, and maintenance costs. For RVs and larger USVs, sensor payload capacity is not a limiting factor, but smaller USVs must be large enough to accommodate the required echosounder transceivers, control and logging electronics, cabling, and transducers. Transducer size depends on the transducer frequency and beamwidth and the required detection range. For the same beamwidth, transducer size is proportional to wavelength and inversely proportional to frequency. As an example, an 18 kHz, 11-degree beamwidth Simrad ES18-11 MK2 transducer weighs 85 kg and has a diameter of 625 mm, whereas a 200 kHz, 7-degree beamwidth Simrad ES200-7C transducer weighs 5 kg and has a diameter of 120 mm (Kongsberg Discovery, Horten, Norway). The echosounder must have the required frequencies, beamwidths, source levels, receiving sensitivities, and noise levels to sample the targets to the required ranges (see Renfree et al. 2019). These considerations are common to echosounder sampling irrespective of the platform, but USV size will constrain the use of higher transmit powers, narrower beamwidths, and lower frequencies.

Small fuel (e.g. Mayer and Schmidt 2023) and battery-powered USVs (Totland and Johnsen 2022) have maximum speeds approaching those of RVs, but much shorter deployment durations between refuellings or rechargings. In contrast, sail-powered USVs, e.g. Explorer (Saildrone, Inc.), can be deployed for over a year (Meinig et al. 2019), but with speeds typically <2 kt and up to ∼4 kt, depending on the wind speed and direction, and USV course.

Echosounder data quality

Installations of echosounders and transducers on USVs must be designed to minimize noise. Electromagnetic noise originates from many sources, such as inverters, switching power supplies, motors, and actuators. Acoustic noise results from sources such as engines, propeller cavitation, hull or sail motion, or interference from other acoustic instruments. For USVs with internal-combustion engines, the acoustic noise levels may be higher than for RVs (e.g. Handegard et al. 2024). This is because noise sources may be closer to the echosounders, transducers, and cabling on USVs compared to RVs. Acceptable noise levels depend on the signal levels and application requirements (Demer et al. 2017).

Echosounder calibrations are required for all quantitative echosounders irrespective of the platform, but calibrations on small USVs may require special apparatus and techniques (e.g. Renfree et al. 2019). The echosounders must be calibrated following standard methods and protocols (Demer et al. 2015).

During some weather conditions, the calibrated echosounder data will be degraded by bubbles entrained in surface waters or swept down the USV hull (Bruno and Novarini 1983, Jech et al. 2021). Although this is a potential issue for all echosounder deployments, bubble attenuation is worse for transducers located near to the sea surface, e.g. on small USVs. To mitigate signal attenuation and reflections in the echosounder data, the transducers must be mounted as deeply as possible. However, the unsampled depth from the sea surface increases with the transducer depth (Totland et al. 2009).

Pitch and especially roll motions are also more pronounced for small USVs compared to submerged vehicles or larger vessels. The transducer orientation should be stabilized to make the transmit and receive beam patterns as coincident as possible. Approaches include gimbal (De Robertis et al. 2019) or active-roll stabilization on the transducer mount, or low-motion hull designs. Changes in the transducer orientation should be measured and, if necessary, used to correct the equivalent two-way beam angle (Stanton 1982, Dunford 2005) and estimates of scatterer depth. The data quality may prompt navigational changes such as a reduction in speed, a change in course, or a delay until weather conditions improve (De Robertis et al. 2021).

Sampling biases may differ between platforms, which could affect time series used in fish-stock assessments. For example, due to shallower transducer depths, USVs may sample closer to the sea surface than RVs. Due to shallower drafts, USVs can sample in shallower water closer to the shore than RVs. Also, due to differences in vessel sizes and radiated noise, fish of various species may react differently to USVs than to RVs (De Robertis et al. 2019, Handegard et al. 2024). These behaviours are likely to be species-specific and change with fish depth, location, season, and time of day (De Robertis and Handegard 2013).

Data telemetry, quality control, and automated processing

Data are stored in the USV for post-mission retrieval and processing, processed aboard, or transmitted via satellite or cellular telephone for processing ashore. High-resolution acoustic data are generally not available from the USV during operation due to bandwidth limitations. Real-time data processing may be used to monitor and improve data acquisitions and provide information needed for adaptive sampling using the echosounder or different sensors on the same or another platform. For example, analysed echogram data provide information on where and when to navigate or trawl from an RV or fishing vessel (FV).

Data-acquisition decisions should be guided by manual or automated evaluations of data processed onboard, or interpretations of compressed echograms transmitted ashore (Swart et al. 2016, De Robertis et al. 2019). Cellular and satellite-telemetry systems facilitate data transfers and remote control and monitoring of the USV and its scientific instruments. The complexity of the interface depends on the bandwidth of the telemetry system, but the aims are to ensure the quality of onboard data collection with some level of shoreside data backup and to provide actionable information.

Automated data processing and telemetry also enhance monitoring and facilitate adaptive sampling, particularly when using multiple USVs. Echo classification may be performed by automated methods (Korneliussen 2018), including artificial intelligence models (e.g. Brautaset et al. 2020) run on graphics processing units on the vehicle, and the model classifications can be telemetered to the operator. The information can be used to optimize sampling for reduced noise or sampling variance or to highlight ecosystem parameters.

Echosounder data collections and analyses must consider, and optimally eliminate, aliased seabed echoes (Renfree and Demer 2016). Although this is another challenge that is common to echosounder data collections irrespective of the platform, autonomous operations from USVs require real-time data access or automated changes in logging ranges and pulse-repetition rate to mitigate these issues in real-time.

Biological information

In traditional survey applications, biological sampling is needed to attribute animal echoes to species, and to convert the integrated acoustic backscatter to estimates of abundance separated by size and age, cohort, or sub-population. This information is typically provided by trawl sampling, and small USVs lack trawling capability. Thus, biological information must be obtained from other sources. For example, echosounder data from the USV may be interpreted using catch data from a nearby RV, particularly if the two data sets are collected contemporaneously (Stierhoff et al. 2023a, 2023b); samples from other fishery-independent surveys (Bolser et al. 2023); or, if selectivity is characterized, from fishery catches or predator diets.

Without biological samples, it may be possible to perform echo classifications based on sound-scattering models and frequency response methods (Korneliussen 2018). In well-characterized, low-diversity ecosystems, inferences can be based on prior knowledge (De Robertis et al. 2021).

Without adequate biological sampling or echo classification methods that are independent of biological sampling, the echo attributions are uncertain and limited to inferences about broad taxonomic and size groups. This limitation reduces comparability with RV-based survey results, even if the underlying acoustic data are similar.

For applications that require only presence–absence information or acoustic backscatter gradients (e.g. Ludvigsen et al. 2018, Bandara et al. 2022), a lack of biological information may not be limiting. For example, USVs can be used to evaluate differences in backscatter from animals inside versus outside of marine preserves or wind-energy areas, with assumptions about the species and sizes of animals contributing to the backscatter. When considering the use of USVs, any requirements for biological information must be thoroughly evaluated.

USV infrastructure, operations, and regulations

The USV infrastructure or support system must match the type, size, and number of USVs. Some USVs do not require vessel support, whereas others require RV-based infrastructure for deployment, recovery, and reprovisioning. Battery- and fuel-powered USVs must return to a station to be reprovisioned. Depending on their size, USVs may be handled manually and deployed from a dock or skiff, or they may require custom launch and recovery systems. There must be emergency procedures for when a USV becomes inoperable.

USV operations, whether facilitated in-house or contracted, require infrastructure and legal compliance. In-house infrastructure may have a higher initial cost, but lower running cost compared to contracting. To reduce infrastructure cost, USV resources could be pooled regionally, nationally, or internationally. Irrespective of the approach to infrastructure, specialists in echosounder sampling should participate in the echosounder integration, performance testing, and noise mitigation.

The laws and regulations for USVs are rapidly evolving. In April 2023, the International Maritime Organization (IMO) established a joint working group on Maritime Autonomous Surface Ships. The resulting IMO guidelines (IMO 2023) allow national administrations to develop their own regulations to facilitate the use of USV technology. Consequently, depending on the type of USV, its length, and operation, the regulations differ for each nation and area of operation.

Currently, the Norwegian Maritime Authority follows the IMO regulations for autonomous vessels and therefore requires that USVs remain visible to the operator. For over the horizon operation, approval is initiated following IMO MSC.1/Circ. 1455 (Sjøfartsdirektoratet 2020). The US Coast Guard evaluates each USV operation. In the UK, USVs with lengths <24 m are regulated by the Workboat Code of the Maritime and Coastguard Agency. Both New Zealand (Maritime New Zealand 2023) and France recently updated their guidelines for USVs.

Because USV laws and regulations differ and are evolving, consult the international and national authorities to learn the relevant governance for each USV, application, and operation area. An internationally accredited ship classification society such as Lloyd's register, Bureau Veritas, or Det Norske Veritas could also be consulted for guidance on current laws and regulations.

USV implementations

In this section, we present four example applications of small USVs equipped with echosounders. The examples are not intended to be a comprehensive review, but illustrate a range of USVs, objectives, approaches, and requirements. These example applications cover an ecological study of sandeel distributions; a test of a motorised USV, the sustained use of multiple sail-powered USVs for acoustic-trawl surveys; and the reconnoitring and monitoring of fishing opportunities.

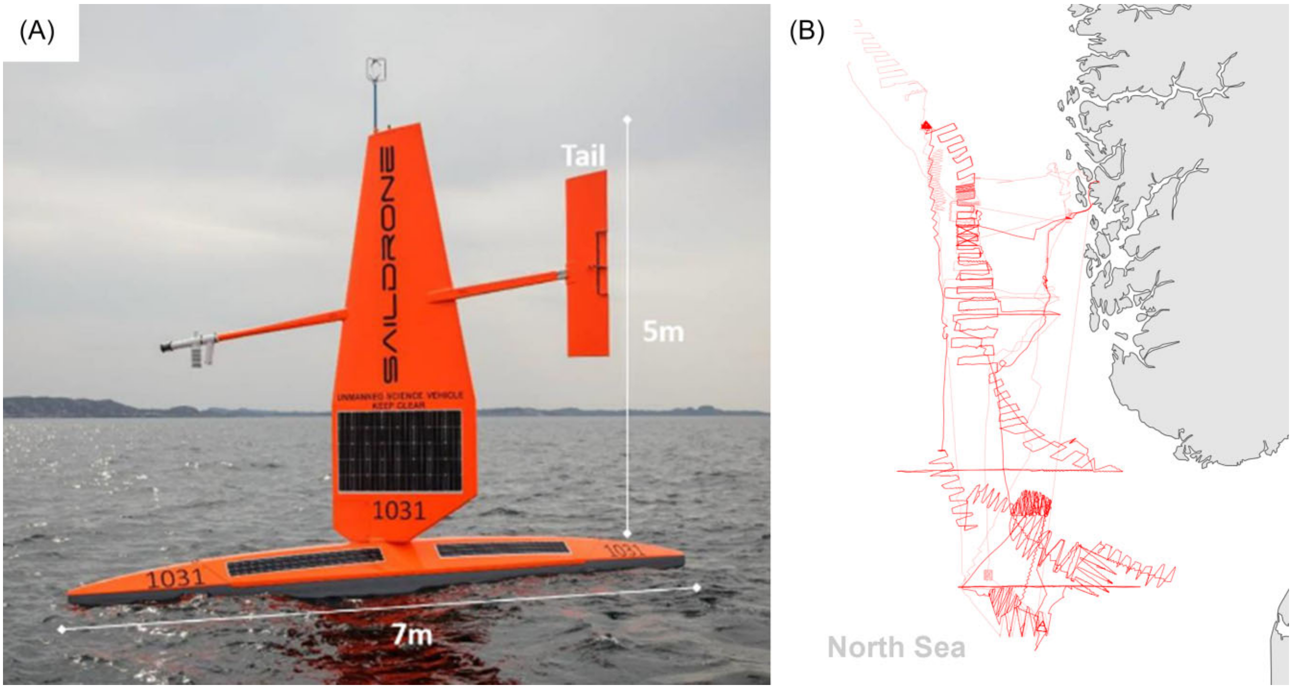

Figure 1. The experiment use case: One of two Saildrone Explorers (A) used to study the schooling behaviour and the spatial and temporal distributions of lesser sandeel along their track lines in the north-eastern North Sea (B).

Schooling behaviour and spatial-temporal distributions of sandeel

The objectives of this experiment were to observe the schooling behaviour and map the time-varying spatial distributions of lesser sandeel (*Ammodytes marinus*) in the North-east North Sea (Fig. 1). The experiment required a silent platform that could operate for 2 months in the North Sea and unobtrusively record acoustic backscatter from feeding lesser sandeel.

Two wind-powered, 7-m long and 5-m tall Explorer USVs (Saildrone, Inc.) were used (Mordy et al. 2017, Komiyama 2021) (Fig. 1A). Each was equipped with an automatic identification system (AIS) transceiver, navigation lights, high-visibility wing colours, cameras, a radar reflector, and a two-frequency (38 and 200 kHz) echosounder (EK80 WBT-mini; Kongsberg Discovery, Kongsberg, Norway). The transducer was gimbal-mounted in the keel at 2-m depth (De Robertis et al. 2019).

Two Explorer USVs were shipped in containers from the USA to Norway. They were deployed in Bergen harbour, where the echosounders were calibrated using the standard sphere method. The USVs were towed offshore before conducting their missions. Under contract, Saildrone Inc. provided the USV navigation; data collection, quality control, organization, and access; and regulation compliance (Meinig et al. 2019). Each Explorer was operated independently.

The USV mission plan was provided to the Norwegian Navy, seismic and oil operators, and fishermen in the survey area. The missions and sensor performances were remotely monitored by Saildrone, Inc. in Alameda, California, USA, and by the Institute of Marine Research (IMR, Norway) cruise leaders. Saildrone, Inc. provided all the echosounder and sensor data to IMR over the Internet.

Reduced-resolution echograms were telemetered via satellite ashore for data quality monitoring. The raw echosounder data were retrieved and analysed following the mission. The data were processed using the LSSS system (MAREC, Norway). Sandeel echoes were distinguished from the echoes of other scatterers using a frequency-response model (Johnsen et al. 2009), however, the lack of a 18 kHz transducer likely reduced the classification accuracy. The sandeel echoes were converted to density using sandeel sizes and ages sampled during a concomitant sandeel survey conducted by IMR. After 120 days, the mission ended and the USVs were towed back to Bergen harbour, where the echosounders were calibrated again to ensure that the instruments were still performing as per the specifications.

In this experiment, the USVs facilitated longer-term deployments than RVs, due to availability and cost. In contrast to RV operations, the USV contractor prepared and operated the vessels, collected and curated the data, and integrated the ancillary meteorological and oceanographic data and provided it to the scientists using a web application in near-real time. Moreover, the echosounder measurements made from the USVs resolved more detail on the lesser sandeel than those from RVs, likely due to vessel-specific avoidance behaviours. On the other hand, the USV did not collect biological data, so the echosounder data had to be interpreted using previously collected data and trawl catches from a concomitant RV survey. Furthermore, the USVs had a lower speed than the RV, so the survey took longer to complete.

Pilot acoustic-trawl survey with a motorized USV

The objective was to explore the potential for a ship-deployed motorized USV (Fig. 2A) to conduct echosounder sampling along a subset of transects usually conducted during a RV-based survey. In this tandem-survey concept, the USV and the RV operate side-by-side on adjacent parallel transects (Fig. 2B), with the RV targeting trawls on aggregations detected by the RV or USV at short time lags (<3 h). While

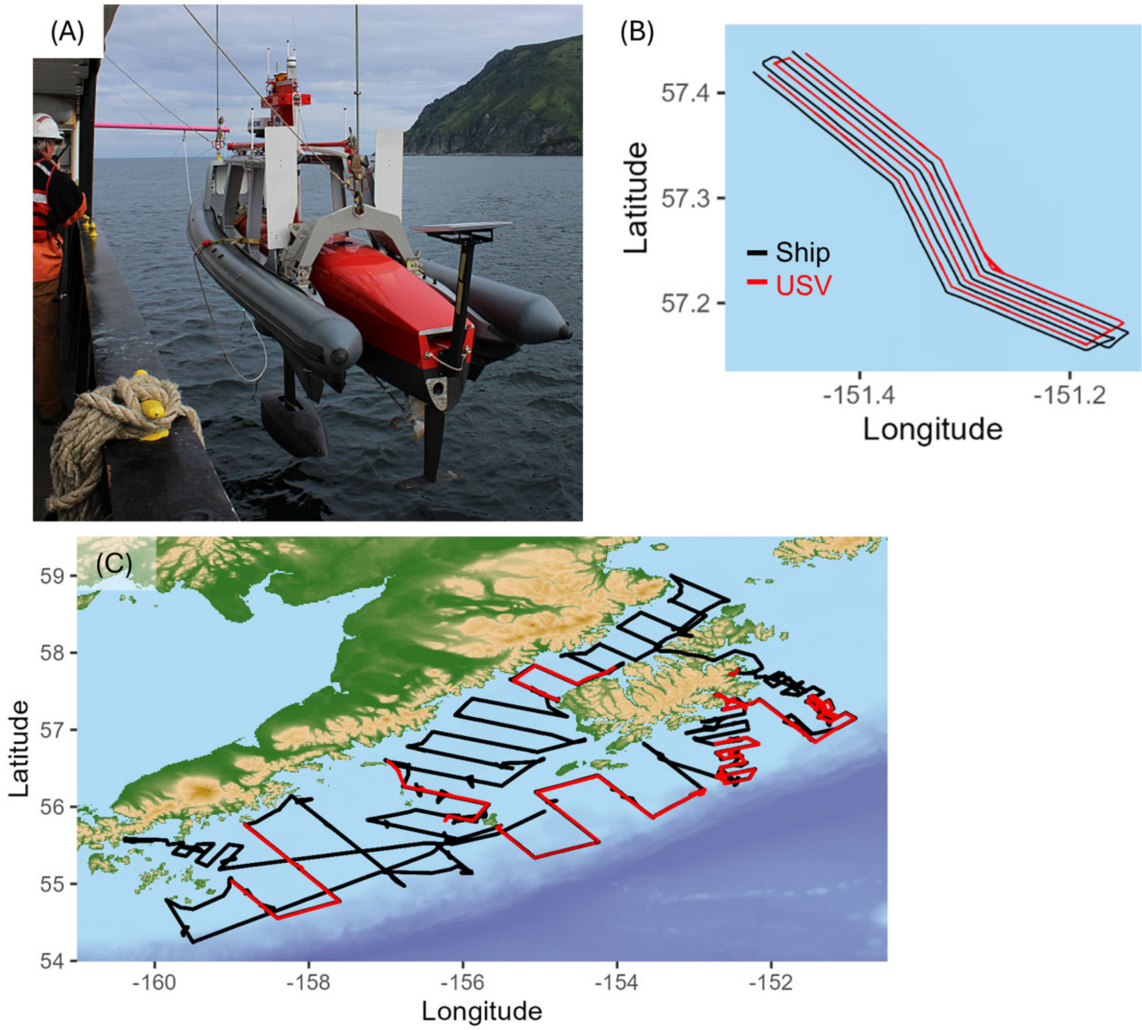

Figure 2. Survey use case. (A) Motorized USV (red vehicle) being deployed in the launch and recovery system (grey structure). (B) Small-scale survey of interspersed RV and USV transects (9 h duration). (C) Track of the RV and the USV in the survey area.

this introduces operational complexity, this design has the potential to maintain survey data quality while reducing RV time, cost, and carbon emissions. A pilot study was conducted during the RV-based, summer 2023 acoustic-trawl survey of walleye pollock (*Gadus chalcogrammus*) in Alaska (Fig. 2C).

To meet the objectives, the following approach and requirements were adopted. The USV had to progress at approximately the same speed as the RV-based survey to avoid the RV having to wait for the USV and to allow for coincident acoustic and biological sampling. A DriX USV (Mayer and Schmidt 2023) was used. The DriX is a 7.7-m long vehicle powered by a 37-HP diesel engine. In this application, the USV progressed at ∼8.5–9.5 kts, which did not impede the forward progress of the survey vessel, which transited at ∼11.5 kts but paused to trawl. The USV included an AIS transponder and an obstacle avoidance system that blends data from onboard radar, lidar, and cameras to detect obstacles and alter course as necessary to avoid collision.

The USV included a four-frequency (38, 70, 120, and 200 kHz) echosounder (EK80 WBT-tube; Kongsberg Discovery, Horten, Norway), which was calibrated at the start of the survey. The echosounder electronics and transducers were mounted in an instrument pod extended to 2 m depth. The USV has a hull design that minimizes motion and an active roll-stabilization system, which reduces vehicle motion, improving sonar performance.

The vehicle was controlled from the RV or a land base via satellite telemetry. Downsampled echosounder data were telemetered to the RV over a satellite link and displayed in the same application used to process shipboard data. The down-sampling and data transfer were achieved using the Blue Insight platform (Kongsberg Discovery, Norway), and the data were displayed and processed using Echoview (Echoview Software Pty Ltd, Tasmania, Australia). This real-time data visualization allowed for quality control during acquisition and for shipboard survey staff to target trawls on fish aggregations detected by either the RV or the USV. The raw echosounder data were downloaded after the USV was recovered.

The DriX USV was transported, deployed, recovered, and refuelled by the RV. The RV's boat davit was modified to accept the DriX launch and recovery system (Fig. 2A; see Mayer and Schmidt 2023 for a different arrangement). The RV was fitted with a refuelling system. The US Coast Guard was informed of the planned USV operations.

The implementation was a first feasibility test of the concept aiming to integrate the motorized USV with the RV and develop operational procedures. Although the deployments were conducted during an acoustic-trawl survey, the USV data were not collected on transects interspersed with those of the RV or used in the survey abundance estimate as would be the case for a full implementation.

The USV was transported aboard the RV to the survey area. It was launched and recovered in sea states with wave heights up to 2 m. The USV was deployed 13 times with increasing durations up to 2.5 days (Fig. 2C). The vehicle was operated at distances up to 35 km from the RV while monitored and controlled by operators on the RV and/or a remote operations centre in France via a Starlink satellite connection. Echosounder data were primarily collected along transects that were offset by 0.5 nmi from the RV's transects.

This pilot study aimed to examine the feasibility of using an RV-deployed USV to reduce RV time requirements while maintaining high-quality trawl sampling. These trials indicated that a RV-deployed USV could be integrated into an operational acoustic-trawl survey. High-quality acoustic data were collected at speeds matching the forward progress of the RV-based survey. However, practical endurance at a survey speed was ~2.5 days, and launch and recovery were limited to sea states of 1.5–2 m, which limited when the vehicle could be deployed.

Operational acoustic-trawl survey with sail-powered USVs

Five species and seven stocks of coastal pelagic fish species (CPS) were surveyed using a combination of USVs, RVs, and FVs in the California Current Ecosystem off the west coasts of Vancouver Island, Canada, the USA, and Baja California, Mexico, during summer, June to October 2019 to 2023. The objectives were to collectively sample farther offshore and closer to shore than the RV could sample (2019) and along transects interleaving the RV transects (2021–2023) during annual acoustic-trawl surveys of CPS (Fig. 3). Sampling from the various platforms close in space and time was necessary to allow interpretation of the USV echosounder data using proximate catch data from another vessel.

As described above, Explorer USVs have an average survey speed of ~2 kts. Therefore, three or four Explorers were used to collectively sample at approximately the same speeds as the RV, ~10 kt, which conducted trawl sampling.

The contractor installed the 38 and 200 kHz echosounders and calibrated them (see Renfree et al. 2019) before and after the survey using the standard sphere method (Demer et al. 2015). To maintain calibration accuracy throughout the survey, the RV collected depth profiles of temperature and salinity to correct for the local sound speed and absorption coefficients, during post-survey analyses.

The contractor (Saildrone, Inc.) deployed, operated and recovered the USVs, and provided the data (Meinig et al. 2019). The contractor informed the US Coast Guard of the planned USV operations and filed a Local Notice to Mariners. To coordinate sampling among the RV, FVs, and USVs, each platform continually exchanged its location information using satellite telemetry. The contractor monitored the progress of each USV, and adaptively coordinated its sampling to collectively complete the USV transects while minimizing temporal offsets with the RV and FV sampling. Reduced-resolution echograms were telemetered from the USVs, and an Internet application was used to monitor progress, ensure data quality, and select trawl locations.

Following recovery of the USVs, the raw echosounder data were downloaded and processed using Echoview (Echoview Software Pty Ltd, Tasmania, Australia). The frequency response was used to distinguish echoes from CPS and other scatterers (Demer et al. 2012). CPS echoes were apportioned to species and converted to biomasses using species, size, and age information from the closest catch.

This combination of sampling from an RV, two FVs, and multiple USVs expanded the survey into previously unsampled regions both farther offshore and closer to shore while increasing transect density and maintaining biological sampling. The USVs extended transects farther offshore, where the RV did not have time to sample. The FVs extended acoustic transects closer to shore than the RV could safely navigate and provided purse-seine catch information. Multiple USVs sampled interleaved transects (Fig. 3) while maintaining pace with the RV, which provided relevant trawl-catch information (Stierhoff et al. 2020b).

Both the USVs and the FVs sampled with fewer echosounder frequencies than the RV, which created differences in the echosounder-data processing and the identification of CPS echoes. However, the results from the RV, FV, and USV sampling (e.g. Stierhoff et al. 2020a, 2023a) were deemed sufficiently comparable to be combined in the survey results and were used in the assessments for management of Pacific sardine *Sardinops sagax*, northern anchovy *Engraulis mordax*, and Pacific mackerel *Scomber japonicus*.

Locate and monitor harvestable Antarctic krill using a USV

The objectives were to locate and monitor harvestable densities of Antarctic krill, *Euphausia superba*, using a USV rather than a FV, reducing cost and carbon emission by minimizing vessel time spent searching (Fig. 4); and to contribute to sustainable harvesting by providing data to organizations responsible for the management of resources in the Southern Ocean.

The target species was Antarctic krill, near the Antarctic Peninsula and South-Orkney and South Georgia islands (Fig. 1C). The USV was required to monitor krill densities around an FV and in remote fishing areas, in the prevailing weather conditions, for months.

The USV was a Sailbuoy (Offshore Sensing, Norway), which is wind-powered, 2-m long, and weighs 65 kg (Fig. 4A). It can operate in the Southern Ocean conditions and can withstand collisions with icebergs or larger vessels. The Sailbuoy was equipped with a 200 kHz echosounder (EK80-WBT mini; Kongsberg Discovery, Norway) with the transducer gimbal-mounted at 0.5-m depth. The echosounder was calibrated prior to deployment. During deployments, a custom electronic circuit onboard the Sailbuoy was used to access the raw acoustic data.

The onboard processing unit reduced the size of the acoustic data, and both raw and reduced data were stored onboard the USV. Reduced resolution echosounder data were telemetered via satellite to the fishing company (Aker Biomarine) for decision-making. The fishing company developed a custom user interface to the data. The raw data were downloaded and processed after the USV was recovered.

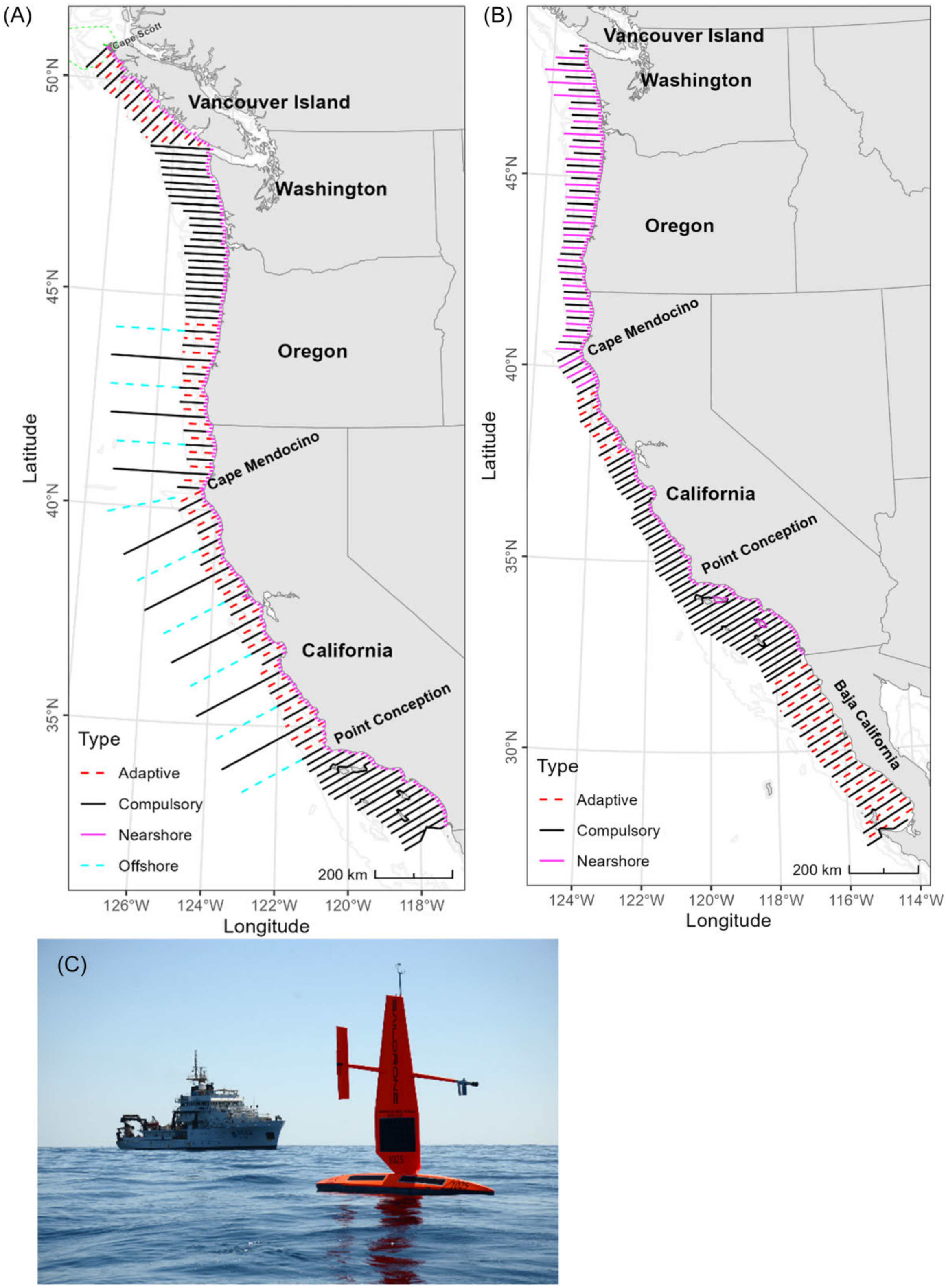

Figure 3. Examples of planned compulsory and adaptive transects sampled by the RV during summer 2018 and 2019 (A) and summer 2020, 2022, and 2023 (B). In 2018 and 2019, offshore extensions to the compulsory acoustic transects were sampled by USVs (C), photo by Chris Hoefer, and nearshore transects were sampled by USVs and FVs. In summers 2021, 2022, and 2023, interstitial transects were sampled by USVs, and nearshore transects were sampled by FVs. Also shown are 50, 200, 500, and 2000-m Isobaths (grey lines).

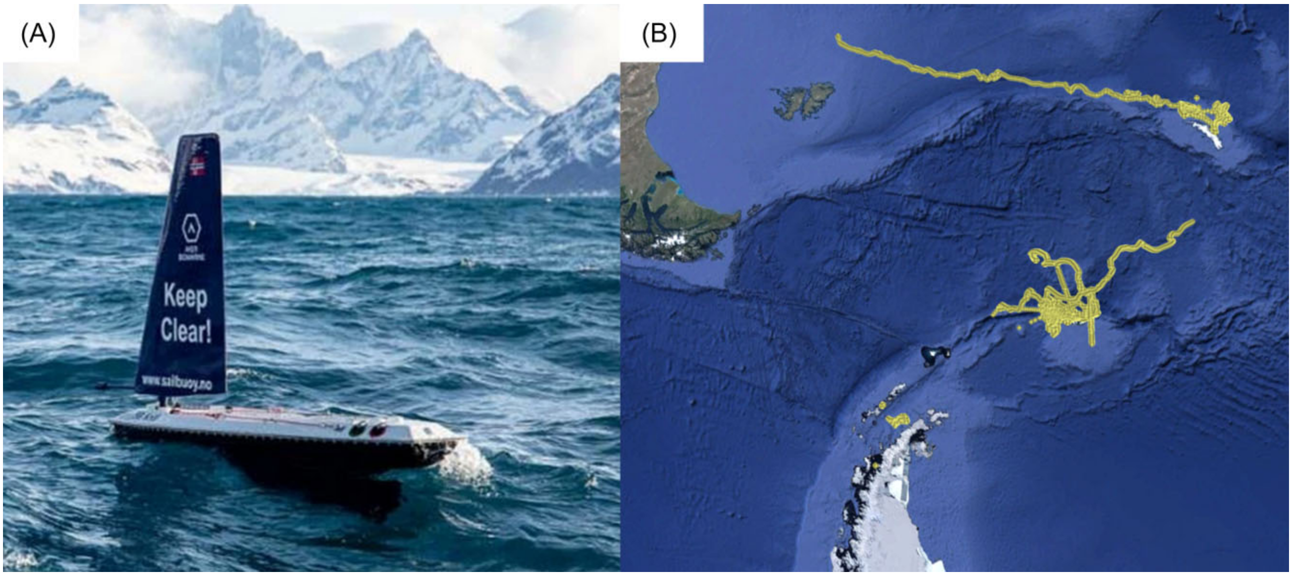

Figure 4. Monitoring use case: Harvestable densities of Antarctic krill were located and monitored using a Sailbuoy USV (A) (Photo: Aker Biomarine) along track lines Northeast of the Antarctic Peninsula (B).

The Sailbuoy was deployed from an FV and operated autonomously without specialized infrastructure, collected echosounder data in all weather conditions, and was recovered using a skiff. The Sailbuoy had buoy lights and marks in compliance with the regulations.

The implementation consisted of controlling the Sailbuoy from land and from the FV, with recovery for maintenance every 1–3 months. The echosounder data were processed onboard the USV using the LSSS software (MAREC, Norway) and included noise reduction, swarm detection, and echo integration in addition to reducing the resolution. The swarms were assumed to be Antarctic krill, and their integrated volume backscatter was assumed to be proportional to their aerial density.

From 2020 to 2023, the USV transited a total of 17 000 km during 10 months in the Austral summers, and the monitoring of remote fishing areas using the Sailbuoy provided the fishing company with data to make decisions on whether to relocate their fishing activity. The distances between fishing locations, e.g. Bransfield Strait to South Orkney Islands is ∼380 nmi, and South Orkney Islands to South Georgia is ∼450 nmi. Searching with the FV and relocation consumes time and fuel.

In this monitoring application, the USVs sampled more area for larger durations than could be economically sampled using ships. On the other hand, the USVs moved slower than an FV, necessitating multiple USVs to shorten the operation. Also, the USVs did not do biological sampling, so interpretation of the echosounder data required multiple assumptions, e.g. what species and sizes contributed to the echoes.

Discussion

Small USVs equipped with echosounders have a range of applications, including experiments, acoustic trawl surveys, and monitoring. Relative to conventional RV-based sampling, this advancing technology can reduce cost and carbon emissions while increasing temporal and spatial coverage. Based on the results of the example applications, we discuss present and future applications of USVs for echosounder surveys in fisheries surveys and science and note some considerations to facilitate the evolution.

Small, wind- or wave-propelled USVs are commercially available and are used for experiments, surveys, and monitoring. They can be transported on land to distant operation locations. They cost less per sampling distance and emit less carbon compared to RVs. They can collect data in previously unsampled regions, both farther offshore and closer to shore, but at lower speed than RVs, unless multiple slower USVs sample in coordination. Small, motor-propelled USVs are a new innovation. They have the potential to survey at speeds comparable to RVs, which enables interleaving of USV and RV transects. However, further advancements are needed for launching, refuelling, and recovering the USV in the high seas. In the meantime, multiple slower USVs may be used to interleave USV and RV transects (e.g. Stierhoff et al. 2020a, 2023a).

USVs may augment or replace RV-based sampling if there is a source of biological information to interpret the echosounder data. Estimates of species and size composition of acoustic scatters are generally required for acoustic estimates of abundance. Consequently, many USV applications are limited by a lack of coincidentally collected biological data (De Robertis et al. 2019, 2021). Other applications have less strict requirements, e.g. when detecting the presence or absence of scatterers is sufficient. The uncertainties introduced by reduced biological information are important in many applications, and users must be aware of these limitations.

To obtain biological information, USV transects may be interleaved with RV transects so that the echosounder data can be interpreted using the RV's nearby trawl catches. To achieve synoptic sampling, the survey speeds of the RV and the USV must match, either by using a faster motorized USV, or multiple slower USVs to collectively achieve the same sampling speed (Stierhoff et al. 2023a, 2023b). The combined USV and RV operation must be sufficiently reliable to avoid slowing the survey progression and creating a lag between the echosounder and biological sampling.

Alternatively, biological data may be obtained from samples of industry catches (Bolser et al. 2023) or using chartered FVs, as long as the selectivity is characterized. Also, eDNA (Shelton et al. 2022) samples may provide information on species contributing to acoustic backscatter, and in some cases, assumptions on scatterer species and size composition are sufficient.

To extend survey time series, the information collected by USVs must be comparable to that previously collected from another platform. Studies could be conducted to characterize the USV performance compared to the previous platform, including biases in the backscatter between the platforms (De Robertis et al. 2019) and the effect of, when applicable, alternative biological data (Bolser et al. 2023).

Reductions in measurement biases will alter time series. For example, animals may react less to smaller, quieter USVs compared to RVs, and therefore echosounder data collected from USVs may be less biased and resolve more detail on undisturbed organisms. Also, USVs can sample with less bias near the sea surface and seashore, in marine reserves, and in commercial energy and aquaculture zones.

Although we have only discussed small USVs currently used for fisheries surveys and science, larger USVs, even the size of RVs, are in development. In addition to echosounders, larger USVs can be equipped with sensors that require more space and power, such as multiple echosounders with lower frequency transducers; multibeam sonars; acoustic doppler current profilers; profiling winches; water samplers for eDNA; and adaptive-sampling cameras and AUVs. Larger USVs also offer higher speeds, longer endurances, and better stability for improved offshore operations. However, not unlike large RVs, large USVs cost more, alter animal behaviours, and emit more carbon compared to small USVs.

In the future, USVs will travel faster, farther, and more reliably; include more meteorological, oceanographic, and biological sampling; integrate multi-disciplinary data; telemeter all data; cost less; and serve multiple users. For example, USVs may be powered using hybrid sources, e.g. using wind, solar, and fuel power, and fuel and electric motors to allow a better combination of speed, endurance, and reliability. Manned small-craft, small USVs, or aerial drones may be used as tankers to refuel USVs without consuming RV time. USVs may sample surface water underway, and a profiling system may be used to measure temperature, salinity, dissolved oxygen, chlorophyll concentration, pH, and sample eDNA versus depth. Onboard the USV and in the cloud, artificial intelligence and machine learning tools may be used to integrate and process the data. Combined with high-bandwidth telemetry, these results will facilitate real-time monitoring and adaptive sampling. Support infrastructure to operate and maintain USV operation will mature, and international laws and regulations for autonomous operation will evolve. These innovations will be driven across all fields where USV use is evolving (e.g. military and bottom mapping applications).

Practitioners of fisheries acoustics should take advantage of these collective efforts and address the unique requirements for echosounder applications, e.g. instrumentation and data processing, transducer motion and noise minimization, and biological sampling innovation. Combining these developments with institutional commitment, USVs equipped with echosounders shall become ubiquitous and useful components of a worldwide network of autonomous ocean observation platforms.

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Author contributions

N.O.H. organized the work, D.A.D. organized the paper, E.J., D.P., D.A.D., and A.D.R. wrote the use cases, all co-authors provided input to the content and critically reviewed the manuscript.

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