Testing the feasibility of unmanned surface vehicles to estimate the distribution and abundance of cetacean species

Trials conducted as part of the *Sphyrna Odyssey* collaborative project between ACCOBAMS, Marine Conservation Research, SeaProven, Marine & Océans, and the University of Toulon in March 2020

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Summary

Marine Conservation Research (MCR) were invited by the ACCOBAMS Secretariat to join the *Sphyrna Odyssey* mission in March 2020 with the specific aim of investigating the feasibility of using a USV (SeaProven's *Sphyrna 70*) to estimate the distribution and abundance of cetaceans using acoustic techniques and distance sampling methodology. The MCR team implemented the PAM system on board Sphyrna 70 on 10th March, with the following four days dedicated to field trials. Unfortunately, the collaborative field project was cut short due to the unforeseen and rapid shut-down of travel and movement throughout Western Europe due to coronavirus. Although environmental conditions were not ideal during the three field days that were able to take place, significant progress was made in assessing the abilities of *Sphyrna 70* to tow a 50 m hydrophone array in order to detect cetaceans. The capabilities of the unmanned surface vehicle were assessed in terms of its range, ability to maintain speed and heading, manoeuvrability, stability and access. Generally, *Sphyrna 70* showed some potential as a platform for performing acoustic density estimation of cetaceans. Several features would, however, need to be

improved before a large-scale survey such as the ACCOBAMS Survey Initiative could be considered. Despite these shortcomings, it was possible to record sperm whales from *Sphyrna 70* on at least one occasion using the towed array whilst underway at 3 knots, and subsequent range estimation suggested the focal animal was approximately 1400 m away. This appeared to be near the upper limit of detection for the relatively short 50 m array deployed in the field, and this range could be improved with the use of a longer array. Other key attributes of an unmanned surface vehicle, such as *Sphyrna 70*, that would be necessary for a larger scale survey are discussed.

1. Introduction

Robust baseline information on parameters such as abundance and density is necessary to inform conservation actions and to implement and evaluate the efficacy of any measures currently in place. This is particularly true in the Mediterranean and Black Seas, where several of the cetacean populations occurring in the region are threatened by human activities and maintaining good conservation status requires effective mitigation steps. In response to an urgent need to improve the knowledge of cetacean population abundance and distribution, the ACCOBAMS (Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and continuous Atlantic area) Secretariat coordinated the first ever large-scale survey of marine megafauna in the Mediterranean Sea during the summer of 2018. In the context of the uncertain effects of climate change and increasing human activities at sea, the ACCOBAMS Survey Initiative (ASI) was organised with the participation of ACCOBAMS range states to assess the status of cetacean populations at the regional level. It provides a robust basis for their long-term monitoring and conservation, contributing to a number of global and regional environmental commitments.

The ASI was the first wide scale, comprehensive systematic survey of its kind in the Mediterranean. It was coordinated by the ACCOBAMS Permanent Secretariat in close collaboration with country representatives and with the support of a Steering Committee composed of strategic partner organisations. After extensive training and preparation, the ASI scientists conducted fieldwork by plane and vessel to collect visual and acoustic data on all cetacean species encountered. During the surveys, line transect sampling methodology was applied to allow densities and abundances to be estimated through both design-based and model-based approaches. The use of planes or vessels for systematic surveys, however, can be costly both in terms of research budget and person-hours. The requirement to use experienced crews and fieldworkers can also provide logistical challenges, and can generate additional costs for a research project such as training, insurance, travel, board and lodging.

In recent years, autonomous underwater vehicles (AUVs) and unmanned surface vehicles (USVs) have shown some potential as effective survey tools for marine mammals (Bittencourt *et al*., 2018; Klinck *et al*., 2015; Verfuss *et al*., 2019). These autonomous solutions may mitigate several of the logistical and budgetary requirements associated with using traditional vessels or planes and may enable long-range surveying beyond the typical range of human observers. However, as an emerging field of development, AUVs and USVs may currently be unable to conduct large-scale surveys such as the ACCOBAMS Survey Initiative if constrained by factors including battery power, manoeuvrability, a limited capacity to carry instrumentation and local operational regulations. Any future applications of AUVs and USVs to determine cetacean distribution and/or density must be able to fulfil certain requirements of traditional survey methods. The vessel-based ASI surveys, for example, used line transect distance sampling methodologies (Buckland *et al*., 2001; Buckland, 2004) to provide robust estimates of the abundance and density of cetacean species in a given space and time. Standard line transect methods involve observers and/or hydrophones (underwater microphones) moving along transects at a prescribed survey speed, with the transects placed at random in such a way to ensure each part of the study area has an equal probability of being surveyed. An efficient design for vessel-based surveys is to use ‘equal space zigzags’, with the vessel turning at the end of each transect to commence surveying of the next transect . For passive acoustic monitoring, the vessel needs to position the relevant hydrophone elements in the water column, for example by towing an array as in the ASI surveys, and have on-board systems in place to either archive the acoustic data and/or transmit them to another site.

Marine Conservation Research (MCR) were invited by the ACCOBAMS Secretariat to join the *Sphyrna Odyssey* mission in March 2020 with the specific aim of investigating the feasibility of using a USV (SeaProven's *Sphyrna 70*) to estimate the distribution and abundance of cetaceans using acoustic techniques and distance sampling methodology compatible with those used during the ASI. MCR had previously assisted the ACCOBAMS Secretariat with the implementation of the ASI vessel-based survey component in 2018 and 2019, and successfully completed a passive acoustic monitoring (PAM) survey covering a large part of the Mediterranean Basin with the Research Vessel *Song of the Whale*. The field trials were planned to take place for two weeks off Toulon, France, according to the ASI protocol adapted by MCR. As sperm whales produce regular loud clicks and are found throughout the deep waters of the western basin in the Mediterranean Sea, they were considered suitable candidate species for testing acoustic methodologies. The field trials aimed to compare acoustic data on the presence of sperm whales collected both with the multi-hydrophone system aboard *Sphyrna 70* and towed arrays deployed from both *Sphyrna 70* and a support vessel. This report summarises the preliminary findings from field trials using SeaProven's *Sphyrna 70* off the coast of Toulon in March 2020 as part of the Sphyrna Odyssey collaborative project between ACCOBAMS, Marine Conservation Research (MCR), SeaProven, Marine & Océans, and the University of Toulon.

2. Methods

A series of trial acoustic surveys were planned for March 2020 using SeaProven's autonomous vessel *Sphyrna 70*. The deep waters off Toulon, France were selected as the study site for various logistical reasons and the nearby presence of known sperm whale habitat.

2.1 Research aims

The primary aims of the trial survey work were to:

1. Deploy a modified towed hydrophone array and associated equipment from *Sphyrna 70* to collect acoustic data in keeping with the equipment and protocols used during the ASI,
2. Within an experimental survey block, run a series of short survey transects to assess the ability of *Sphyrna 70* to maintain a steady course, speed and predetermined track lines while collecting acoustic data suitable for distance sampling analysis,
3. Collect acoustic data using the fixed array aboard the *Sphyrna 70* according to the standard methodology used by the University of Toulon to allow comparison with the towed array data,
4. Locate sperm whales acoustically using an identical towed array deployed from the support vessel, *OneCat*, to allow comparison between a detection system deployed from a traditional platform and the same system deployed from *Sphyrna 70*, and
5. Investigate the datasets from *Sphyrna 70 and OneCat* to assess the feasibility of using standard distance sampling techniques in conjunction with USVs to estimate local cetacean densities and to determine if the methodologies might be able to complement future wider scale surveys such as ASI.

2.2 Surveying requirements

Several specific survey requirements were identified and examined during the field trials. These included assessments of whether *Sphyrna 70* would be able to:

- store and/or produce sufficient on-board energy to provide a range of several hundred kilometres,
- maintain a specific survey speed over prolonged periods,
- follow a course along a transect without significant deviation,
- execute appropriate manoeuvres at the end and start of each transect,
- carry and power the relevant survey instrumentation (in this case, a 50 m towed array plus data acquisition system),
- provide a safe and secure on-board environment for the data acquisition system used in a range of environmental conditions,
- carry on-board systems to either archive the acoustic data and/or transmit them to another site,
- provide ready access for routine instrumentation checks and/or data downloads when at sea,
- avoid other vessels and obstacles in the vicinity.

2.3 Acoustic equipment temporarily installed on Sphyrna 70 and OneCat

MCR provided two sets of PAM equipment for installation during the field trials aboard both *Sphyrna 70* and *OneCat*. The first set was optimised for installation on *Sphyrna 70* and was designed to run off either the on-board 12V DC or 220V AC supply or an independent power source (2 x 12V 90Ah AGM batteries). The second set was intended for deployment from the project support vessel *OneCat* where it could be used to assist in locating and tracking sperm whales if required and also to collect comparative data to determine at what range the array towed by *Sphyrna 70* was able to detect sperm whales.

The array specifications were optimised for the trials in terms of frequency response, length and weight. Each set of PAM equipment consisted of a towed array of two hydrophone elements on 50 m of cable plus a 10 m deck cable to run from the waterline to a sheltered internal space where the data acquisition system was housed (Figure 1). The hydrophone elements were separated by 3 m to provide an optimal aperture for localising sperm whale clicks (Figure 2). A 40 bar depth sensor was also implemented in each array. The data acquisition system comprised a buffer box (similar to those used during the ASI) and a Microsoft Surface Pro (on *Sphyrna 70*; Figure 3 and Figure 4) and a Dell Latitude (on *OneCat*; Figure 5). Both computers were running *Pamguard* software (version 2.00.17 beta) with a similar configuration to that used during the ASI and optimised for sperm whale detection.

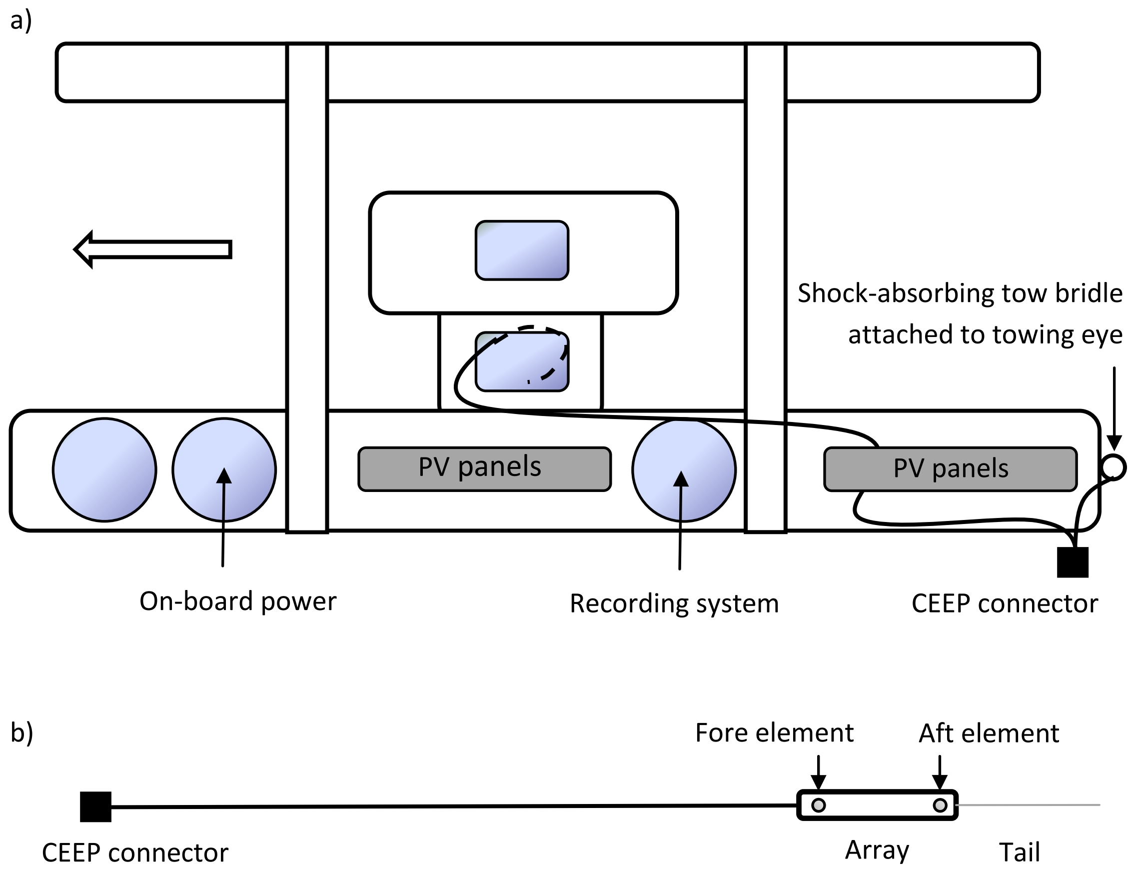

Figure 1. Schematic showing a) the positioning of the data acquisition system and deck cable on *Sphyrna 70* (blue polygons/circles represent accessible hatches), and b) the attachment of a 50 m towed hydrophone behind *Sphyrna 70* array via a marine connector.

Figure 2. Example of one of the two identifal hydrophone arrays used in the field. The two broadband elements in each array were separated by 3 m in an oil-filled tube to provide an optimal aperture for localising sperm whale clicks.

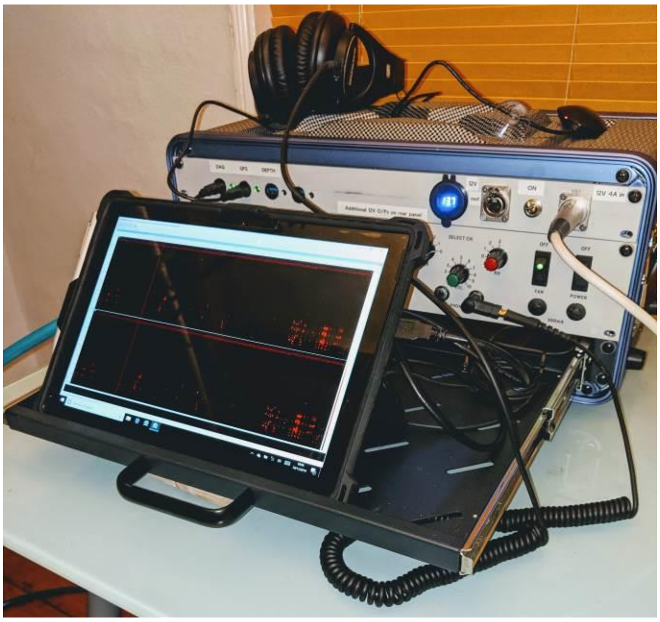

Figure 3. The recording system designed for use within *Sphyrna 70*; the drawer of the 4U 19” rack mounting case contained a Microsoft Surface Pro that could be closed and secured when in use.

Figure 4. The recording system housed within *Sphyrna 70* during testing.

Figure 5. The recording system used on board *OneCat*.

2.4 Acoustic survey methodology

Sperm whales are more easily detected acoustically than visually as they carry out regular deep foraging dives during which they typically echolocate; these dives typically last 30-45 minutes followed by a period of recovery (approximately 7-12 minutes) at the surface before diving again. For most of the duration of their dives sperm whales produce loud regular echolocation clicks. Sperm whale clicks are loud, allowing them to be detected at large distances, typically around 8-10 km from a vessel but up to 37 km in certain conditions (compared with a typical maximum detection range of 4.3 km for visual surveys). Sperm whale clicks are broadband in nature (typically 1–40 kHz) with a centroid frequency at about 13 kHz, allowing clicks to be detected above lower frequency ship, flow and sea noise. Clicks are transient with sharp leading edges with typical rise-times of <1 ms and can be readily detected autonomously using click detector modules in the software package *Pamguard* (Gillespie *et al*., 2009).

Pamguard is an open source software program for acoustic detection, localisation and classification of marine mammals. *Pamguard* works as an autonomous detector and classifier of many cetacean vocalisations including baleen whale calls, dolphins whistle and odontocete clicks. On both *Sphyrna 70* and *OneCat*, *Pamguard* was used to log GPS data, to acquire acoustic data from the hydrophone array and to provide preliminary data analysis via a click detection module. The acoustic data were recorded to disk as 16-bit wav files and archived each night.

3. Results

The MCR team implemented the PAM system on board *Sphyrna 70* on 10th March. The following four days were dedicated to field trials (Table 1), with an unforeseen early termination of the collaborative project due to the impending travel restrictions being imposed due to rapid increase in cases of coronavirus throughout Western Europe.

Table 1. Calendar of events during collaborative project off Toulon in March 2020.

Date	Activity	Notes
09/03	Mobilisation	SeaProven position *OneCat* & *Sphyrna* in Toulon
10/03	Set-up	MCR implement PAM system on *Sphyrna*
11/03	Field trial day 1	Recording with towed array on *Sphyrna*
12/03	Field trial day 2	Concurrent recording with towed arrays on *Sphyrna* & *OneCat*
13/03	Bad weather	High winds
14/03	Field trial day 3	Concurrent recording with *Sphyrna*'s system & towed array on *OneCat*
15/03	Demobilisation	Early end to project due to coronavirus.

Although environmental conditions were challenging during the three field days, sperm whales were recorded from *Sphyrna 70* on at least one occasion using the towed array, and possibly on one other occasion using the on-board array (Table 2).

Table 2. Environmental conditions and recordings of note for the field trials (SS = sea state). * denotes the hull-mounted array aboard *Sphyrna 70*.

Date	Trial	Conditions	Recordings of note
11/03	Day 1	Wind 6 kts, SS 3, waves 0.2 m, swell 0.8 m	Sonar & explosions from local naval operations
12/03	Day 2	Wind 4 kts, SS 2, waves 0.2 m, swell 0.5 m	Sperm whales on both systems for last 30 mins
14/03	Day 3	Wind 20 kts, SS 4, waves 0.5 m, swell 2 m	Possible sperm whale recorded by *Sphyrna**

Over the course of the three trial days, *Sphyrna 70* and *OneCat* both covered approximately 150 km. The first two days each involved approximately 10 hours of effort at sea; day 3 involved 8 hours of effort, the shorter day being due to the elevated sea conditions (Figure 6).

Figure 6. The sea conditions on day 3 prohibited deployment of the towed array from *Sphyrna 70*.

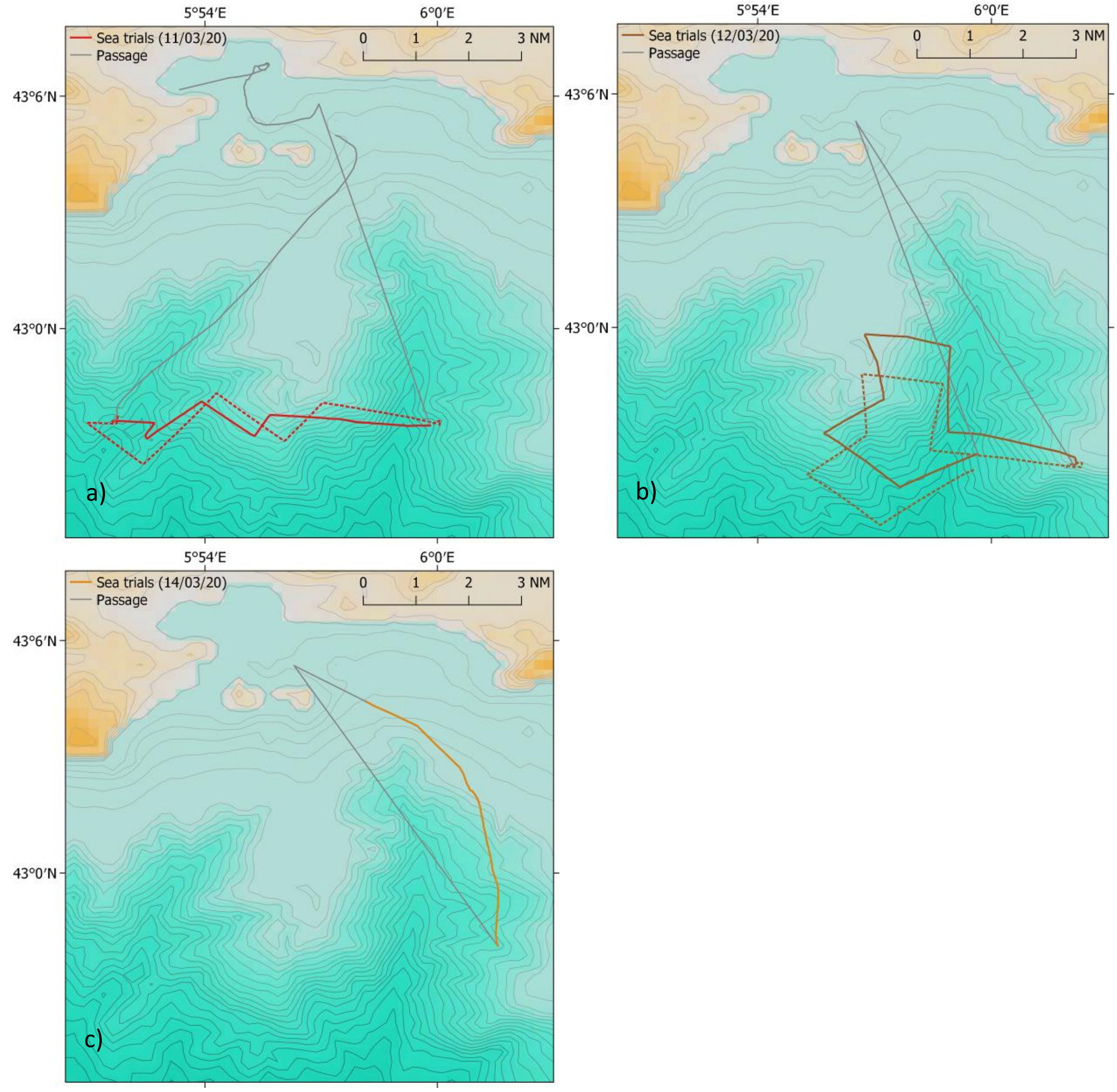

Figure 7. Plots showing the tracks of both *OneCat* (solid line) and *Sphyrna 70* (dashed line) during the three trial days: a) day 1 (11th March), b) day 2 (12th March) and c) day 3 (14th March).

Although the intended two week field trial was cut short due to Covid-19, progress was made in addressing the following fields identified as being key to the feasibility of using USVs to assess cetacean density:

3.1 Range

A USV should be able to store and/or produce sufficient on-board energy to provide a reach of several hundred kilometres.

During the field trials, *Sphyrna 70* would typically be able to tow an array for up to ten hours before the on-board batteries were depleted to 40 % (considered a pragmatic level to allow *Sphyrna 70* to be able to return safely to port). On day 1, *Sphyrna 70* towed the array for approximately 35 km over 5h30m; on day 2, the weather was a little better and the distance covered was 44 km over 6h 50m. On day 3, the weather was too rough to deploy the towed array from *Sphyrna 70* (Table 3). Ordinarily *Sphyrna 70* would draw approximately 10 amps from its propulsion batteries during normal operation; when towing a 50 m array, this went up to between 30 and 50 amps, depending on the wind, swell and local currents.

Table 3. Key parameters achieved by *Sphyrna 70* during the field trials. The towed array was not deployed from *Sphyrna 70* on day 3.

Date	Trial	Total distance (km)	Distance towing array (km)	Duration (hh:mm)	Mean speed (kts)	Maximum speed (kts)
11/03	Day 1	58	35	10:20	3.2	5.1
12/03	Day 2	60	44	09:20	3.0	4.1
14/03	Day 3	29	0	07:40	-	-

3.2 Speed

A USV should maintain a specific survey speed over prolonged periods.

During the field trials, *Sphyrna 70* would typically tow the 50 m array at around 3 knots, but was capable of travelling at 5 knots for extended periods. Buckland *et al*. (2001) advise that a survey vessel should travel at least two or three times faster than the average speed of the animals being surveyed in order to avoid bias related to animal movement. The mean speed of sperm whales has been reported as 2.1 to 2.5 knots (Whitehead, 1989, Whitehead *et al*., 1992). During the ASI, research vessels aimed to maintain survey speeds of 6 to 8 knots; a minimum speed of 6 knots was required to stream any towed array being used and a maximum of 8 knots was implemented to reduce cable strum and excessive strain on the array.

Due to the large swell and choppy sea conditions during the field trials, the speed of *Sphyrna 70* was mostly kept below 5 knots. The speed profiles for the two days on which the towed array was deployed (Figure 8) show *Sphyrna 70* was capable of maintaining consistent speeds over 4 knots (11th March) and 3 knots (12th March) over sustained periods. The different speeds logged were in part due to the dynamic nature of local currents that had some bearing on the performance of the USV.

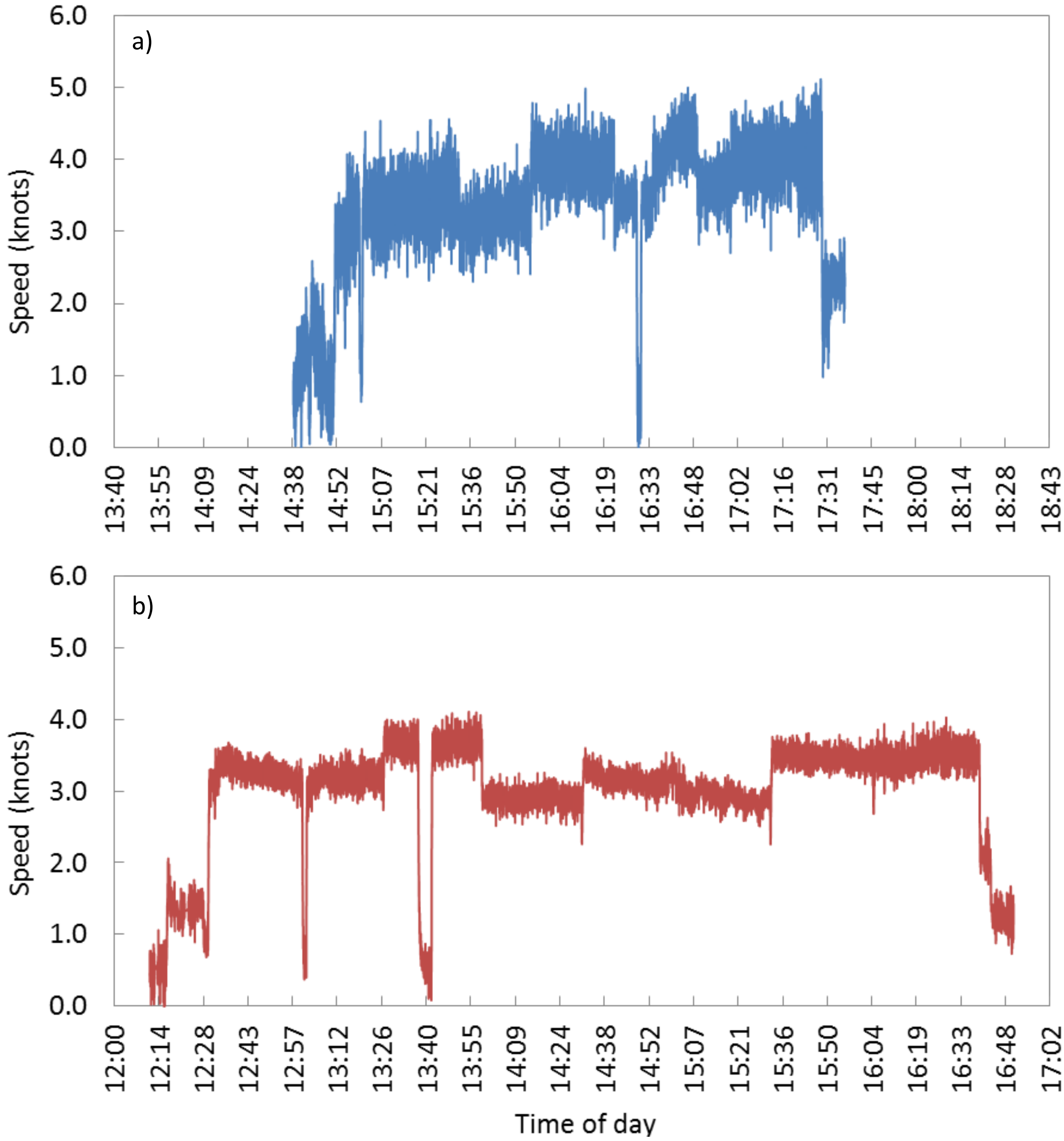

Figure 8. Speed profiles for the two days on which a towed array was deployed from *Sphyrna 70* on a) 11th March and b) 12th March.

3.3 Course

A USV should follow a course along a transect without significant deviation.

A range of sea conditions were encountered during the field trials, and *Sphyrna 70* was able to maintain an accurate and steady course in all scenarios. The course of *Sphyrna 70* was modified in the field to mimic approximately the equal-angle zig-zag approach used by vessels in the ASI (Figure 7). The course of *Sphyrna 70* was controlled remotely from *OneCat* and provided instantaneous response. A more detailed examination of the course of *Sphyrna 70* (as measured every second from a GPS feed) shows that the USV was capable of maintaining a course within ±5° for prolonged periods (Figure 9) and thus would be able to follow a transect without significant deviation.

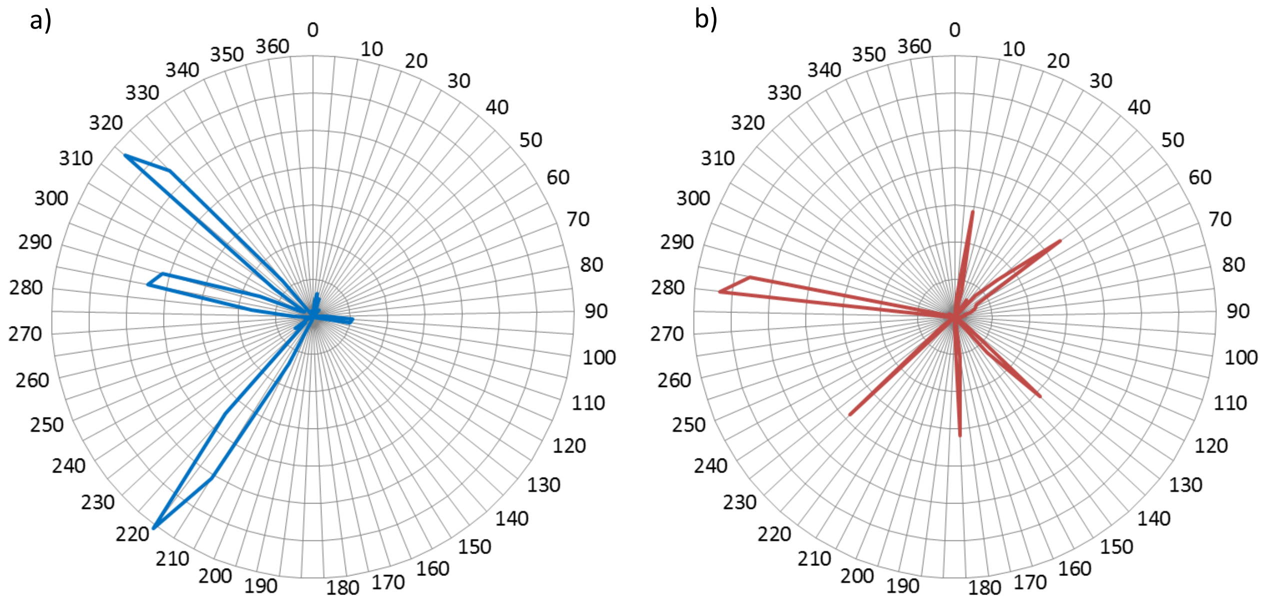

Figure 9. Course maintained (as measured every second from a GPS feed) for the two days on which a towed array was deployed from *Sphyrna 70* on a) 11th March and b) 12th March.

3.4 Manoeuvrability

A USV should execute appropriate manoeuvres at the end and start of each transect.

As mentioned above, the course of *Sphyrna 70* was controlled remotely from *OneCat*; response was instantaneous and the USV was able to readily negotiate sharp changes of course, for example turning at the end of a transect to start the next. Although most course changes were less than 10°, Sphyrna 70 was able to change course by up to 52° in one second (Figure 10).

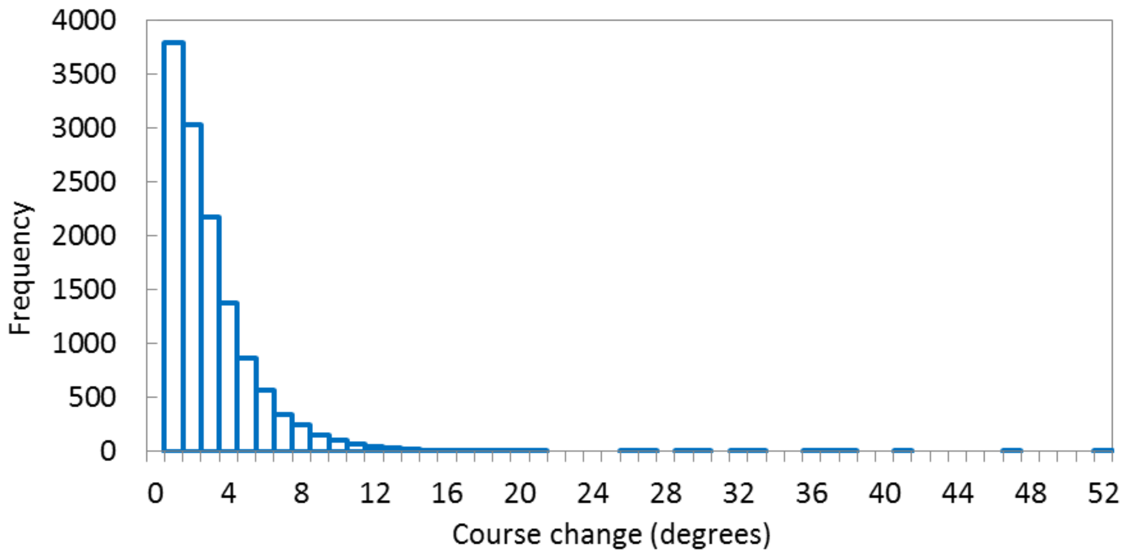

Figure 10. Changes in course (as measured every second from a GPS feed) for the two days on which a towed array was deployed from *Sphyrna 70*.

3.5 Payload

A USV should carry and power the relevant survey instrumentation (in this case, a 50 m towed array plus data acquisition system).

Following ongoing conversations between SeaProven and MCR prior to the start of the field trials, the data acquisition system provided by MCR was designed to fit within the below-decks workspace of *Sphyrna 70*. The entire system weighed approximately 14.4 kg (56 kg with the optional 12v battery system). The on-board 12 v system was used throughout the project and provided all of the energy requirements of the MCR recording system.

The 50 m towed array weighed 14.6 kg in air and was deployed from *Sphyrna 70* when at sea to reduce any fouling or collision risks. This worked well in lower sea states (such as on days 1 and 2) but was more difficult in elevated conditions such as those on day 3, when it was deemed inappropriate to deploy the towed array at sea. However, the wind gusts on that day were over 25 knots and would have been considered challenging for most types of survey work.

3.6 Access

A USV should provide ready access for routine instrumentation checks and/or data downloads when at sea.

The MCR recording system was installed inside the main hull of *Sphyrna 70* under an aft hatch (Figure 1) and was readily accessible both in port and at sea. This was practical in lower sea states (such as on days 1 and 2) but access was less straightforward in elevated conditions such as those on day 3. Indeed, it was deemed too unsafe to access the recording system and/or deploy the towed array in those conditions, and thus recordings were made with the on-board *Sphyrna 70* system alone.

3.7 Platform stability

A USV should provide a safe and secure on-board environment for the data acquisition system used in a range of environmental conditions.

Sphyrna 70 provided a secure platform for both the on-board data acquisition system and the towed array. On day 3, there was some water ingress in to the hatch above the MCR equipment that affected the data acquisition card within the recording system. As the environmental conditions were challenging on that day, it is possible the water came from waves breaking over the pontoons of Sphyrna. Future deployments of research equipment within the hulls of the *Sphyrna* USVs should take this in to account.

3.8 Data management

A USV carry on-board systems to either archive the acoustic data and/or transmit them to another site.

Although the MCR system was designed to be self-contained, with all data recorded to SD card, there is a system on board the *Sphyrna* USVs for the interrogation and download of data. This data transmission feature is used by the research team from the University of Toulon, and was being used throughout the field trials without any known issues.

3.9 Avoidance

A USV should avoid other vessels and obstacles in the vicinity.

Although traffic levels were relatively low during the field trials, the autonomous collision avoidance ability was tested on day 3. Although *OneCat* was accompanying *Sphyrna 70* throughout, an automated avoidance system this will be essential for future surveys with a scope similar to the ASI.

3.10 Acoustic performance

Electrical noise was significant in the recording system aboard *Sphyrna 70* when it was under way using its electric motor. The noise was most prevalent at 10 kHz with pronounced harmonics every octave (i.e. 20 kHz, 30 kHz and so on). In addition to the electrical noise present in the system, lower frequency noise associated with the propulsion system (a Torqeedo electrical motor) was also evident at frequencies below 5 kHz. Despite this self-noise, on day 2 the system was able to detect and record sperm whale clicks whilst under way using the motor at typical operating speeds (e.g. 3-4 knots; Figure 11). However, it should be noted that the self-noise of the system could affect the detection of other species of cetacean.

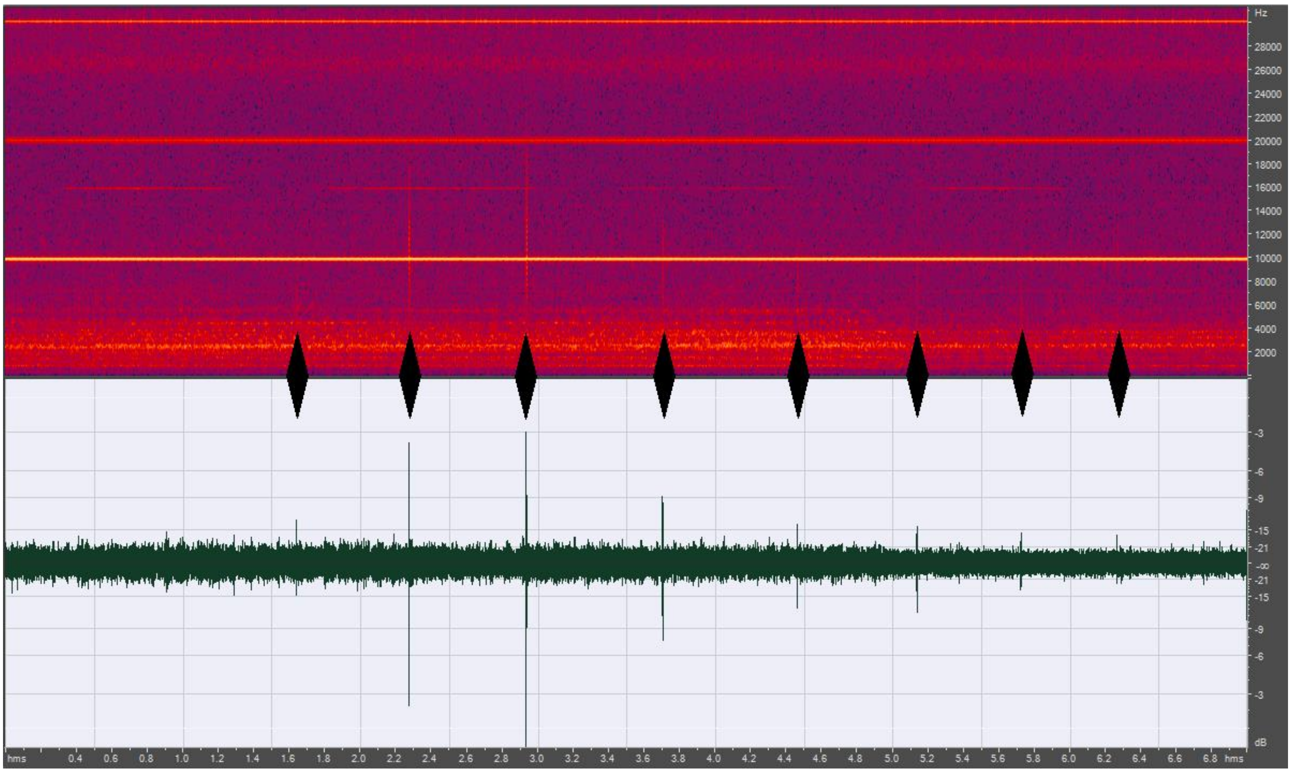

Figure 11. Example of sperm whale clicks recorded with the towed array from *Sphyrna 70* whilst under way using its motor at approximately 3 knots. The top window shows the spectral information of the clicks, and the lower window represents the waveform. Clicks appear as vertical bands approximately every 0.8 seconds; clear examples are identified by black rhombi. Electrical noise is evident at 10, 20 and 30 kHz with propeller noise below 5 kHz.

The recording system deployed on *Sphyrna 70* was able to detect these sperm whale clicks and derive bearing information using a click detector module in Pamguard. Differences in bearing information were used to identify individual click trains (Figure 12). Thus, acoustic detections of sperm whales could be made at the individual level, rather than the group level. The regular clicks of a solitary individual were detected over several minutes, with the vocalisations being intermittently masked by both ambient noise and propeller noise (as evident in Figure 11). In addition to the clicks of a solitary sperm whale, cavitation from the propeller of *OneCat*'s tender was also evident as it approached *Sphyrna 70* to retrieve the towed array (shown as the train of red ovals in Figure 12).

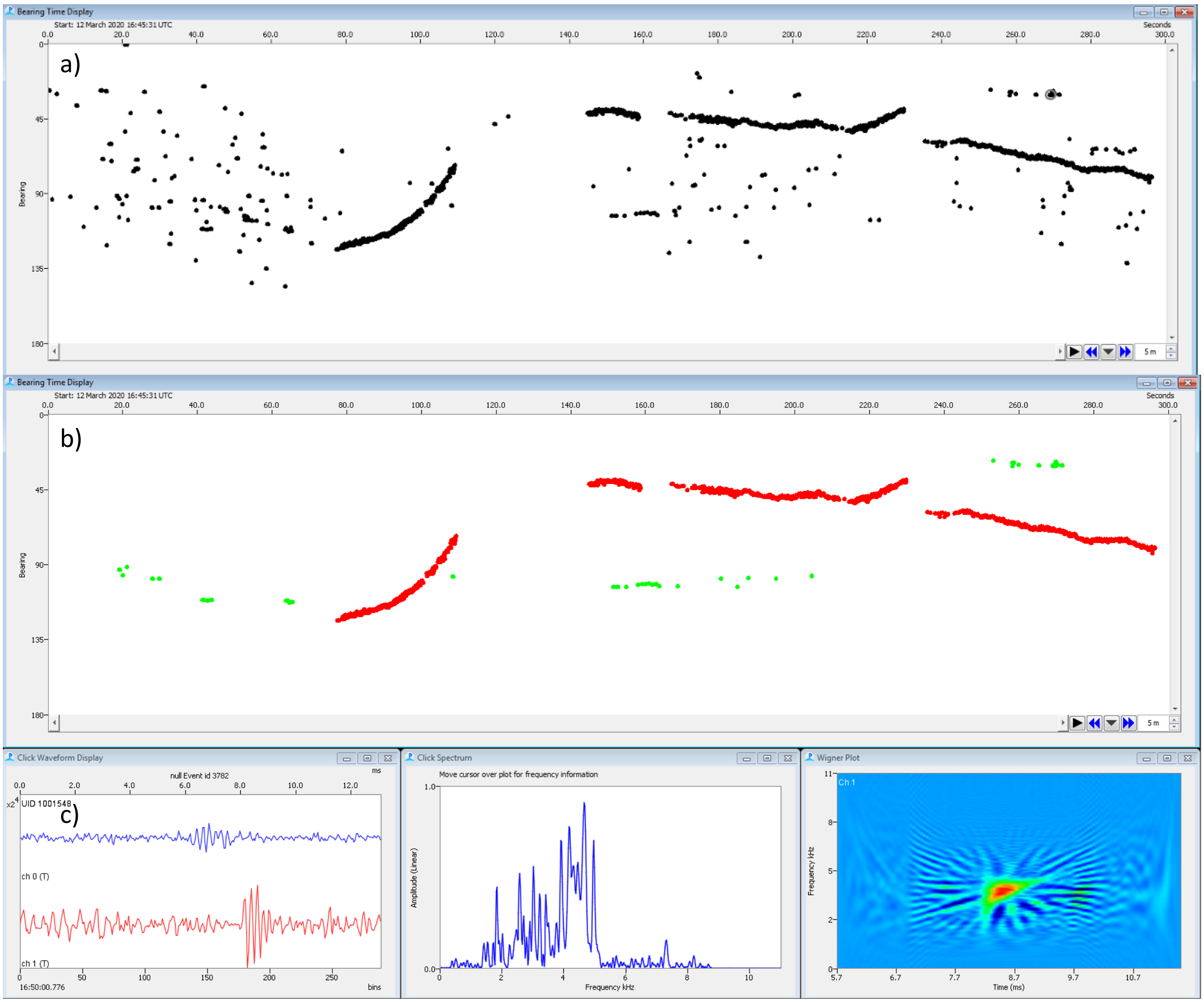

Figure 12. Example of a five minute period of acoustic effort analysed in Pamguard. The upper window show relative bearing information on the y-axis (0-180°) plotted against time (five minutes) on the x-axis. In the first display (a), black ovals represent candidate clicks. Individual click trains have been manually marked up with different colours. Subsequent removal of extraneous false triggers (b), clarifies the bearing information for individual click trains; sperm whale clicks are represented as green ovals, the approach of the *OneCat* tender is represented as red ovals. The lower windows (c) display the characteristic waveform (left), spectrum (centre) and Wigner plot (right) characteristic of sperm whale clicks.

Localisation of the vocalising sperm whale was conducted in Pamguard using target motion analysis. Target motion localisation can be used to detect and localise continuously vocalising cetaceans, such as sperm whales. A towed hydrophone array will detect a series of different clicks from a focal whale as it moves through the water. The path of the array along the trackline can be estimated by the offset GPS log on board *Sphyrna 70*. If the source is assumed to be stationary then each detected click corresponds to a set of time delays at some position along the trackline. Each set of time delays can be visualised as a 2D bearing pointing towards the acoustic source. As more clicks are detected more bearings are calculated along the trackline and eventually they should begin to cross around the likely location of the source. Where possible, Pamguard uses incremental changes in the vessel's heading to resolve left/right ambiguity and identify on which side of the vessel's track the sperm whale is most likely to be. Due to the intermittent nature of the clicks recorded by *Sphyrna 70*, it was not possible to resolve the left/right ambiguity; however, both solutions suggested the whale was between 1381 and 1508 m away. When performing the same analysis with clicks recorded on the array towed behind *OneCat*, the quieter noise environment in that system allowed a more reliable localisation of clicks that suggested the whale was 1153 m to port (Figure 14). Comparison of the localisations from the two towed arrays suggests the vocalising whale was at approximately 42°57'N 005°59'E.

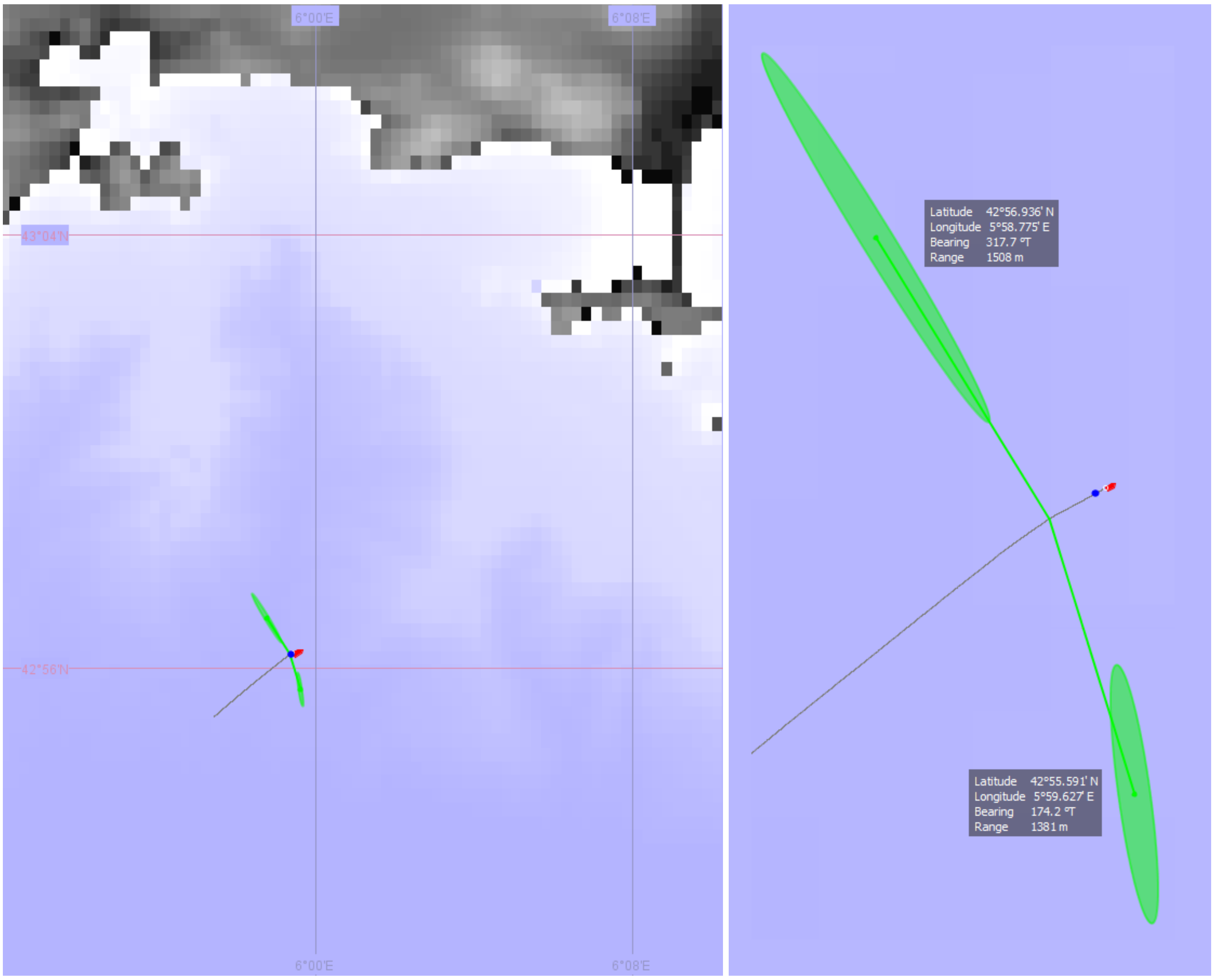

Figure 13. Estimation of perpendicular distances from *Sphyrna 70* in Pamguard using target motion analysis. The vessel's track is shown as the grey line, with bearing lines for consecutive sperm whale clicks projected to either side of the vessel. In this example, the left/right ambiguity could not be resolved and the 2D position of the vocalising whale was estimated as being either 1508 m to port or 1381 m to starboard of the hydrophone array's beam. Localisation results are derived using a 2D simplex method, with the green error ellipses derived from the uncertainty in position of each hydrophone element.

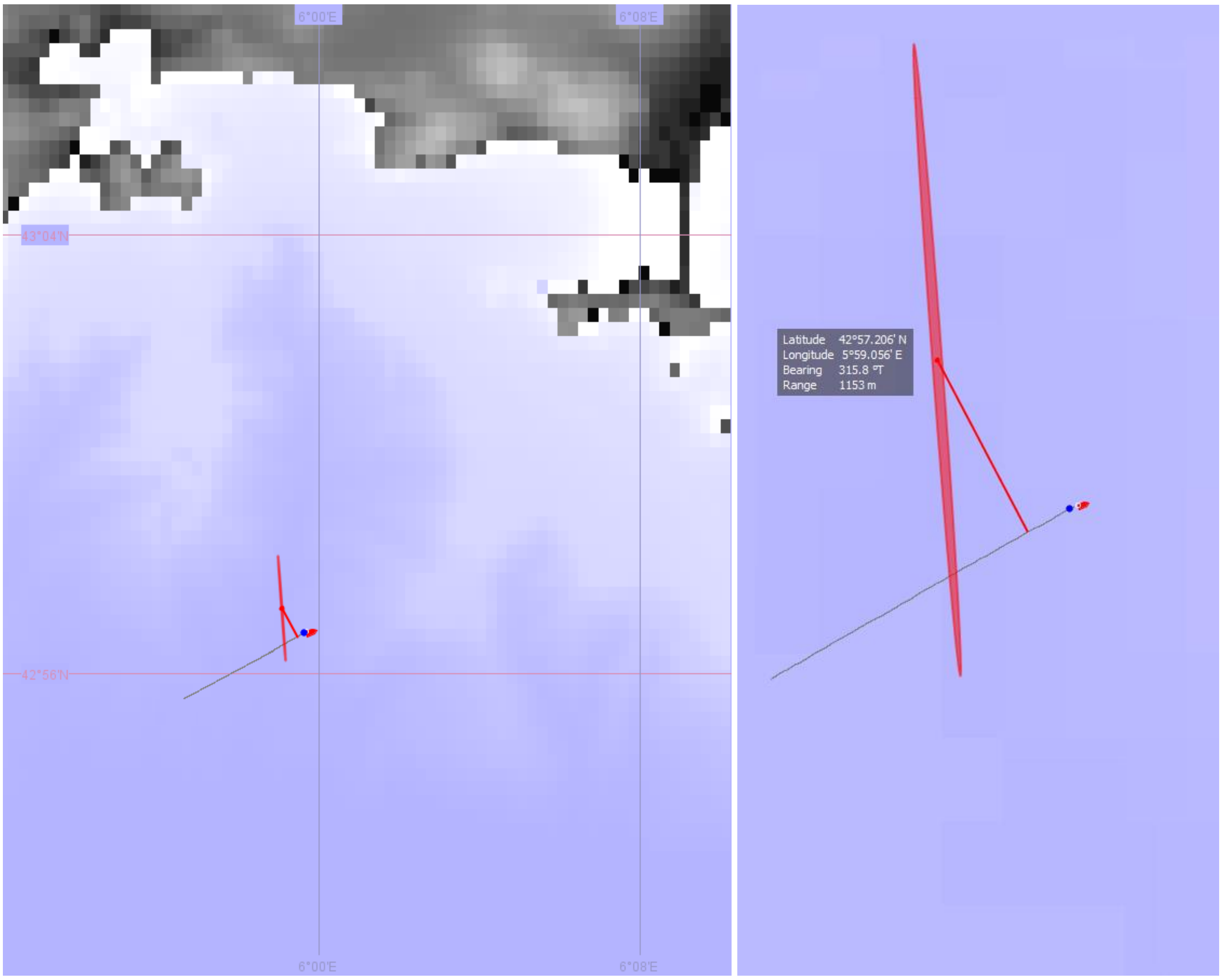

Figure 14. Estimation of perpendicular distances from *OneCat* in Pamguard using target motion analysis. In this example, the 2D position of the vocalising whale was estimated as 1153 m to port of the hydrophone array's beam.

4. Discussion

The aim of the field trials described here was to investigate the feasibility of using a USV (SeaProven's *Sphyrna 70*) to estimate the distribution and abundance of cetaceans using acoustic techniques and distance sampling methodology. Although the field trials were curtailed by the spread of coronavirus, several key capabilities could be initially assessed. Generally, a USV such as *Sphyrna 70* shows good potential as a platform for performing acoustic density estimation of cetaceans; however, there are several features that would need to be improved before a large-scale survey could be attempted.

Battery technology is in a state of rapid improvement, and it is likely that in the near future USVs such as *Sphyrna 70* will experience a dramatically improved range. With the current set-up, *Sphyrna 70* was able to tow an array safely for up to 10 hours and clearly this will need to be improved in order to perform longer surveys. It should be noted that the wind generator on the *Sphyrna 70* was disengaged during the field trials to allow safe embarkation and disembarkation, and independent power sources such as this can help improve reach in future projects. A support vessel may be able to provide the option to recharge the battery systems in the field; however, using a support vessel such as this would negate the need to use a USV at all. Hopefully, improvements in the efficiency and surface area of the photovoltaic cells on-board will improve range, as will any improvements in efficiency of the propulsion system used on board *Sphyrna 70*.

To be able to accurately estimate densities of sperm whales, a USV would need to travel at average speeds of at least 4 knots. Due to the large swell and choppy sea conditions during the field trials, the speed of *Sphyrna 70* was mostly kept below 5 knots, with an average speed of 3.1 knots being achieved when towing a 50 m array. However, during better weather conditions it is anticipated that it would be possible to tow a hydrophone array at higher speeds.

The ability to maintain heading and make the relevant changes of course at the start/end of a transect are important prerequisites for any USV being deployed in a line transect survey. *Sphyrna 70* was capable of maintaining a course within ±5° for prolonged periods, and as its manoeuvrability was found to be very responsive, it would be able to follow a transect without significant deviation. The payload used in the field trials was relatively light (29 kg for the recording system plus array) and a larger scale survey may require a longer array and auxiliary battery banks on board. A heavier set-up of this type may increase the displacement of the USV and thus affect its manoeuvrability.

The electrical system on the *Sphyrna 70* was found to be noisy particularly when the main propulsion motor was running. Future longer-term deployments of towed hydrophone arrays would likely benefit from being powered via a good quality pure sine wave inverter. This may negate the need to run the acoustic system from a separate battery supply. Due to the short-term deployment of the equipment during the trials it was necessary to install the MCR equipment close to the main propulsion motor. It is reasonable to assume that a more permanent installation further from the propulsion motor would result in reduced electrical noise.

Sphyrna 70 proved to be a stable operating platform in calmer conditions. However, there was some water ingress during the rougher conditions encountered on day 3 that caused damage to the recording system. It is possible this may have been caused by a relatively straightforward issue with the seal on that hatch, which could easily be replaced. If the field trials hadn't been cut short, further testing could have identified and remedied the cause of small matters such as this. Access to the recording system mounted on board *Sphyrna 70* was adequate during relatively calm conditions; however, access during higher winds and/or sea conditions could be difficult and potentially unsafe. This would need to be considered in the field protocol designed for a larger scale survey.

As the field trial was short, with *Sphyrna 70* returning to port each night, data management was easily achieved, with the SD cards being available for routine download. For a larger scale survey, it would certainly be worth investigating a remote access system, such as the long-range wireless or satellite systems that have been designed for use with the *Sphyrna* USVs.

It was assumed prior to the start of the field trials that marine mammals would only be available for detection from a towed array when *Sphyrna 70* was drifting (i.e. without its electric motor engaged). However, although only audible for approximately 3 minutes, sperm whale clicks were detected from *Sphyrna 70* as it motored forward at approximately 3 knots. This therefore confirms that USVs have the potential to detect marine mammal vocalisations even when using a motor for propulsion. It appears the detected sperm whale was perhaps 1.4 km away from *Sphyrna 70* and as the clicks of this animal were quite intermittent, it seems likely that this range is near the upper limit for detection using a 50 m long array at those speeds. However, although the electrical noise in the system when using the motor was pronounced, it did not interfere too much with the towed array's ability to detect the broadband clicks of a sperm whale. It seemed the more limiting factor for click detection was the masking of lower frequencies below 6 kHz by the mechanical noise of the propulsion system. Masking issues such as this can be remedied by using a longer array to effectively move the propeller noise as far as possible away from the hydrophone elements at the end of the tow cable. Future field trials such as this should experiment with longer arrays, to realise the ideal trade-off between the benefits of reduced masking and the costs of increased payload/drag. The modified array used during the field trials was based on an array towed from a much larger vessel. It would be possible to use lighter, thinner tow cable and potentially reduce the overall drag imposed on the USV by the array. A small remotely operated winch system could also be used to facilitate the remote deployment and retrieval of the array.

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