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Behaviour of herring (*Clupea harengus* L.) towards an approaching autonomous underwater vehicle

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The reaction of schooling wintering herring (*Clupea harengus* L.) in Ofotfjord in northern Norway is studied when approached by an autonomous underwater vehicle (AUV) with electrical propulsion. The reaction of herring is recorded running the AUV in the beam of the mother vessel's 38-kHz echosounder and in more detail with an onboard 120-kHz echosounder. The results indicate an insignificant reaction of herring to the approaching AUV, although some variations were observed depending on the experimental set-up. Technical uncertainty in the recordings close to the AUV transducer creates some ambiguity in the results. No reaction could be identified from the ship's sounder when the AUV passed under the vessel. Processing of the onboard echosounder data suggests a mean avoidance distance of 8.0 m in these experiments. In a realistic autonomous survey situation it is assumed that the AUV can approach as closely as 5–10 m to herring schools without affecting the acoustic observation, which makes it a potentially useful platform for hydroacoustic research and survey. More systematic studies are needed to precisely define the threshold reaction distance to the AUV, and the work should be conducted with transducers on a more silent platform than RV "Johan Hjort", which was used in this study.

Keywords: acoustic sampling, autonomous underwater vehicle, AUV, avoidance distance, over-wintering herring.

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Introduction

Acoustic measurement methods have frequency-dependent limitations in range. The low frequencies and long pulse duration used for long-range observations reduce resolution, resulting in a loss of detail and a reduction in target position accuracy. Near-bottom observations are affected by the acoustic "dead zone" (Ona and Mitson, 1996). To minimize the effects of these limitations, the sampling instruments can be brought closer to the objects of interest, thus allowing detailed studies to be carried out on high-resolution behaviour, target strength, and tilt angle distributions. In this paper, we use the Hugin Autonomous Underwater Vehicle (AUV) to bring our sensor, a 120-kHz echosounder, closer to the fish targets. The echosounder has a range of 200 m. The Hugin AUV is used primarily for bottom mapping (Kristensen and Vestgård, 1998) and not for bioacoustic surveillance.

Fish avoidance from a research vessel has been reported in acoustic surveys (Olsen, 1971, 1990; Olsen *et al.*, 1983; Soria *et al.*, 1996), in combined acoustic and visual surveys (Fréon *et al.*, 1992), and in trawl surveys (Ona, 1988; Ona and Godø, 1990; Nunnallee, 1991). In contrast, Fernandes *et al.* (2002) observed no avoidance of North Sea herring (*Clupea harengus* L.) from a silent research vessel when using an AUV to describe fish behaviour. The problem of avoidance from AUVs has never been addressed previously. Before introducing the AUV as a standard platform in fisheries research, the avoidance effect needs clarification. Here, we investigate herring avoidance from an approaching AUV.

The experiments were conducted in Ofotfjord in north Norway during the period 23–26 November 2002, when the herring is in a non-feeding state (Slotte, 1999) and energy minimization is important. This period can thus be looked upon as an exercise in predation avoidance and energy conservation (Huse and Ona, 1996). We expect the herring schools to be in a vigilant state, since killer whales (*Orcinus orca* L.) feed on herring in this area during the study period (Nøttestad and Axelsen, 1999).

Material and methods

The noise level of the AUV was measured at a military acoustic measuring station located at Hegreneset in

Norway. During the measurements, RV "Johan Hjort", the mother vessel for all our experiments, was positioned about 1000 m away from the station with engines running. The AUV was run through the dynamic measurement location 13 times maintaining a speed of 3−4 knots. Data from all the runs show that noise from RV "Johan Hjort" totally dominated the sound spectra (H. P. Knudsen, pers. comm.).

The AUV was painted red-orange. Shaped like a torpedo, it is 6-m long, the diameter at its thickest point 0.7 m. Tests were conducted during both *autonomous* and *steered* runs. During steered runs, the AUV and its sensors can be operated remotely through an acoustic link. We could also view real-time data from the 120-kHz echosounder through the acoustic link.

Operation

When the AUV is running horizontally, the 120-kHz beam points down. The transducer fixed to the hull tilts and rolls with the AUV. Some of the acoustic links used by the AUV interfered with the 38-kHz and 120-kHz sounder. During the steered surveys, the trajectory of the AUV could be altered so that the herring schools could be approached at different angles. To ensure that the school was approached as planned, we tried to keep the AUV in the beam of the mother vessel's 38-kHz echosounder. This gave us a real-time overview over the AUV's position in relation to the herring school. We also continually observed the position of the AUV relative to the mother vessel using a High Precision Acoustic Positioning system (HiPAP). This enabled us to maintain the AUV within a horizontal distance of 50 m from the mother vessel. Data were collected during three separate experiments. AUV trajectories for all experiments are shown in Figure 1.

In the analysis, we used data from the 38-kHz and 120-kHz sounders. Data from the AUV have a vertical resolution of 0.048 m for experiment 1, and 0.19 m for experiments 2 and 3. The reduction in vertical resolution was done to reduce the bandwidth and hence reduce the amount of noise in our data from the RV "Johan Hjort" in the steered experiments. Data from the RV "Johan Hjort" have a vertical resolution of 1.0 m. For the AUV, the horizontal resolution is determined by the vessel speed (1.9 m s^{-1}) and echosounder pulse repetition rate (1 s^{-1}). On RV "Johan Hjort", we used log-based pinging with one ping per 9.3 m. For experiments 1 and 2 we kept the AUV below 150 m to minimize avoidance associated with RV "Johan Hjort" by herring (Vabø *et al.*, 2001).

Autonomous operations

Experiment 1 was an autonomous survey. A zigzag path was programmed into the AUV. RV "Johan Hjort" monitored the survey by remaining stationary at the pre-programmed corner points of each zigzag line. The AUV position could then be updated each time it was within communication range. Since the AUV was outside the echo beam of the research vessel, we had no overview of the school extension and therefore had to rely on the AUV echosounder data to determine when it was inside the schools.

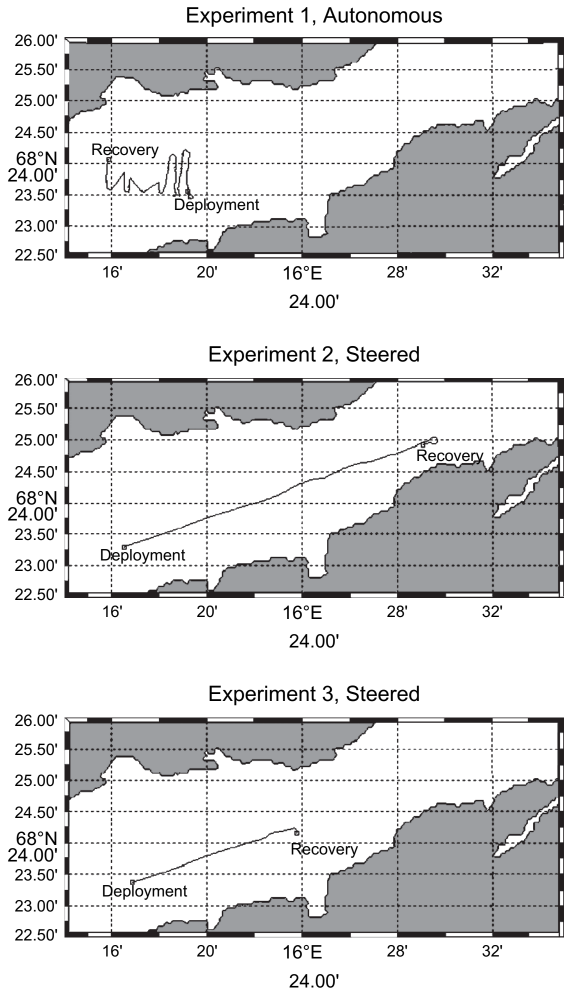

Figure 1. AUV path for each experiment.

Steered operation

Experiments 2 and 3 were run in this mode. The AUV was run in straight lines along the fjord. In both cases, we positioned RV "Johan Hjort" directly above the AUV, except when course change was needed due to commercial fishing activities, mainly small vessels, fishing saithe (*Pollachius virens* L.), with handlines. As a result, we lost the AUV's echo from the mother vessel's echo beam for short periods. This did not interfere with the data acquisition, as we could use the HiPAP system to determine the position of the AUV. Figure 2a, b shows echosounder data from the mother vessel and the corresponding data from the AUV.

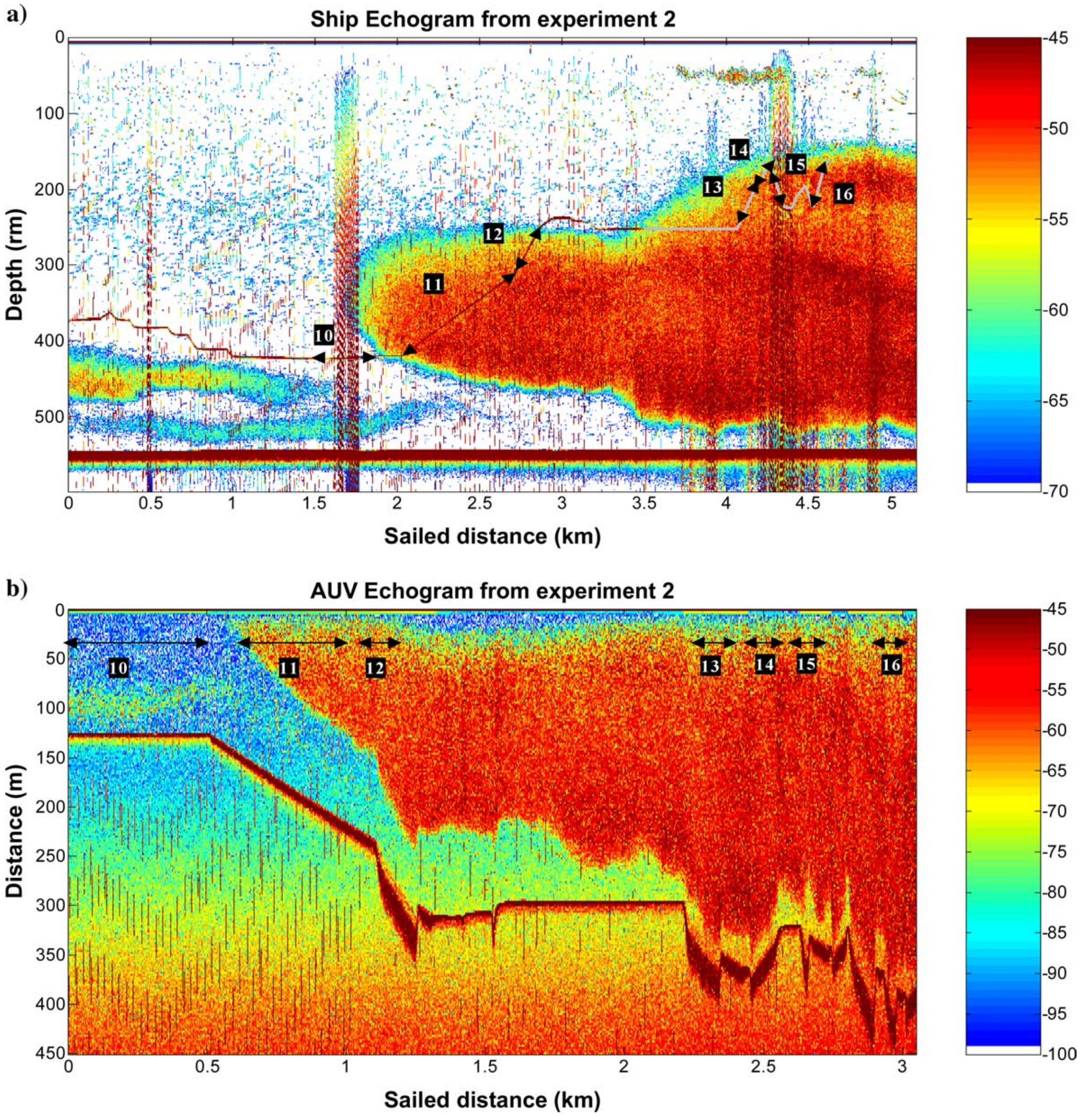

Figure 2. Data from experiment 2. The arrows on the AUV path correspond to the AUV echosounder data sets used in our analysis (Table 1). The colour bar gives volume backscattering strength (dB rel 1 m^{-1}) (a). AUV as observed from the ship's echosounder during the experiment. The backscattering from the AUV can be seen from 0 to 3.5 km sailed distance in the echogram. From 3.5 to 4.6 km the AUV could not be seen in the ship's echogram and a line draws the path. The slope of the path reflects the AUV's tilt angle, as measured by sensors in the AUV (b). Data collected from the AUV during the experiment. Note that the y-axis is the distance from the AUV's transducer.

Analyses

Analyses were done after segmenting the data, each segment corresponding to a continuous path and a constant tilt angle of the AUV. Some of the data sets indicated varying school density caused by navigation in the periphery of the schools and not as a result of avoidance. These data sets were discarded. An exception is the potential inclusion of such data in autonomous operation (experiment 1), as the mother vessel did not monitor the vertical extent of the herring schools. Avoidance was expected to appear as a reduction in density close to the AUV. Because the data considered in this study are close to the transducer, where the signal-to-noise ratio is high, acoustic interference was considered to be negligible.

A background signal was extracted by using areas where there was little evidence of the presence of fish and was subtracted from the data to suppress the effect of ringing. To determine avoidance distance from the AUV, we fitted a sigmoid function to the average density profiles from the 120-kHz echosounder as a function of distance from the body. This type of function has a maximum and minimum marginal value, the maximum value representing normal school density and therefore reflecting a situation without avoidance. The minimum value corresponds to the point nearest the AUV, where avoidance is maximal. The avoidance distance, d95, was defined as the distance where the sigmoid function reached 95% of its maximum value. The 95% of maximum point was chosen to avoid numerical artefacts associated with estimating the asymptote of the relationship. The distance where the sigmoid function reached 5% of its maximum value is denoted d05 and represents the distance from the AUV where few fish occurred. The avoidance span is defined as the distance between d05 and d95 (Figure 3). Data sets greater or equal to 200 pings were split into intervals of 90−100 pings. We calculated the d05 and d95 values for each interval and used these to calculate the standard deviation for the data set. We also carried out a visual inspection of the AUV echogram to look for single fishes closer to the d05 distance.

Earlier avoidance experiments from this area show that herring can react strongly to vessel stimuli at this time of the year (Vabø, 1999). No significant avoidance from the research vessel is expected below 150 m (Vabø *et al.*, 2001). Diurnal time variations for over-wintering herring have been reported. Herring aggregations are deeper and denser during daytime (07:00 to 16:00) and more disperse and higher in the water column during night-time (16:00 to 07:00) (Huse and Ona, 1996; Huse and Korneliussen, 2000). However, because of the limited data in this study, we do not discriminate between daytime and night-time runs.

The data from the mother ship were investigated to see if we could observe any avoidance was contaminated by acoustic interference. Subsections free from acoustic contamination were used to investigate any AUV avoidance. We plotted density profiles as a function of depth around the position of the AUV. Any avoidance would appear as density reduction close to the AUV echo.

Results

Data from experiment 1 (41, 51, 71, and 61 in Table 1) showed a mean avoidance distance of 13.7 m, and a mean avoidance span of 10.6 m. There was a noticeable drop in standard deviation for the smallest d05 distances, while values for d95 were more stable. Figure 3 shows the corresponding echograms and density profile for data sets 41 and 51. The high variances in data sets 41 and 71 may be an artefact caused by running the AUV on the outer edges

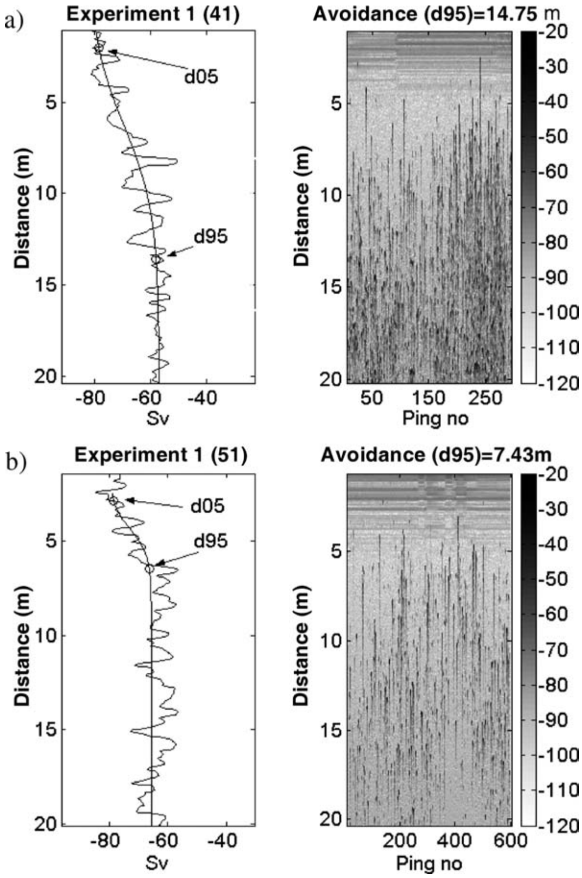

Figure 3. Echogram and density gradient with fitted sigmoid function from data sets 41 (a) and 51 (b) from experiment 1. The colour bar gives volume backscattering strength (dB rel. 1 m^{-1}). Numbers above echogram correspond to data sets in Table 1. The estimates of d95 and d05 are marked with circles. Note that ping scale differs between data sets 41 and 51.

of a school. For example, data set 41 gives a high variance because of the upward-sloping school boundary (Figure 3).

We encountered the densest schools during experiment 2 (data sets 1−8, Table 1). The mean avoidance distance was 4.6 m and the mean avoidance span 2.1 m, with relatively low overall variances.

Data from experiment 3 (data sets 11, 13, 15, 16 in Table 1) gave a mean avoidance distance of 8.9 m and a mean avoidance span of 5.27 m. Visual inspection of the AUV echograms showed individual fish closer than the minimum d05 value in Table 1.

The echogram data from the mother ship did not reveal any density reduction around the echo from the AUV. This lack of density reduction can be explained by the acoustic beam coverage at the AUV depth and the sampling interval of 1 m. In Figure 2a, b the data are segmented into seven corresponding intervals numbered from 10 to 16. Intervals 11 to 16 contain data where the AUV is inside the school. Close examination of the data (Figure 2b) 0−10 m from the

Table 1. Results of the analyses from the three experiments. The d95 and d05 values give the distance to the AUV in metres, with their corresponding standard deviations; Svd95 and Svd05 are the volume backscattering corresponding to the d95 and d05 distances; the angle column gives the AUV tilt angle; time represents the start time when the first ping in the data set was obtained along with its duration. The missing standard deviation in data sets 1, 8, 12–16 is due to lack of data.

Data set	No. of pings	d95 (m)	S.d. d95 (m)	Svd95 (dB rel 1 m^{-1})	d05 (m)	S.d. d05 (m)	Svd05 (dB rel 1 m^{-1})	Angle (deg)	Time (hh:mm)	Duration (min)
Experiment 1										
41	295	14.72	2.66	−57.7	3.86	2.65	−76.3	0	13:52	5
71	160	27.06	3.30	−57.0	2.81	2.22	−77.7	0	15:52	2.5
51	600	7.43	2.38	−62.8	3.14	1.28	−77.4	0	18:05	10
61	180	5.48	2.06	−69.6	2.47	1.38	−83.4	0	18:42	3
Experiment 2										
1	113	4.38	–	−59.5	3.24	–	−75.8	−20.0	19:34	1.8
2	280	3.05	2.43	−54.2	1.72	0.50	−69.1	0	19:40	4.7
3	450	4.57	1.44	−54.1	2.29	0.62	−65.8	12	19:45	7.5
4	480	3.24	1.28	−54.5	1.90	0.22	−73.0	0	19:52	8
5	92	4.38	2.3	−54.8	1.91	0.30	−67.6	−19.3	20:01	1.5
6	860	3.24	1.90	−55.6	1.72	0.39	−77.9	0	20:03	14.3
7	480	8.39	1.07	−55.5	2.48	1.44	−73.7	12.0	20:24	8
8	120	5.15	–	−58.7	4.76	–	−69.8	27	20:32	2
Experiment 3										
11	466	4.19	2.12	−58.1	2.47	1.14	−76.5	12.4	16:30	5.44
12	100	21.44	–	−56.0	2.67	–	−79.8	29	16:36	5.4
13	113	2.85	–	−64.8	1.71	–	−85.2	25.0	16:50	1.4
14	96	7.81	–	−60.0	6.86	–	−73.7	13.5	16:51	1.1
15	86	7.24	–	−56.5	2.29	–	−78.1	−19.0	16:52	1.0
16	77	10.10	–	−61.1	3.62	–	−78.4	29.5	16:57	0.9

AUV's transducer shows weaker backscattering than for greater distances. If avoidance can be detected from the mother ship's echogram it should appear as regions of weaker echo above and under the AUV echo.

Discussion

No avoidance reaction around the AUV was seen on the mother vessel's echosounder. This means that avoidance, if it exists, is too small to be detected with the ship's echosounder resolution. However, a limited avoidance was inferred from the AUV's data at a mean distance of 8.0 m. This is seen as low intensity areas in front of the AUV transducer. We discovered during the analysis that sampling problems and acoustic effects might have biased our conclusion.

The acoustic beam, in our case a circular cone of 7°, is very narrow within the threshold distance. Detection probability close to the transducer is therefore low, but few and strong signals are assumed to give an unbiased mean with higher variance. The interpretation of the density profiles with decreasing density and distance was complicated because of the increase in variance, which resulted in oscillating profiles. Background radiation and side lobes give positive bias, while saturation gives a negative bias. The effect of ringing was observed when examining the background signal. For each data set we calculated the background noise and subtracted it from the data set. Echoes at close range to the transducer may drive the signal to saturation; this will give a negative bias to the signal, and appear as density reduction and apparent avoidance reaction. Samples closer than the far field range (1 m) are discarded. Similar considerations should also be done for ranges shorter than far field of herring. In our analysis, we assume that this far field is shorter or equal to that of our instrument. The AUV's echosounder transmitted at 1000 W, and therefore underestimation caused by non-linear acoustic effects may occur (Baker and Lunde, 2002). These effects can still result in uncertainties in our estimates of avoidance distances, but they are more related to estimation of the near-field distance (d05) than to the distance where avoidance is difficult to detect (d95), which we consider relatively robust. As a result, we feel that our interpretation of avoidance distances of the AUV is not strongly influenced by acoustic effects.

Avoidance may be defined as fish escaping out of the echo beam, or as biased tilt angles leading to reduced backscattering. Both effects will lead to underestimation and similar reaction range profiles. Since the fish's behaviour is affected in both cases, we have not discriminated between these two effects. The observation of single fish closer than the minimum d05 distance can give the impression that some of the herring are not driven by an anti-predator alertness. These events were rare and can be considered as abnormal behaviour.

Our study indicates that the AUV is a gentle intruder, its presence seemingly being ignored beyond an average distance of 8.0 m. This form of intrusion can be viewed as a car moving at very slow speed through a dense crowd of people. The gradients close to the AUV from this kind of behaviour would most likely look like the one obtained from experiments 2 and 3. Fernandes *et al.* (2002) observed an avoidance of 7 m from the Autosub AUV, which is generally consistent with our estimates. By comparison, RV "Johan Hjort" is expected to have an avoidance distance of 150 m (Vabø *et al.*, 2001).

For more detailed investigation of avoidance reaction to the AUV a sonar approach as used in studies of predator–prey interaction may be useful (Nøttestad and Axelsen, 1999; Nøttestad *et al.*, 2002a, b). To gain more accurate avoidance distance measurements one could also apply cameras or Doppler profiler integrated within the AUV to observe tilt angles and swimming speeds relative to the AUV. Similar studies should be repeated to record the potential avoidance reaction threshold for different species. Some noise measurements have been done for the AUV, but more detailed studies, such as those described by Mitson (1995) and Mitson and Knudsen (2003) and performed by Griffiths *et al.* (2001) on the Autosub AUV, should be carried out.

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