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On the radiated noise of the Autosub autonomous underwater vehicle

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Autonomous Underwater Vehicles (AUVs) can be very quiet platforms from which to make observations of marine living resources. With few moving parts and very low propulsion power they should have a very low underwater radiated noise signature. The purpose of this paper is to describe measurements on Autosub to test this assumption. The measured noise level and spectrum are compared to the ICES proposal for the radiated noise of fisheries research vessels. Integrated over the band 100 Hz to 5000 Hz the AUV source level, at 124 dB relative to 1 μPa at 1 m, was about 39 dB below of the ICES specification and about 30 dB quieter than the noise-reduced vessel "Scotia". Autosub is in fact exceedingly quiet. The difficulties of making measurements of the underwater radiated noise of a quiet submerged vehicle are discussed and suggestions are made for improvements in techniques.

Keywords: AUV, vessel avoidance, noise.

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Introduction

Acoustic surveys for fish stock assessment can provide independent information for the management of fisheries that complements that obtained from catch data. However, concern over vessel avoidance by fish in response to noise radiated from some vessels has cast doubt on the precision of acoustic and trawl surveys (Mitson, 1995). Against this background of concern, the ICES study group on Research Vessel Noise recommended that "Vessels engaged in fisheries research . . . should conform as closely as possible to the proposed noise signature, namely:

$SPL = 135 - 1.66 \log f_{Hz}$ between 1 Hz and 1 kHz and
$SPL = 130 - 22 \log f_{kHz}$ between 1 kHz and 100 kHz

where SPL is expressed as dB relative to 1 μPa at a reference distance of 1 m in a 1 Hz bandwidth" (Mitson, 1995).

In contrast to surface vessels, all-electric autonomous underwater vehicles (AUVs) have very few moving parts. For the Autosub AUV there are only three of significant size or power: the direct-drive, brushless DC propulsion motor and two small motors operating the rudder and stern dive planes (Millard *et al.*, 1998). The propulsion motor is usually operated with between 150 and 650 W electrical input power and the fin actuator motors consume some 10 W. For comparison, a fisheries research vessel may have machinery with a power of over 1 MW installed, although during surveys the power generated would usually be below 500 kW.

Fernandes *et al.* (2000a,b) reported the results of an experiment to test the hypothesis that the biomass of fish detected by the fisheries research vessel "Scotia" was not different from the biomass detected by Autosub. The rationale underpinning the experiment was that the underwater radiated noise of the AUV was far less than that of "Scotia" and hence avoidance by fish of Autosub in response to its acoustic signature should be minimal.

Using "Scotia" as the vessel for the experiment had the important advantage that she was the first fisheries research vessel to be designed to the radiated noise specification proposed by Mitson (1995). The experiment was, in part, an evaluation of the noise specification. Unfortunately a quantitative measure of the underwater radiated noise of Autosub was not available

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Figure 1. Autosub's five-bladed propeller. The large diameter hub houses the direct-drive DC propulsion motor.

to Fernandes *et al.* (2000a). Nevertheless they surmised that the vehicle was "extremely quiet" from the fact that it was able to pass "unprecedently close" (seven metres) to a school of herring.

This paper reports the first measurements of the underwater radiated noise from Autosub, measurements that confirm the supposition by Fernandes *et al.* (2000a) that it is a very quiet platform. In fact, experiments to determine the radiated noise spectra proved more difficult than would be the case with a surface ship because it was such a quiet platform. This was not altogether unexpected. Godo and Vestgard (personal communication) had reported that at-sea noise trials of the "Hugin" AUV had proved very difficult, as the recording was dominated by the noise radiated from the support vessel about 1000 m away.

Environmental and shipping noise at the location of the Autosub noise-signature experiment was a limiting factor. It restricted the frequency range over which acceptable data could be obtained. The accepted band of interest for fisheries research purposes, 10 Hz to 100 kHz, could not be covered in its entirety. Nevertheless the results do cover an important band from 100 Hz to 5000 Hz. A qualitative result from this experiment is that measurements of the radiated underwater noise of the AUV could not be measured accurately below 100 Hz and above 5 kHz because its level was too close to ambient noise at the trials' location.

Propeller cavitation, when it occurs, is a major source of underwater radiated noise for any vessel. The propeller of an AUV differs significantly from that of a typical propeller-driven ship. Autosub's propeller, Figure 1, is of a fixed pitch, with relatively long and narrow blades. These are inherently noisy but the propeller was designed for optimum propulsion efficiency rather than low radiated noise. The blades are 131 mm long with a chord of 29 mm mounted on a 198 mm diameter hub, giving an overall diameter of 460 mm. However the rotation rate of the propeller is high, typically 325 revolutions per minute (rpm) at a speed of 1.8 m s^{-1}, compared to a typical value of less than 50 rpm for a ship at the same speed.

Ross (1975) developed the "tip cavitation" index K_t as an index of the possible onset of cavitation, which, for a submerged submarine, was given by:

$$K_t = \frac{2}{3} \frac{(h+9)}{\left(\frac{N}{100}\right)^2 D^2} \quad (1)$$

where h is the depth of the propeller tip below the surface in metres, N the rotational speed in revolutions per minute and D the diameter of the propeller in metres. For these trials h = 4.77 m, N = 325 and D = 0.46 m giving $K_t = 4.1$. Cavitation is unlikely for $K_t > 5$ (Ross, 1975), but, at $K_t \simeq 4$, cavitation could occur if the propeller was operating in a "poor wake". Whilst Autosub has been designed to have a low drag and the propeller has been optimised for use with the vehicle, the vehicle has developed many protuberances, cut-outs and rough areas during use. These imperfections have increased the drag and, by implication, have resulted in a less than perfect wake. Consequently, it was not a foregone conclusion that Autosub would have a low noise signature, similar to "Hugin", especially when operating close to the surface.

Low radiated noise is but one advantage of an AUV; others have been explored by Fernandes and Brierley (1999). Because of their low noise and low impact on the environment we expect AUVs to be used increasingly to obtain information on marine living resources and their environment, especially as their endurance and sensor payload capacity increase.

Methods

The experiments described in this paper were carried out on 11 November 2000 in Plymouth Sound on the south coast of England. The timing, duration and location of the trials were constrained because of logistics. Poor weather conditions prevailed for the period of the measurements. Westerly winds were up to 17 m s^{-1} with Sea State 3 estimated within the Sound. These conditions led to the work being done inside rather than outside Plymouth Sound, taking advantage of the lee offered by the breakwater that runs approximately east-west. However, the advantage of reduced sea state noise when working in a sheltered harbour was at the cost of accepting a higher ambient noise from harbour traffic.

The noise measurements were made using Ultra Electronics' Transportable Overside Noise Evaluation System (TONES), Enoch and McGowan (1997). The in-water component of TONES comprised a surface

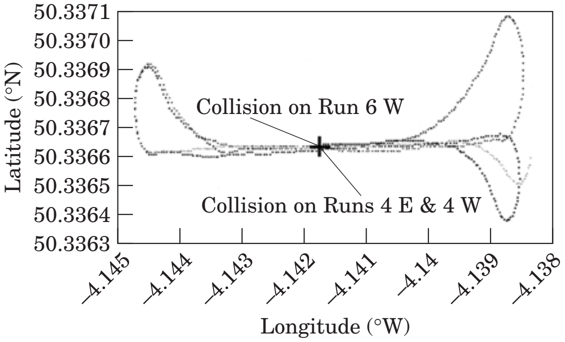

Figure 2. Track chart of the second series of Autosub runs past the TONES mooring, from Run 4 West in light grey to Run 6 West in black. The collisions on Run 4 West and Run 6 West are shown, together with a cross at the position of the TONES mooring. Note that the Latitude scale has been exaggerated by 6.4 in this Figure compared to Longitude in order to show detail near the TONES mooring.

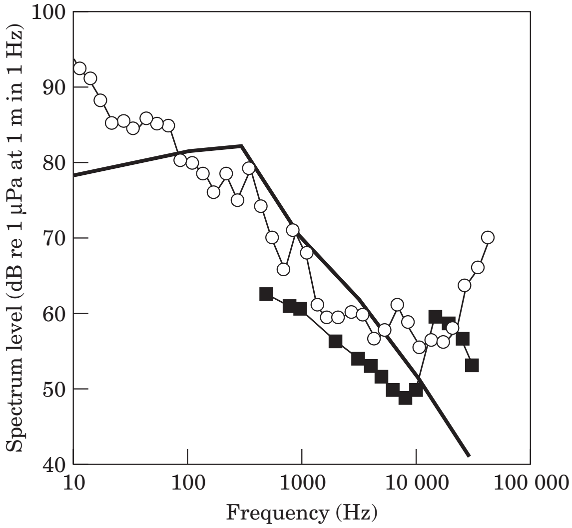

Figure 3. Ambient noise measured at the trials' location within Plymouth Sound on 11 November 2000 within one-third octave bands (open circles), together with the ambient spectrum level redrawn from Wenz (1961) for the highest, but unspecified, level of shipping and weather (solid line). For comparison the ambient noise recorded by Quartly *et al.* (1998) in Loch Etive, Scotland for a wind speed of 5 m s^{-1} accompanied by drizzle is also shown (filled squares).

marker buoy with a radar reflector moored to the seabed. From the surface buoy a short tether was attached to a secondary surface buoy from which a hydrophone and preamplifier were suspended. Sounds recorded at the hydrophone were relayed to a support ship via a VHF radio link where they were recorded on to DAT tape and, in parallel, the sound was processed to give narrow-band and one-third octave spectra. The TONES real-time signal processor provides two spectra per second for a period of one minute either side of the closest point of approach (CPA).

The usual procedure of measuring the CPA for a surface ship using a visual rangefinder could not be used for the submerged AUV. Instead the CPA for the real-time signature analysis had to be estimated from the dead-reckoning navigation of the vehicle. Subsequently post-processing from raw data recorded on the DAT tape enabled more precise estimates to be made of the CPA.

When submerged Autosub navigated using dead-reckoning (DR) based on speed over the ground, measured using an acoustic Doppler velocity log, and heading obtained from a three-component fluxgate magnetometer (McPhail and Pebody, 1998). Both instruments were calibrated as the first operation at the trials' site, resulting in a DR position error of less than 1% of the distance travelled. For this series of experiments the vehicle was programmed to shuttle back and forth on east-west courses between two waypoints some 460 m apart (50°20.199′N 4°8.302′W and 50°20.199′N 4°8.692′W, see Figure 2). The TONES buoy was deployed approximately half way between these two waypoints at 50°20.198′N 4°8.504′W, in a water depth of 10 m, with the hydrophone at a depth of 6 m. During the experiment the support vessel stood off some 300 m from the buoy. The Autosub runs to the west were made with a motor power of 450 W, providing a speed of 1.30 m s^{-1}, while those to the east were at a higher motor power, 650 W, providing a speed of 1.70 m s^{-1}.

Autosub was programmed to traverse between the waypoints at a depth of 5 m. Two series of three pairs of west-east transects were planned (twelve passes of the TONES buoy in all), preceded by a recording of ambient noise. At the start and end of each series of runs the vehicle surfaced for a Differential GPS satellite fix to reset its DR position. Confirmation of the accuracy of the DR navigation came from two of the runs (Runs 4 West and 4 East) where the vehicle brushed the TONES mooring. Unfortunately while on Run 6 West the vehicle propeller hit the mooring line causing damage to the blades and ending the trial.

Figure 2 shows the tracks of the vehicle on the second series (Runs 4–6), together with the position of the TONES mooring. Of these five passes three came into contact with the mooring, thus providing a clear reference for the CPA and maximising the ratio of the vehicle radiated noise to the ambient noise.

Post-processing

The indications from the real-time spectral analysis suggested that the vehicle noise signature was only detectable above the ambient noise for a short distance on either side of the CPA. To improve the spatial

Table 1. Correlations between the ambient noise and Autosub runs past the TONES hydrophone.

	Ambient	Run 1 W	Run 2 W	Run 3 E	Run 4 W	Run 4 E	Run 5 W	Run 5 E
Ambient	1							
Run 1 W	0.9492	1						
Run 2 W	0.8965	0.9518	1					
Run 3 E	0.9149	0.9536	0.9530	1				
Run 4 W	0.9620	0.9622	0.9460	0.9782	1			
Run 4 E	0.9642	0.9514	0.9355	0.9657	0.9942	1		
Run 5 W	0.9119	0.8137	0.7505	0.7992	0.8870	0.8937	1	
Run 5 E	0.9839	0.9246	0.8814	0.8767	0.9448	0.9466	0.9277	1

resolution near the CPA the original DAT recordings were post-processed to provide ten spectra per second, rather than the two per second obtained in real time. This was done for a window of 15 s either side of the CPA. As described below the timing of the CPA was confirmed using the noise of the AUV colliding with the mooring.

Results

Ambient noise

A recording of ambient noise was made on 11 November 2000. The spectrum levels in one-third octave bands are shown in Figure 3 together with the spectrum from Wenz (1961), as reproduced in Mitson (1995), and recent data reported by Quartly *et al.* (1998) from a Scottish sea loch with a 5 m s^{-1} wind and drizzle. The Wenz (1961) data is not ideal as a comparison as it appertains to deep, open-water conditions. The Quartly *et al.* (1998) curve is a more appropriate comparison, although Quartly's data were obtained under less severe conditions. The higher resolution spectra (not shown) exhibited considerable tonal activity from 10 Hz to 1000 Hz, indicative of shipping noise and a broad peak from 6 kHz to 10 kHz whose origin was not established. Clearly the ambient noise level was far from ideal for a noise signature experiment, although not untypical of the conditions that the AUV would encounter at sea.

Autosub runs past the TONES mooring

Of the eleven runs made by Autosub past the TONES hydrophone, seven contained information that was of use in assessing the vehicle's noise signature. The first analysis step for these runs was to compare the one-third octave band spectrum levels at each estimated CPA with those of the ambient noise and with each other. This was done using a scatter-plot matrix. The correlations are summarised in Table 1. Three of the seven noise-to-run correlations exceeded 0.95 compared with eight out of 21 correlations for the run-to-run pairs, indicative of a low signal-to-noise ratio between the vehicle signature and the ambient noise at the estimated CPAs.

This initial step was followed by a more detailed analysis of those runs where the Autosub brushed past the TONES mooring. These runs had two advantages. First, the time of impact could be determined accurately from the sound recorded on the DAT tape and, consequently, the path of the vehicle could be interpolated accurately from its speed and heading in the close vicinity of the mooring. Second, the close approach maximised the signal-to-ambient noise ratio.

Analysis of Run 4 West

At 20 minutes and 25 seconds into the DAT tape, during Run 4 West, Autosub was heard to collide with the mooring. Immediately prior to the collision there was no audible signature from the vehicle above the background noise.[1] Only when the vehicle continued on its path and the machinery at the rear of the vehicle passed the hydrophone could its sound be heard above the ambient noise.

A spectrogram covering 15 s either side of the collision is shown in Figure 4. The collision is seen clearly as a brief, sharp increase in spectral level, quite distinct from the fading in and fading out expected from radiated noise. With the vehicle travelling at about 1.3 m s^{-1} the spectrogram covers a distance from the hydrophone of 23.8 m during approach and 15.2 m on the retreat. The intermittent tonal bursts at around 1100 Hz were caused by a loose shackle on the mooring. Near-continuous tonals below 500 Hz were part of the ambient noise in Plymouth Sound. The spectrogram confirmed the auditory assessment that there was no AUV noise signature audible above the ambient noise before the collision. However, between about 19 and 21 s, four to six seconds after the first sign of collision, the spectrogram shows above-background signal levels primarily below 3000 Hz. After 21 s the succeeding

[1]A 16-bit dynamic range.wav file encompassing 15 s either side of the collision on this run can be downloaded from http://www.soc.soton.ac.uk/OED/gxg/asubnt4.wav

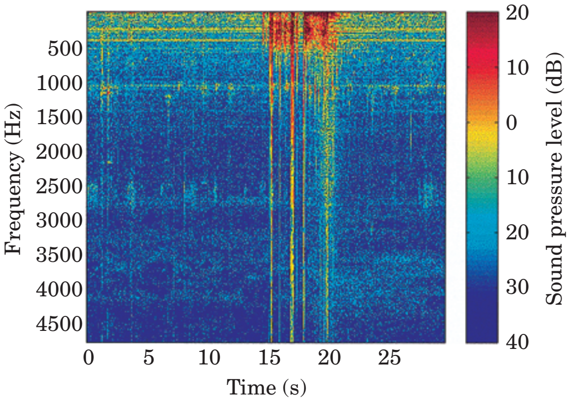

Figure 4. Spectrogram covering 15 s either side of the collision on Run 4 West between Autosub and the TONES mooring.

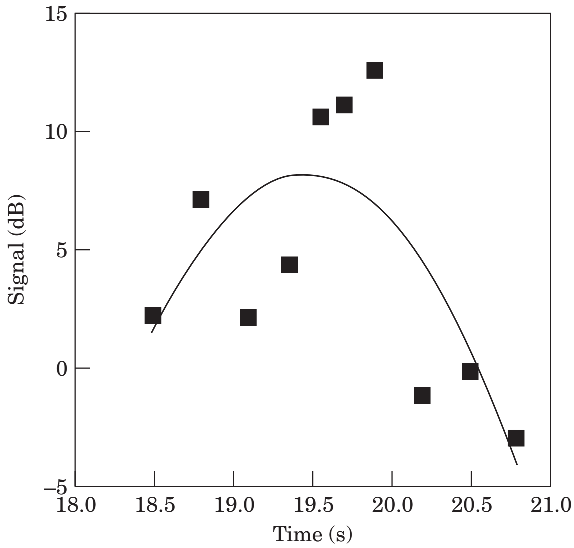

Figure 5. Average spectrum level in the 137–275 Hz band over the period t = 18.5 to 20.8 s of the spectrogram in Figure 3, with a least squares quadratic fit to estimate the point of closest approach.

spectra were very similar and indistinguishable from the ambient noise.

Did the Autosub collide with the mooring line or with the hydrophone tether? This can be answered by examining the time (distance) difference between the knock of the collision and the maximum noise signature. Autosub is 6.7 m long, with its motor, propeller, and control surfaces at the rear. With the hydrophone on the tether streaming some 6 m to the west of the mooring line on this run, the distance between the moving machinery of the AUV and the hydrophone would have been about 13 m at the time of the collision of the nose of Autosub with the mooring line, equivalent to 10 sec at 1.3 m s^{-1}. If Autosub collided with the hydrophone tether itself the distance to the moving machinery would only have been 6.7 m, equivalent to about 5 s, which was the observed time difference.

The collision caused the vehicle to veer clockwise off its course at a rate of $\frac{1}{3}$ °s^{-1} for 9 s. Over the next 6 s the autopilot brought the vehicle back on course. There was no discernible change of speed at or after the collision.

To estimate the distance at closest approach to the hydrophone itself, the average levels near the peak of the spectrum (between 137 and 275 Hz) were calculated for the period 18.5 to 20.8 s, covering a distance of 3.0 m. The unknown range *r* between the hydrophone and the moving source (Autosub) at time t can be expressed as:

$$r^2 = d_{CPA}^2 + v^2(t - t_{CPA})^2 \qquad (2)$$

where d_{CPA} is the distance between the source and hydrophone at closest approach and t_{CPA} the time of closest approach. As the spreading loss is proportional to r^2 (for $r \ll h/2$ where h is the water depth) it is proportional to the expansion of Equation (2), that is:

$$\text{loss} \propto (d_{CPA}^2 + v^2 t_{CPA}^2) - (2v^2 t_{CPA})t + v^2 t^2 \qquad (3)$$

which is a quadratic equation in t. While the loss is not known directly from the observations, its inverse, the spectrum level is known. Therefore a quadratic fit to the spectrum level data, shown in Figure 5, was used to estimate the moment of closest approach. The peak spectrum level at that instant, and the times (distances) where the best-fit quadratic curve showed a spectrum level 3 dB below the peak were estimated. The spectrum level was 3 dB below the peak at ± 1 m from the moment of closest approach. Using simple geometry, and assuming spherical spreading over the very short range involved, gives the distance at closest approach of the "centre of noise" as 1 m. The spectral levels from the spectrogram can then be converted to a sound pressure level at the reference distance of 1 m to give the best estimate of the AUV underwater radiated noise spectrum, which is shown in Figure 6. In the absence of a detailed directional radiated noise pattern for the vehicle this analysis has assumed that the noise came from an omnidirectional point source. In practice, there may well be a hull masking-effect prior to arrival at the CPA and possibly a higher radiated noise level than from an omnidirectional source after the propeller has passed the CPA. There is some evidence in Figure 5 that this was indeed the case. The two observations prior to the CPA were below the best-fit curve while the three observations after the CPA were above. Hence while the estimate of the time at the CPA is not affected by the assumption of an omnidirectional source, the estimated distance at the CPA could be in error.

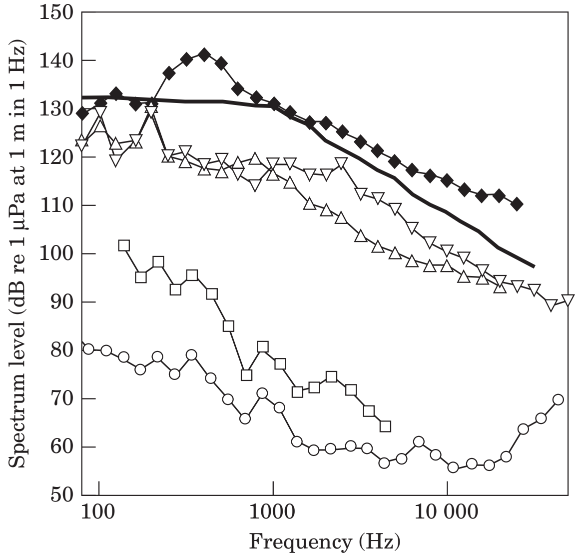

Figure 6. Comparison of the radiated noise spectrum of Autosub (□) with the ICES fisheries research ship recommendation (solid black line), the FRV "Scotia" at 4.1 kt (▽) and at 9.9 kt (△), the RRS "James Clark Ross" at 9.8 kt (◆) and, for reference the ambient noise during the Plymouth Autosub radiated noise trials (○). Note that FRV "Scotia" is quieter at 9.9 kt than at 4.1 kt as the vessel has been optimised for underway acoustic surveys at the higher speed.

Discussion

The assumption by Fernandes *et al.* (2000a) that Autosub was an "extremely quiet" vehicle has been confirmed by the radiated noise trials described in this paper. Against an ambient noise spectrum commensurate with winds of Beaufort scale 5–6 and Sea State 3 and with tonals present from shipping, the vehicle could only be detected within a range of ± 2 m from the hydrophone. Furthermore the vehicle's signature could only be established with confidence from 100 Hz to 5000 Hz. Outside that band its radiated noise was indistinguishable from the background. Compared to the specification for fisheries research vessels proposed by ICES, Autosub was some 30 dB quieter below 500 Hz and between 40 and 50 dB quieter between 1000 Hz and 5000 Hz. Based on the integrated power spectral density over the 100 Hz to 5000 Hz band Autosub radiated noise (at 124 dB relative to 1 μPa at 1 m) was 39 dB lower than the ICES specification; about 30 dB lower than the "Scotia" at 9.9 kt and 45 dB lower than the "James Clark Ross" at 9.8 kt (Figure 6).

The results have shown that the "centre of noise" of Autosub was towards the rear of the vehicle. In the configuration used in the Fernandes *et al.* (2000a,b) experiment the EK500 transducers were placed in the nose of Autosub. This had the beneficial effect of reducing the level of vehicle radiated noise at the locations observed with the sonar, i.e. directly under the nose.

Ideally the radiated noise trials should be repeated at a quieter location and at a time with less ambient noise from wind, sea and rain. For such trials the DR navigation should be improved to provide repeatable transects with the vehicle passing within 2 m of the hydrophone. Recognising that the machinery is at the rear of the vehicle, the distance between the hydrophone and the tail of the vehicle should be measured with sub-metre accuracy. This need not necessarily be done in real-time but it should be available for post-processing. Finally the mooring itself should be designed to be quiet.

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