Review: Effects of seal scarers on harbour porpoises

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1 Summary

Seal scarers or seal scrammers are devices designed to deter seals from fishing gear and aquaculture installations to avoid depredation on fish. The deterrence effect towards porpoises is increasingly exploited as a mitigating tool for harbour porpoises in connection with installation of offshore wind turbines. When evaluating the effectiveness of seal scarers as mitigation devices, it is of particular importance to know the minimum deterrence distance of the device. The minimum deterrence distance is the distance within most or all porpoises can be expected to be deterred and this range is important for assessing the risk of porpoises acquiring hearing damage from the subsequent pile-driving noise. For a seal scarer to be effective as a mitigation tool, it must thus be able to deter porpoises beyond this critical distance, before the pile-driving operation begins.

Based on re-evaluation of the results of a number of field studies where reactions of porpoises to seal scarer sounds were studied, we conclude that the minimum deterrence distance of porpoises within which all harbour porpoises can be expected to be deterred, is about 350 m for the Lofitech seal scarer, and somewhat less, about 200 m for the Airmar seal scarer. If the protocol for mitigation allows for less than total deterrence, the minimum deterrence distance for the Lofitech seal scarer increases to somewhere in the range between 1300 m and 1900 m.

2 Background

This review was commissioned by the Danish Energy Agency to evaluate the current knowledge about the effectiveness of seal scarers as a mitigation tool for porpoises during construction of offshore wind farms, in order to protect the porpoises from exposure to noise levels capable of inflicting hearing damage. The aim is thus to review the results from experimental studies, where porpoises were exposed to seal scarers and to evaluate the usefulness of seal scarers as mitigation tools. More specifically, the goal is to derive from the literature an estimate of the effective minimum deterrence distance.

2.1 Seal scarers

Figure 1 Two seal scarers: Left: Lofitech (Leknes, Norway), the orange box contains the battery, the orange cylinder is the transducer; right Airmar dB II plus (Airmar, Milford, NH, USA), the black cylinder is the transducer.

Seal scarers or seal scrammers are devices designed to deter seals from fishing gear and aquaculture installations to avoid depredation on fish. They are often referred to as acoustic deterrent devices (ADDs), together with for example acoustic alarms (pingers) used to deter harbour porpoises from gill nets. As the seal scarers are significantly more powerful than porpoise pingers, they are often also referred to as acoustic harassment devices (AHDs).

AHDs transmit short sounds in a frequency range of 10-40 kHz (most often with main energy at 10-14 kHz) with source levels up to 195 dB re. 1 µPa. The length of pulses and intervals between them are often randomized to decrease the potential for animals habituating to the sounds, so that aversion effects can be maintained over time. Producers of AHDs include Ferranti Thompson, Terecos, Airmar, Ace Aquatec and Lofitech (*figure 1*). Most AHDs emit sounds in the frequency range 10-14 kHz, where pinnipeds, including harbour seals (*Phoca vitulina*) have their best hearing (Reichmuth et al. 2013). However, this frequency range is also within the hearing range of toothed whales, and even high frequency specialists, such as the harbour porpoise (*Phocoena phocoena*; see next section) has a good hearing around these frequencies. This has led to studies of the negative side effects of AHDs on porpoises when used at fish farms. In addition, the deterrence effect towards porpoises is increasingly exploited as a mitigating tool for harbour porpoises in connection with installation of offshore wind turbines. In this context they are sometimes referred to as acoustic mitigation devices (AMDs), although the distinction from AHD is purely semantic and related only to the use of the device. The aim in this mitigation is to ensure that porpoises are outside the zone of auditory injury before pile driving commences, to fulfil the requirements of national and international legislation to protect this species. The use of AHDs in mitigation has resulted in a number of studies to investigate the effectiveness of AHDs in deterrence of harbour porpoises from marine construction areas.

2.2 Harbour porpoises

The harbour porpoise (*Phocoena phocoena*) is a small toothed whale common in coastal and shelf habitats on the northern hemisphere. They have their best hearing around 110 kHz (Kastelein et al. 2010). However, this species also has good hearing in the 10-40 kHz frequency range, where AHDs operate (*figure 2*).

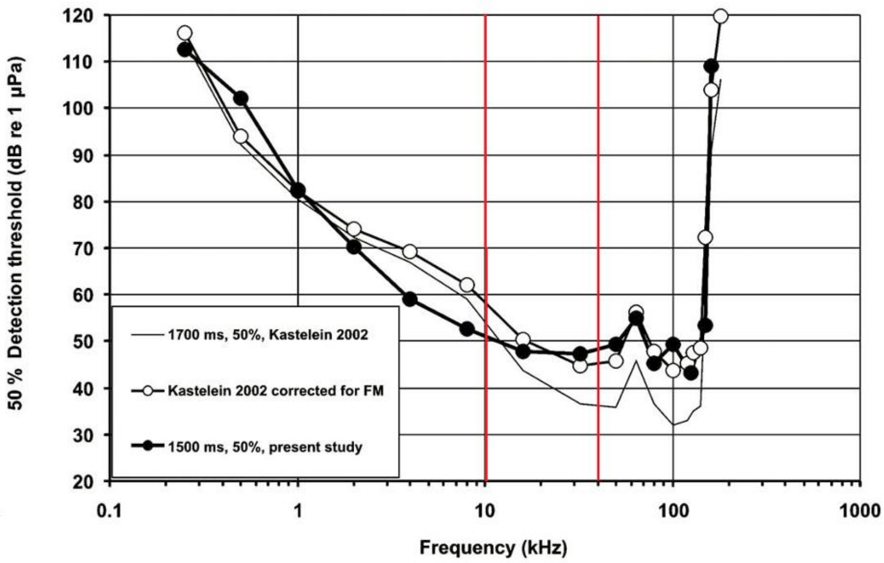


Figure 2 The 50 % hearing threshold of a harbour porpoise based on a psychophysical go/no go paradigm with tonal signals of 1500 or 1700 ms duration. Red lines mark the lower and upper limit for the main energy in most AHD signals. From Kastelein et al. (2010).

As porpoises, like other toothed whales, are fully adapted to life in water, they rely heavily on sound both passively and actively (biosonar) for finding food, navigating and communicating with their conspecifics. AHD sounds have the potential to affect these tasks by causing aversive behavioural responses or impact the hearing directly, either by masking other sounds of importance to the animals, or by inflicting temporary or permanent damage to the inner ears. Most studies have focused on observable behavioural responses such as displacement. The deterrence effects of AHDs are exploited actively when used as mitigation device, with the aim to deter porpoises from exposed areas before there is risk of hearing damage from the noise exposure from pile driving, explosions etc. Previous studies have shown that harbour porpoises are displaced from areas with activated AHDs. Yet, considerable uncertainty is present about the range at which the porpoises react to and are affected by these deterrence sounds. This distance is critically important in assessments of the effectiveness of AHDs as mitigation tools to reduce the risk of auditory injury to porpoises due to pile driving noise. As auditory injury accumulates over time, the exposure to multiple pile driving noise pulses must be factored in, as well as the movement of porpoises away from the piling site as a reaction to the noise. If porpoises are closer than some critical distance at the start of piling, they may not be able to swim sufficiently far away from the noise source before the accumulated acoustic energy exceeds safe levels, with increased risk of hearing damage (see Skjellerup et al. 2015). The critical distance is determined by the source level and impact rate of the pile driving, as well as assumptions on swimming speed and threshold for hearing damage. For an AHD to be effective as a mitigation tool, it must thus be able to deter porpoises beyond this critical distance, before the pile driving operation begins.

In the following, the current knowledge of the impacts of AHDs on harbour porpoises will be discussed. In particular, the aim is to derive a minimum estimate of the effective deterrence distance to be used in modelling of noise mitigation according to Skjellerup et al. (2015).

3 Behavioural effects on harbour porpoises

The effects of AHDs on harbour porpoises have been studied mainly in relation to two issues: To investigate the side effects of devices used to decrease seal predation at fish farms and to evaluate the effects of devices used to intentionally deter porpoises away from noisy construction activities. The findings of relevant studies will be discussed in detail below and are summed up in *table 2*.

3.1 Olesiuk et al. 2002

Olesiuk et al. (2002) studied the effects of an Airmar AHD (Airmar Technologies Corporation, frequency 10 kHz, source level 194 dB re 1µPa pp) on harbour porpoises around Broughton archipelago, British Columbia, Canada. They monitored the porpoises visually, both with the naked eye and binoculars, from the roof of a float-house (6.4 m above sea level), whenever sea state permitted. AHD signals were transmitted from four transducers placed at 10 m depth about 80 m from the observation station. In total, 49 exposure trials and 55 control trials were conducted over an 18-week period. Trials were divided into three 6-week periods to decrease effects of season.

Results showed that no porpoises were observed within 200 m of the AHDs, when they were active, which is a measure of absolute deterrence distance. The received sound level at this range was not given, as no sound measurements of the AHD were made. Also, the uncertainty in visual range estimates makes it difficult to estimate the exposure levels of an animal and thereby the reaction threshold. However, the following section gives a rough estimation of exposure levels based on a few simple assumptions. Within a short range of the AHD it is fair to assume an absorption loss (α) of 1 dB/km of a 10 kHz sound, following Ainslie and McColm (1998), and spherical transmission loss (TL = 20log r), based on a source level of the AHD of 194 dB re 1µPa pp, the received level (RL) at an estimated 200 m range would have been approx. 148 dB re 1 µPa pp following this equation:

$$RL = SL - TL \qquad \textit{Equation 1}$$

where TL = 20log(r) + αR, where r is range.

At longer ranges, both environmental properties and the increasing uncertainty in range estimation result in greater uncertainty on RL estimates. It is therefore important to have sufficient information about environmental factors and good range estimates in order to reach good estimations of reaction thresholds of a porpoise.

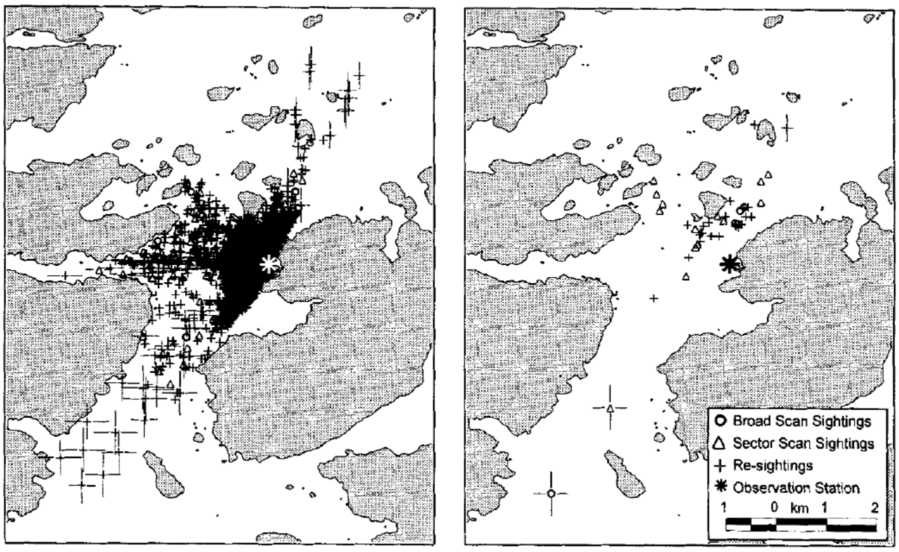


Figure 3 Sightings of porpoises during control periods (left) and treatment periods (right), when the AHD was active. From Olesiuk et al. (2002).

The results of Olesiuk et al. (2002) also showed that the relative porpoise abundance decreased dramatically to just 8.1 % of pre-exposure density out to a range of 3500 m (their maximum sighting range; *figure 3*). This abundance estimate was calculated by dividing the mean number of sighted animals by the scanned surface area. However, to obtain a good estimate of the relative change in abundance it is required that: 1) observers distribute their effort in the same way in all trials (sound and control), i.e. that they do not spend more time looking for animals further away when the sound is on because they anticipate a deterrence; and 2) the detection function is not affected by the sound exposure, i.e. that animals are equally likely to be observed if present, independent of whether the sound is on or off. In relation to the observer bias, this was minimized by using the same observer throughout the study. Although the study was not performed blind, i.e. the observer knew when the AHD was active, the authors did not believe that this affected the observations, as the protocols for scanning were standardized and strictly followed.

Whether the detection function was affected by the AHD exposure is more difficult to determine. First of all, when comparing sightings before and during sound exposure, it is necessary to ensure that sighting conditions are comparable between trials. Here environmental conditions were taken into account by estimating a simple detection function based on the correlation between mean number of observed porpoises and sighting conditions (1-5, where 1 is flat calm and 5 is light chop; *figure 4*) in control periods. This correlation suggested that around 50 % of the present porpoises in the area were likely not observed, in particular at longer distances. The strong decrease in observations with increasing wave height was largely caused by their observation station only being 6.4 m above the sea. The low observation point also influenced the precision on the estimated positions of the porpoises heavily, as these were based on the angle below the horizon. The authors acknowledged that range uncertainties increased with increasing range, being ± 900 m at 2000 m range. The effect of environmental conditions can be expected to be the same or similar independent of sound/no sound. However, the number of observations when the AHD sound was active and when it was not, is likely not directly comparable. For example, depending on how porpoises react to AHD signals, their visibility to observers likely changes. Strong responses, such as porpoising, will result in higher visibility, whereas rapid displacement while submerged will lead to fewer sightings. The impact of sound exposure on the detection function is therefore expected to have affected the estimate of relative abundance of porpoises, although the magnitude of this effect cannot be assessed.

There was no evidence of habituation to the AHD, but avoidance effects were short-term and porpoise abundance returned to normal within the following four days after a trial.

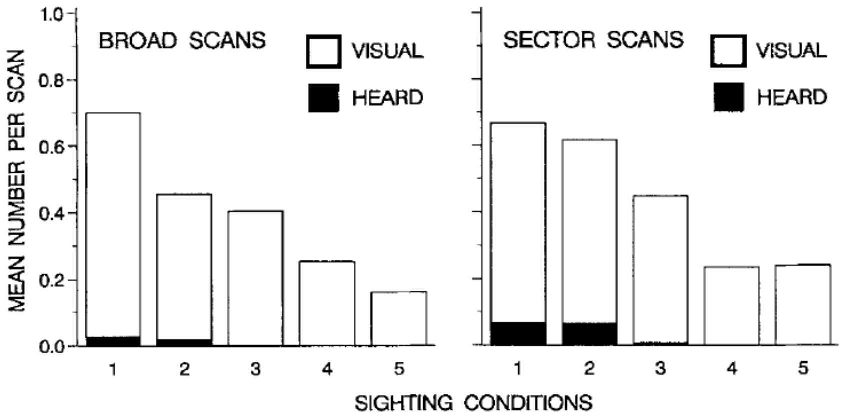
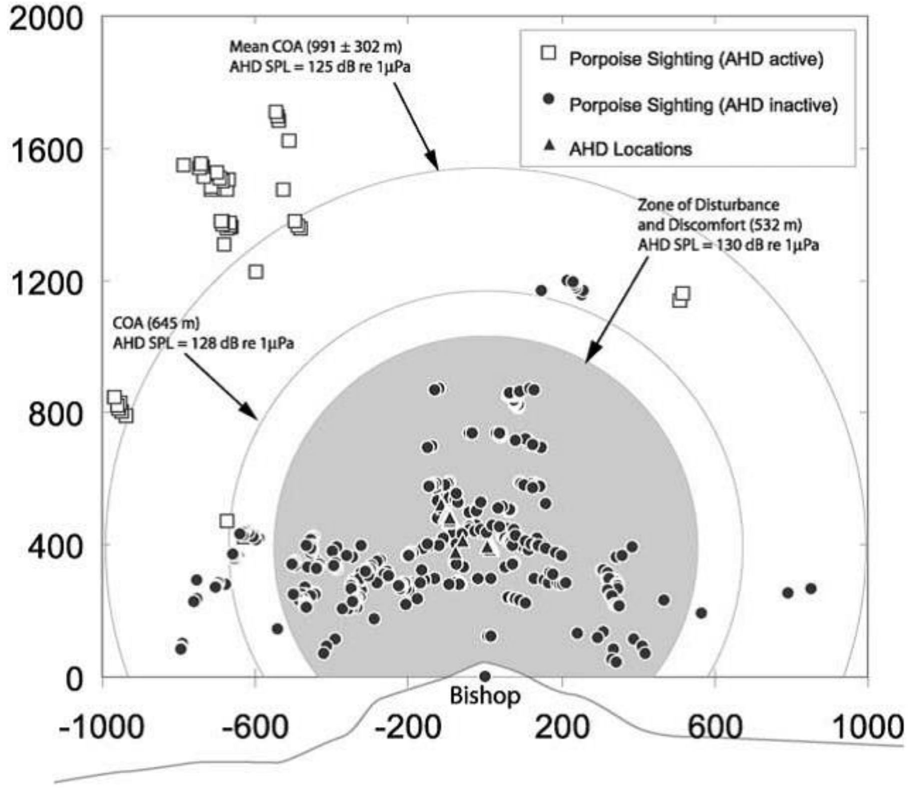


Figure 4 Correlation between the mean number of porpoises per scan and sighting conditions, where 1 = flat calm, 2 = calm-rippled, 3 = rippled, 4 = rippled-light chop, and 5 = light. From Olesiuk et al. (2002).

3.2 Johnston 2002

Four years later than Olesiuk et al. (2002), but reported simultaneously, the effects of a similar AHD (Airmar dB II plus, frequency 10 kHz, source level 194 dB re 1µPa pp) was studied by Johnston (2002) around Grand Manan, Bay of Fundy, Canada. He monitored porpoises for a six-week period by tracking the animals visually and with a theodolite from a cliff 31-34 m above sea level, while exposing them to sound from an AHD. The device was moored at a depth of 4 m from a small boat approx. 450 m from shore, and was active for a 2-hour period transmitting a 2.5 ms pulse every 17 seconds. Results showed that porpoises were deterred from a minimum distance of 645 m (*figure 5*). In comparison, porpoises were observed down to 6 m from the AHD, when the device was inactive. The author did not record sound levels from the AHD. Instead he used a spreading model to estimate received levels, which was developed in a previous study (Johnston & Woodley 1998) following a shallow water model by Marsh & Schulkin (1962). This model used a spherical spreading loss (20 log r) out to a transition range defined as the water depth, and a 15 log r model to approximate transmission loss beyond the transition range. These estimates of sound pressure levels (SPLs) were linked to observations, which suggested that porpoises avoided the zone, when SPLs were above 128 dB re 1µPa pp, which was 645 m from the AHD (*figure 5*). The author estimated this to fit well with the zone of disturbance and discomfort from Taylor et al. (1997); 130 dB re 1µPa, which he translated to being within 532 m of this AHD. However, the support for this comparison is weak and it is questionable whether disturbance and discomfort can even be considered comparable effects.

Figure 5 Porpoise sightings when AHD was either active or inactive. Closest observed approach and zone of disturbance and discomfort are shown together with estimated received levels based on a spreading model (see text for details). From Johnston (2002).



As in Olesiuk et al. (2002), range estimates had considerable uncertainty attached. However, Johnston (2002) had improved precision due to a considerably higher observation platform (31-34 m in comparison to 6.4 m above sea level). Additionally, by using a theodolite to obtain the position of an animal, their range estimates were likely more accurate, despite estimates being based on fewer trials. No uncertainty in range is given for the minimum deterrence distance, but it is expected to be considerably smaller than in Olesiuk et al. (2002) given the increased visual height and the improved methods.

3.3 Northridge et al. 2010

A different approach to studying the effects of an Airmar AHD (frequency 10 kHz, 2 msec pulses repeated every 46 msec) was taken by Northridge et al. (2010), who instead of visual surveys used acoustic recorders to monitor the presence of harbour porpoises in an area with an active AHD. This was done both by 1) continuous recordings of underwater sounds with hydrophones in a vessel survey covering approx. 800 km during 2006-2008 in areas with three active AHDs and by 2) deploying passive acoustic data loggers (T-PODs, Chelonia Limited UK) at ten positions in an area with two active AHDs in 2008-2009. In both cases, click detections were used as a proxy for relative density of porpoises and AHD outputs were recorded with the towed hydrophone system to estimate received sound levels.

3.3.1 Acoustic survey

The acoustic survey used a towed system with two hydrophones (flat frequency response between 2 and 140 kHz) mounted 25 cm apart on a 100 m cable. Results showed that on the site, where an AHD was installed for the first time in 2008, detections were considerably lower than in the two previous years (2006-2007; *figure 6*). No porpoises were detected within 4300 metres from the AHD. At the two other sites, where AHDs had been deployed throughout the study period, porpoises were detected within 1-2 km of the active AHD (*figure 6*). This highlights the importance of considering the motivation of the animals to react to a certain sound. In this case, the AHDs were deployed at fish farms and initially porpoises reacted strongly with displacement behaviour, when a new noise source was introduced. It is conceivable that habituation to the AHD took place, explaining why deterrence distance was smaller for the AHDs that had been active for a longer period.

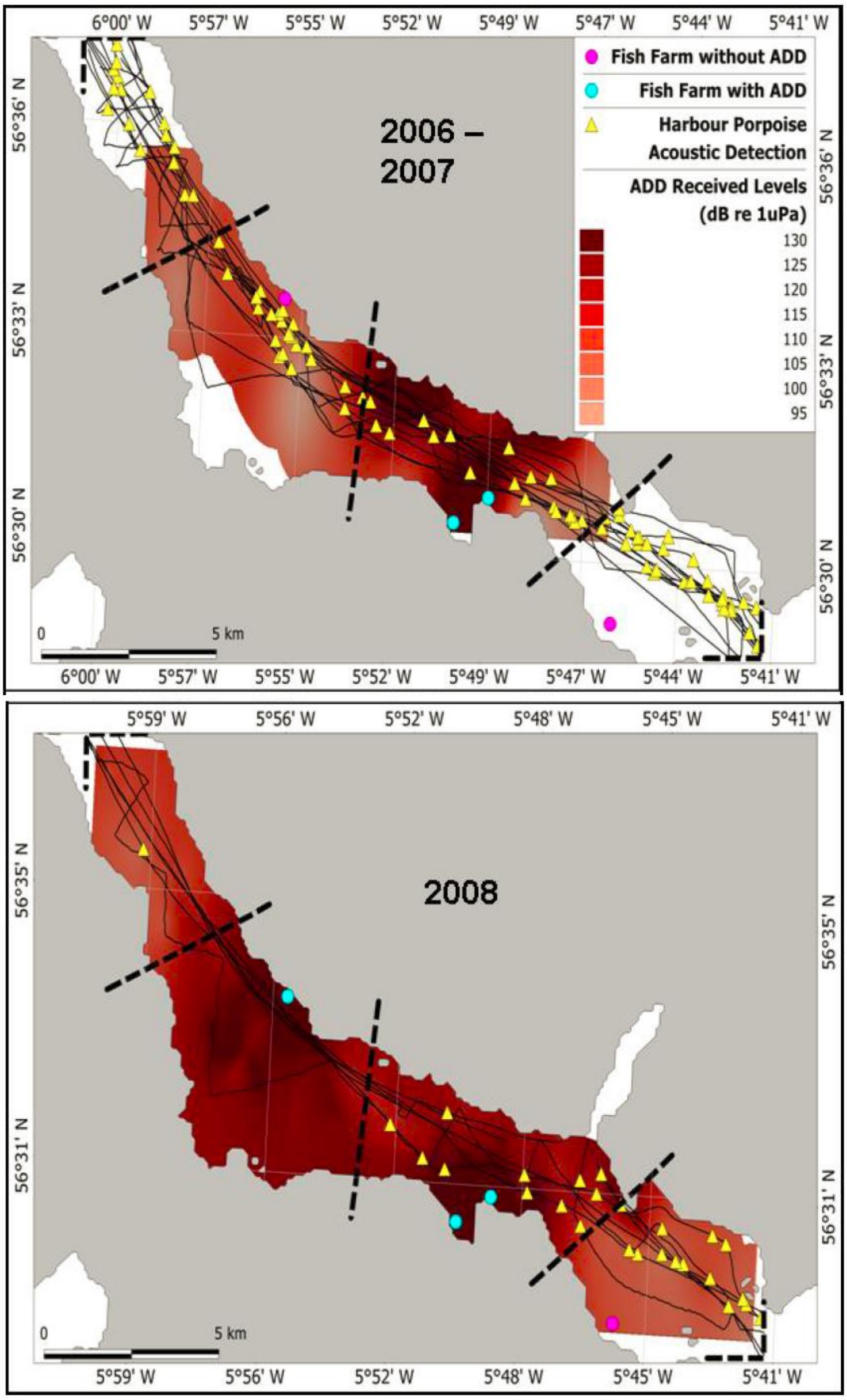


Figure 6 Acoustic detections of porpoises in areas with fish farms with (blue) and without AHDs (pink) before (top) and during (bottom) active AHDs. From Northridge et al. (2010).

3.3.2 Passive acoustic recorders

In the second part of the study, T-PODs (designed to specifically detect porpoise clicks) were set to record continuously in water depths of 20-60 m at ranges 200-8000 m from AHDs at two Scottish salmon farms; for six months at one farm site (Fiunary, Sound of Mull) and six weeks at another salmon farm (Laga Bay, Loch Sunart). The AHDs had slightly different output signals (the device deployed in Laga Bay also emitted a 7.4 kHz pulse) and were active for various time periods following a randomised schedule. At both sites, results showed that porpoise detections were low when the AHD was active, and that they increased after the AHD was switched off. At the Fiunary site, results also showed that porpoise clicks were detected even 200 m from the active AHD (*figure 7*, top panel) and rapid click repetition frequency indicated possible feeding behaviour. The authors did find some false positives, where noise was falsely classified as porpoise clicks, but reported that these did not affect the results. These results highlight that there may be a trade-off between avoiding the AHD and staying in a favourable habitat. The authors suggested that the high porpoise density in proximity to a fish farm may be linked to good feeding opportunities caused by presence of wild fish, as well as by elevated water temperatures close to shore. A larger depth at this site of approx. 60 m may also have played a role. It is not simple to translate changes in click detection rates to changes in animal abundance and therefore it cannot be excluded that the high porpoise density close to the fish farm was one or a few individuals (e.g. an old animal with reduced hearing) not representative of the population. Furthermore, the detection of porpoise clicks 200 m from the AHD cannot be interpreted directly as one or more animals present at this range, as acoustic recorders can detect porpoise clicks emitted from animals at larger distances. For T-PODs the detection range is at least a few hundred metres (Kyhn et al. 2012), which means that the animals recorded on the T-POD at 200 m could have been at any range between 0 m and 3-600 m from the AHD.

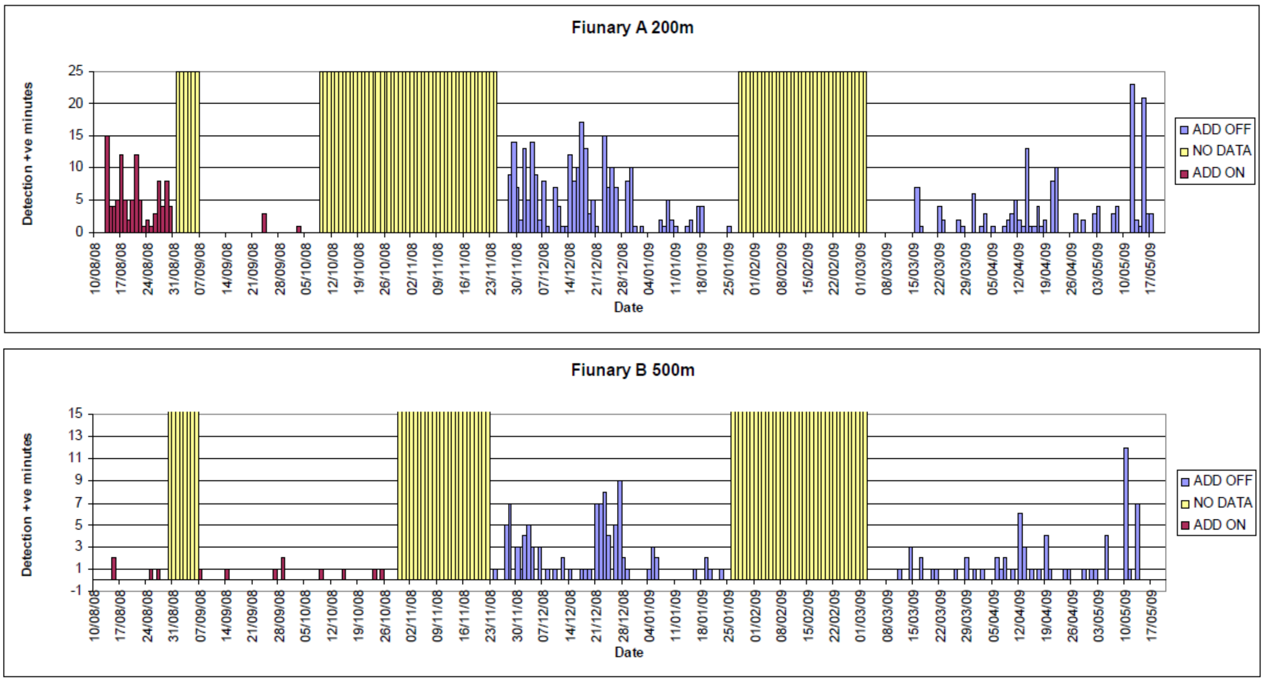


Figure 7 Click detections at 200 m (top) and 500 m (bottom) from the Fiunary site, where an AHD was deployed. Periods when the AHD was active are shown in red and periods when it was off, are shown in blue. From Northridge et al. (2010).

Nevertheless, recordings 500 m from the AHD showed a pronounced lower detection rate when the AHD was active, indicating that the area affected by the AHD extended out at least some hundred metres beyond the 500 m T-POD.

3.4 Brandt et al. 2012

To better investigate the effectiveness of AHDs to deter animals from a construction area, two dedicated studies were initiated by Brandt et al. in 2009. One study (Brandt et al. 2012) took place in the German North Sea, where 16 acoustic dataloggers (C-POD, Chelonia Limited UK) designed to detect porpoise signals were deployed at various distances from an AHD. CPOD data were continuously collected for five months in 2009 during which ten exposure trials with a Lofitech AHD (frequency 13.5-15 kHz, source level 189 dB re 1µPa, www.lofitech.no) were conducted. Acoustic data on porpoise presence were supplemented on one trial day by two aerial surveys: one before and one when the AHD was active. On days with an exposure trial, the AHD was deployed at a depth of 7-10 m from a boat and was active for a four-hour period, transmitting 0.5 s long pulses with random repetition rate between 1 and 90 seconds. There was a break between trials of at least four days. To check the output levels of the AHD, a setup with a Brüel and Kjær 8103 hydrophone was deployed to conduct recordings at ranges of 100-2000 m. To minimize the effects of the deployment boat, data from one hour before and one hour after start of a trial were excluded from the analysis.

The study found that porpoise activity decreased out to 7.5 km from the seal scarer when active (*figure 8*). Aerial surveys confirmed that the decreased activity was reflecting that porpoises were deterred from the area rather than changing their vocal behaviour, making them less detectable by the C-PODs. As reactions were shown out to the station furthest away from the AHD (7.5 km), porpoises were probably affected beyond this range, and it was not possible to determine the true reaction threshold based on these data. By fitting a curve to actual recordings of the AHD and an assumed absorption loss of 1 dB/km, received levels at 7.5 km range from the AHD could be estimated to 113 dB re 1 µPa (*figure 9*). It is not clear whether these values are rms (root mean squared) or peak-peak measures of the sound levels.

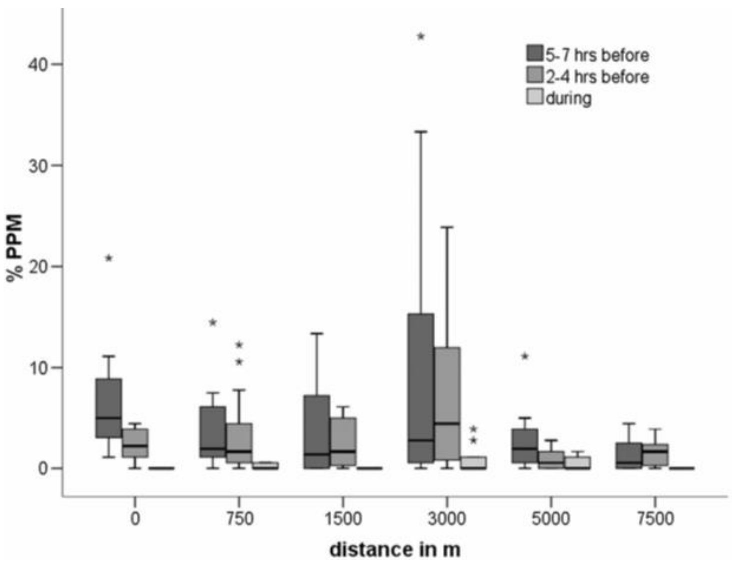
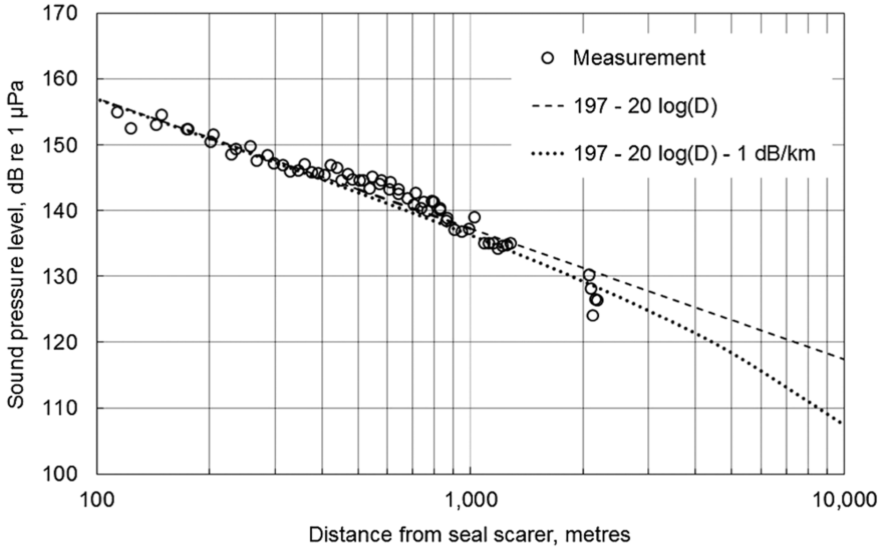


Figure 8 Porpoise activity estimated as porpoise positive minutes (PPM) for six different ranges to the AHD, in two periods before and one period during AHD activity. From Brandt et al. (2012).

Figure 9 Estimated transmission loss (TL) based on measured levels in Brandt et al. (2012). TL is shown with and without absorption assumed to be 1 dB/km for a 10 kHz signal.



At the C-PODs 750 m from the AHD, porpoise activity decreased significantly with 92 %, whereas at the C-POD station at distance zero, no porpoises were detected (*figure 8*). These data can provide information about the extent of the absolute deterrence distance. As the C-POD has a maximum detection range of some few hundred metres (400 m stated by the manufacturer), the likelihood that any porpoises were within this range when the AHD was on is very low. A few porpoise clicks were detected at a distance of 750 m implying that the animal/animals could have been anywhere between 350 m and 1150 m from the AHD. As a precautionary approach, these results indicate that all porpoises were deterred from an area of 350 m around the AHD, where the received level is estimated to 146 dB re 1µPa (*figure 9*; TL with absorption). No clicks were detected at 1500 m indicating that most animals were deterred from an area of approximately 1900 m (1500 + 400 m) around the AHD.

3.5 Brandt et al. 2013

At the same time another study was conducted by the same authors and published the following year (Brandt et al. 2013) to further investigate the zone of reaction for porpoises exposed to AHD sounds. Here porpoises were monitored with visual surveys and theodolite from a high point (20 m above sea level) at Fyns Hoved, Denmark, following the methods used in Johnston (2002). The estimated limit for accurate tracking of porpoise was 800 m and only possible in sea state 0 and 1. An AHD (Lofitech, frequency 13.5-15 kHz) was deployed from a boat from where it was operated to randomly transmit either real pulses (0.55 s pulses with random pauses) or no pulses over 30 minutes. In the first part of the study the boat was positioned a few hundred metres from shore, but in an attempt to overcome the limited tracking range from the cliff, the boat was later positioned at 1-4 km from the observation point, so that reactions of porpoises within the tracking range, which was now some kilometres from the active AHD, could be assessed. In total, seven days with exposures and nine days without were conducted.

Results showed for the first part of the study that within 1 km of the AHD, seven out of eight animals reacted to the AHD; six animals disappeared and one animal was clearly moving out of the area, when the AHD was switched on (*figure 10*). In contrast, the last animal stayed in the area when the AHD was active and was sighted eight times during a period of 11 minutes when the AHD was on, with a closest approach of 798 m (*figure 10*, track H). The many surfacings in the same area were characterized as milling behaviour and indicated that this animal was feeding. Based on a generalized linear model (GLM), the overall conclusion was, however, that there was a lower sighting rate of porpoises, when the AHD was on for all distances (0-1000 m) (*table 1*: 'Seal scarer'). Sea state and time of day ('Hour') were also found to have significant effects on porpoise sightings.

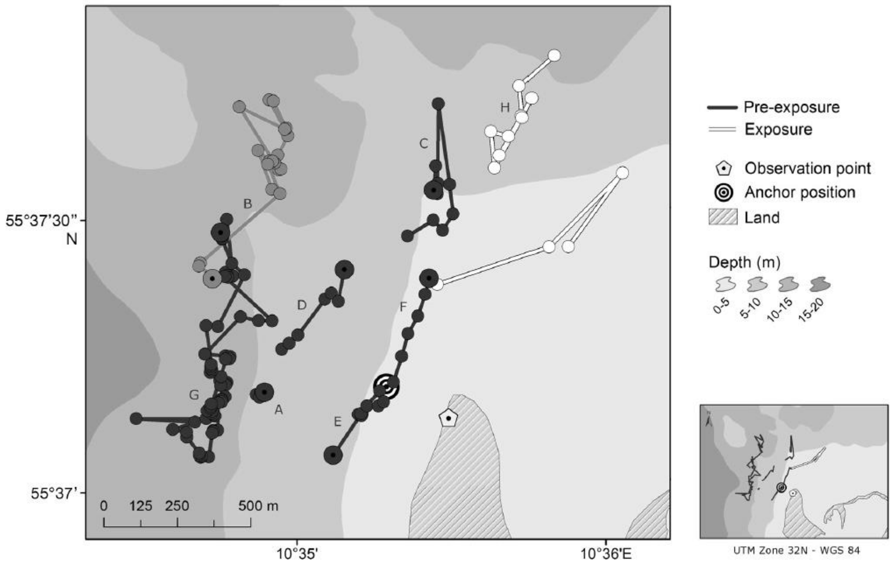


Figure 10 Theodolite tracks of eight porpoises within 1 km from an active AHD (at anchor position). Observations prior to and during exposure (if any) are marked. From Brandt et al. (2013).

Table 1 Results of generalized linear model. From Brandt et al. (2013).

Parameter	*b*	SS	*F*	df	p
Hour	0.44	21.62	12.99	1	<0.001
$Hour^2$	-0.02	19.87	11.95	1	<0.001
Sea state	-0.45	26.17	15.73	1	<0.001
Seal scarer	-4.72	342.22	205.71	1	<0.001
Residuals		1069.69		643	

For the other part of the study, where the AHD was placed 1-4 km from the observation point, tracks from 13 porpoises during exposure to the AHD were obtained. Four of these animals were tracked within 1.9 km and movements of all of them indicated that they reacted to the AHD signal, as they either avoided the area or disappeared from sight, when the AHD was switched on. Beyond 2.6 km none of the five tracked animals exhibited an obvious reaction to the sound. Between 1.9 and 2.6 km, four animals were tracked: two of them (2.3-2.4 km range) were concluded to react with avoidance behaviour, one (mom-calf pair; 2.2 km range) may have had a delayed avoidance reaction and one (mom-calf pair; 2.0 km range) was judged not to show any obvious reaction, as it was not possible to determine whether the avoidance behaviour was caused by the AHD exposure or the approach of a small motorboat. Tracks for two of these animals are shown in *figure 11*. Porpoise A was at an initial range of around 1890 m from the AHD (anchor position A) and was clearly reacting to the sounds by immediately swimming in the opposite direction, when the device was activated. It is also seen that the distance between surfacings increased. This is likely because the animal was swimming faster (no time information is given in *figure 11*), but could also be because it was more difficult for the theodolite-tracker to follow the animal causing some missed surfacings. Even when the AHD was inactivated, the animal kept moving away in the same direction. Porpoise B was at an initial range of 2050 m from the AHD (anchor position B; *figure 11*) and was not showing any obvious reaction to the sound and stayed in the area throughout the exposure.

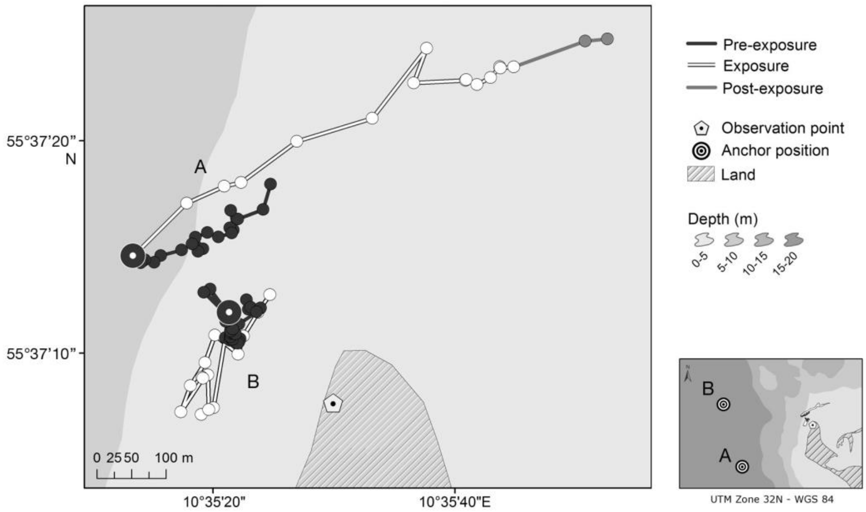


Figure 11 Theodolite tracks of two porpoises (A and B) before, during and after exposure to AHD signals. AHD anchor positions (also A and B) are shown in the small plot at the lower right. From Brandt et al. (2013).

Based on the four tracks obtained at 2.0 to 2.4 km from the active AHD, the authors concluded that half of the time an animal within this range would react to the AHD signals. However, as the sample size was small and there was a high uncertainty whether the two mom-calf pairs did in fact react to the AHD sound, this conclusion is not very convincing. Of the four closest animals within 1.9 km from the AHD, two of them clearly avoided the sound and showed up again at longer ranges (2.3-2.5 km from the AHD), while the other two animals disappeared and were not seen again.

Although the experiment was conducted with blind trials (i.e. observer did not know if the AHD was active or not and therefore did not have any expectations of where to observe the animals), it cannot be ruled out that the two animals that disappeared did in fact stay within the same range or even moved closer to the source. This is in particular true for the exposures, where the AHD was placed at 1-4 km from the observation point, as the tracking range was limited to approx. 800 m from the cliff and the observers would therefore likely have missed animals that were at ranges beyond 800 m, but closer to the active device.

To obtain an estimate of the reaction threshold of porpoises based on all exposures, the results of the 14 exposures to porpoises at different distances from the AHD have been reanalysed in *figure 12*. This was done by performing a simple logistic regression providing a best fit. From *figure 12*, the mean reaction distance has been estimated to 2.3 km and 95 % of the porpoises were estimated to be deterred out to a distance of 1.3 km. Due to the low sample size, there is, however, considerable uncertainty about these numbers.

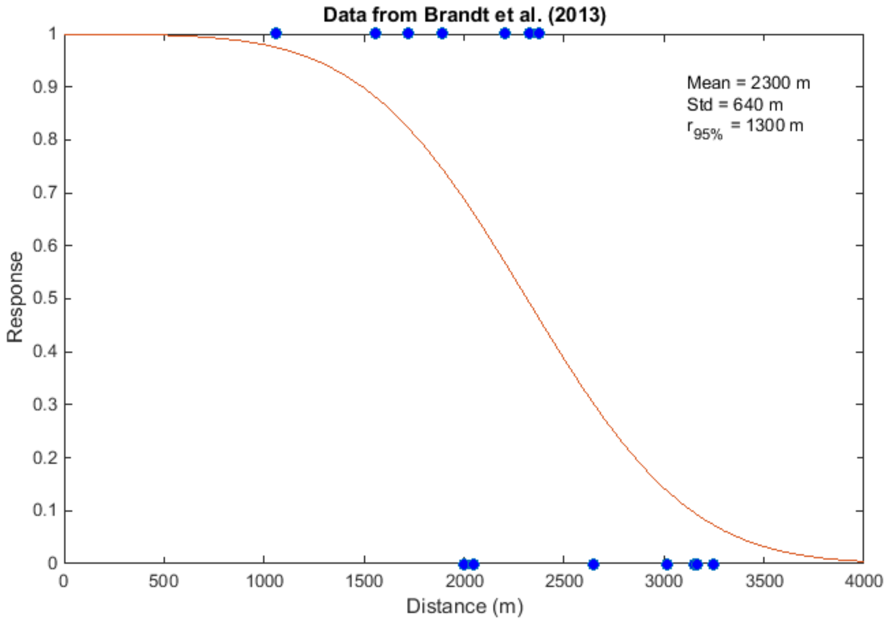


Figure12 Data points (blue dots) from Brandt et al. (2013) replotted as a function of distance, where 1 indicates a response to the AHD and 0 indicates no response. Red curve shows best fitting logistics regression based on a cumulated Gaussian distribution. Values in top right corner based on regression line estimate that 95 % of porpoises will react to AHD at a range of 1300 m and that the mean reaction distance is 2300 m. Std is a measure of the steepness of the curve.

For all exposures in this study, the first porpoise observation in the area following exposure was within 34-67 minutes after exposure indicating that the effect was short-term. However, it was not obvious in which range animals were re-sighted and sightings of a single or a few porpoises do not allow for conclusions on how long time it took to re-establish conditions to normal.

3.6 Kastelein et al. 2015

Kastelein et al. (2015) conducted a controlled study of how captive porpoises reacted to AHD sounds. They tested the ability of a porpoise to hear sounds from two types of AHDs (Lofitech 193 dB re 1µPa rms and Ace Aquamark 186 dB re 1µPa rms). The behaviour of the free-swimming animal during exposure to AHD sounds was monitored with cameras both underwater and above the pen. The behavioural part of the study showed that when the animal was exposed to sounds above levels of 117 dB re 1µPa rms for the Ace Aquatec and 121 dB re 1µPa rms for the Lofitech, it increased the distance to the transducers (*figure 13*) and changed to more erratic behaviour with increased swimming speed with more surfacings and jumps.

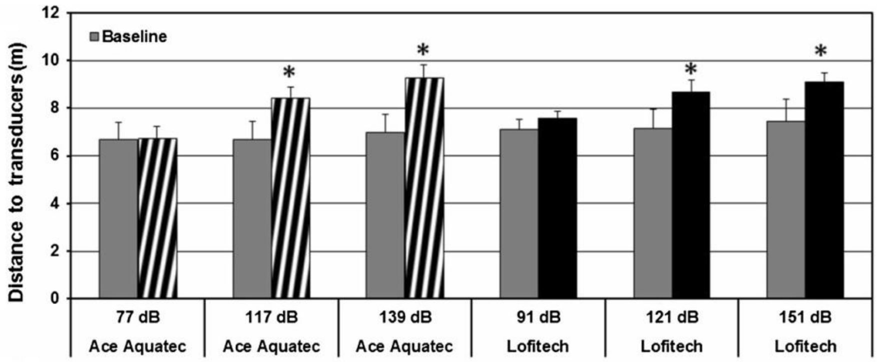


Figure 13 The distance of a captive porpoise to two types of transducers (Ace Aquatec and Lofitech) at different output levels. Baseline data are shown with grey bars. Significant changes in behaviour are marked with an asterisk. From Kastelein et al. (2015).

If assuming a conservative transmission loss model of 20 log r and an absorption of 1 dB/km as in equation 1, a received level of 121 dB re 1µPa from a Lofitech AHD would be experienced by an animal at a range of approx. 2 km from the AHD, whereas a received level of 117 dB re 1µPa from the Ace Aquatec would be experienced at a range of approx. 4 km. This large difference in reaction range between the two devices is caused by their different characteristics: the Ace Aquatec has a higher source level and emits sound at a broader and higher frequency range up to 40 kHz, where porpoises have a lower hearing threshold and therefore likely react to lower received levels of sound. At exposure levels of 139 ± 2 dB re 1µPa (Ace aquatec) and 151 ± 6 dB re 1µPa (Lofitech), the animal exhibited strong avoidance behaviour. These levels correspond to range estimates of 380-590 m and 40-150 m from the two devices, respectively. However, caution is required, when extrapolating from studies on captive animals to reaction distances of wild animals. In the case of reactions to AHDs, the studies of wild porpoises have shown that animals react by displacement out to several kilometres from the deterrent device as discussed previously. In this study, the reactions of a captive animal were restricted to a concrete pool and the animal was therefore limited in its ability to displace itself from the sound source and generally express its full repertoire of behaviours. Instead the reaction may manifest itself by changed diving patterns and swimming speeds, as seen in this study. Also, there is probably an effect of motivation. The captive porpoise being trained to associate the task of listening for the AHD with a food reward, whereas wild animals may not have an incentive to listen for the AHD. Caution is therefore required when transferring conclusions from these findings to estimates of how wild porpoises will react to the AHDs.

4 Discussion

Determining the minimum deterrence distance for AHDs is of prime importance, when assessing suitability of AHDs for deterring porpoises from construction sites before pile driving or similar loud events commence. This minimum deterrence distance is the minimum zone around an AHD where animals can be expected to vacate. This deterrence effect can either be absolute, i.e. include all porpoises in the area or it can be probabilistic, allowing for the least sensitive animals, such as for example individuals with decreased hearing, to remain inside the deterrence area. In some contexts, the maximum reaction distance, which is the furthest distance from an active AHD where porpoises react, may also be useful. For all three ranges it is relevant to estimate how they correspond to received sound pressure levels in order to allow comparison of AHDs with different source levels and frequency characteristics. In the following, the main findings of the relevant studies will be evaluated and summarized in *table 2*.

4.1 Minimum deterrence distance

In the two Canadian studies with visual observations (Olesiuk et al. 2002 and Johnston 2002), the minimum deterrence distance of porpoises around an Airmar AHD (source level 194 dB re 1µPa pp) was estimated to be 200-645 m, if taking ranging errors into account. This corresponds to porpoises avoiding areas where exposure levels exceed 148 dB re 1µPa pp. The passive acoustic monitoring study by Northridge et al. (2010) detected porpoise clicks at one site 200 m from the AHD, reflecting presence of porpoises within an area extending several hundred metres from the AHD. As few porpoise clicks were detected at a station 500 m from the AHD, the minimum deterrence distance for most porpoises was at least some hundred metres more than 500 m. From the observational study by Brandt et al. (2012), it can be estimated that the minimum deterrence distance of porpoises around a Lofitech AHD is 350 m corresponding to 146 dB re 1µPa, whereas findings from the acoustic study by the same group (Brandt et al. 2013) indicated that porpoises avoided an area of around 800 m (798 m) around the AHD. The effects of the same type of AHD on porpoises were also tested by Kastelein et al. (2015) on a captive porpoise and a strong avoidance response was found to exposure levels of 151 ± 6 dB re 1µPa rms, whereas the porpoise reacted strongly to another AHD (Ace aquatec) at considerably lower levels of 139 ± 2 dB re 1µPa rms. This is likely an overestimate of the response threshold, and it is very likely that the animal would have reacted differently had it not been motivated to participate in the experiment, but instead in an unconfined environment with a possibility to displace from the noise source at lower levels. Also, this experiment was conducted on a single animal and it is not known whether the reactions of this individual are representative for harbour porpoises in general. Behavioural reactions can differ widely between individuals and highly depend on both individual characteristics, such as sex, behaviour and previous exposure, and on environmental properties, which affect the transmission loss of the sound and thereby also the sound level that an animal experiences at different ranges from the sound source. The variability in evaluated reactions is evident from the studies of wild porpoises, where in some cases one or a few animals were staying closer to the active AHD than most other animals. Even though these individuals may not be representative for general behavioural reactions of porpoises to AHD sounds and can be seen as outliers in the overall data set, they can be the essential data point to include, if the aim is to ensure that all animals are deterred from an area before construction begins.

Following a precautionary approach, we conclude that the minimum deterrence distance of porpoises within which all harbour porpoises can be expected to be deterred, is about 200 m for the Airmar AHD, primarily based on the study by Olesiuk et al. (2002). On the basis of the studies by Brandt et al. (2012 and 2013), we conclude that the Lofitech AHD effectively deters porpoises away from an area extending at least 350 m from the AHD. However, if the mitigation protocol allows for less than 100 % deterrence, the minimum deterrence distance of a Lofitech AHD is somewhere in the range between 1300 m and 1900 m.

Table 2. Summary of the minimum deterrence distance and minimum reaction distance of harbor porpoises to AHD sounds. Note that these studies have used different AHDs with different main frequency and source levels, which accounts for part of the differences in their findings.

Study	Method	Type of AHD; frequency; source level	Deterrence distance for most animals	Absolute deterrence distance	Maximum reaction distance
Olesiuk et al. 2002	Visual observations	Airmar; 10 kHz; 194 dB re 1µPa pp	Not estimated	200 m 148 dB re 1µPa pp	3500 m (> 90 %); 106 dB re 1 µPa pp**
Johnston 2002	Visual surveys and theodolite tracking	Airmar dB II plus; 10 kHz; 181 dB re 1µPa	Not estimated	640 m (all), 128 dB re. 1µPa pp	Not estimated
Northridge et al. 2010	T-PODs and hydrophone array	Airmar; 10 kHz;	~ 900 m	0 m (worst case assumptions)	4000 m
Brandt et al. 2012	C-PODs and aerial surveys	Lofitech; 13.5-15 kHz; 189 dB re 1µPa pp	1900 m	350 m 146 dB re 1µPa	7500 m 113 dB re 1µPa
Brandt et al. 2013	Visual surveys and theodolite tracking	Lofitech; 13.5-15 kHz; 189 dB re 1µPa pp	1300 m*	< 768 m	2400 m; 129 dB re 1µPa pp**
Kastelein et al. 2015	Visual study on captive porpoise	Ace aquatec (10-40 kHz; 193 dB re 1µPa rms) Lofitech (13.5-15 kHz; 189 dB re 1µPa pp)	2 km (Lofitech); 121 dB re 1µPa 4 km (Ace Aquatec); 117 dB re 1µPa***	Strong avoidance response: 380-590 m**** (Ace Aquatec) 40-150 m**** (Lofitech)	Not estimated

*Based on the logistic regression in *figure 9*.

**Based on a Leq-fast (rms over 125 ms duration) estimate of the Lofitech AHD of 97 dB in Tougaard et al. (2015).

*** Extrapolated from sound levels causing evasive reactions.

****Extrapolated based on assumption of a spherical transmission loss and an absorption of 1 dB/km.

4.2 Maximum reaction distance

From the studies on wild porpoises discussed above, it is clear that some porpoises react to the AHD sounds at distances in the 2400-7500 m range. The large variability is partly caused by the difference in the characteristics of deployed AHDs (source levels and frequency) and environmental conditions, but partly also because of the different observation methods used, often with restricted maximum observation distances. Based on a precautionary approach, we thus conclude that maximum reaction distances is at least 7.5 km for a Lofitech AHD (Brandt et al. 2012).

4.3 Habituation or sensitization

When AHDs are used in mitigation, it is crucial that the deterrence effect remains stable over time. In particular, as indicated by the study of Northridge et al. (2010), porpoises may react strongly to a newly introduced sound, but when they experience with time that there is no danger associated with the sound, they become habituated to it and move back into the area. None of the other studies described above found habituation effects, but this could be due to the observation period being too short or the number of exposures too low and/or dispersed over a too long period.

However, similar for all evaluated studies and different from a real pile-driving setting, is that none of the AHD exposures were followed by loud pile-driving noise. This must be taken into account, because such a subsequent loud noise may interfere with the reaction towards the AHD sound, given that the porpoise has been previously exposed to the AHD sound under similar circumstances. Most notably is the effect of sensitization, which is the opposite of habituation. In sensitization, the response of an animal may increase with repeated exposures to a sound, if this sound is associated with uncomfortable events. This effect has been demonstrated very clearly in a harbour seal in captivity (Götz & Janik 2011), where the response of the seal to a warning sound increased dramatically over just three exposures if the sound was followed by a second sound loud enough to induce acoustic startle in the seal. In the context of using AHDs prior to pile driving, it is therefore possible (and to some degree desirable) that porpoises, in the same way as the seal in the study by Götz & Janik (2011), become sensitized over multiple exposures, where they have learned to associate the AHD sounds with unpleasant pile-driving noise. As a consequence of this learning the deterring effect of the AHD is maintained or even possibly increased.

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