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The Use of Acoustic Devices to Warn Marine Mammals of Tidal-Stream Energy Devices

marine scotland

THE USE OF ACOUSTIC DEVICES TO WARN MARINE MAMMALS OF TIDAL-STREAM ENERGY DEVICES

Report prepared for Marine Scotland, Scottish Government

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Non-technical summary

The incidence of marine mammals colliding with man-made objects (such as ships or fishing gear) is well-known and has received much attention in recent years. It is also conceivable that marine mammals will collide with marine renewable energy devices, with tidal-stream energy devices presenting the most obvious strike scenario. However, it is currently unknown whether injurious mammal-turbine collisions will actually occur with sufficient regularity to be of ecological concern. This is primarily because of the embryonic status of the industry, the limited range of installation sites, the diversity of species so far exposed and the spatial responses of mammals to devices.

For animals to exhibit appropriate spatial responses they will have to be able to accurately perceive the location of the turbines they approach. For marine mammals, vision and mechanoreception are unlikely to be useful senses for anything other than close-range evasion. Longer range upstream avoidance is more likely to come from their auditory senses particularly by picking up turbine noise. The distance that this sound will be audible will be influenced by several factors but particularly the local ambient noise conditions (which are likely to be greater in these sites than other coastal waters). If there is insufficient or inappropriate turbine noise then one solution would be to add further acoustic cues to turbines.

This report therefore explores the underwater acoustic characteristics of several inshore tidal-stream sites to determine whether or not there is actually a need for acoustic warning devices. It then goes on to investigate whether existing mammal warning acoustic devices developed for other applications might prove valuable in a tidal-stream context and if so what risks there may be of using such devices. This report finally goes on to consider what characteristics a purpose-built acoustic warning device might need.

To investigate the characteristics of tidal-stream sites we selected three straits on the west coast of Scotland of which two are of immediate interest to tidal-energy developers (Sound of Islay and Kyle Rhea). We measured and mapped the natural ambient soundscapes of each site over a variety of flow conditions (ebb, flood, springs, neaps). We found that ambient noise scaled with flow speed and showed considerable spatial variability across each site. Overall, the levels of ambient sound were higher than less energetic coastal sites.

Existing acoustic warning equipment developed to dissuade seals from approaching fish farms, warn marine mammals of fishing gear, steer fish away from power stations and other applications were reviewed both in terms of their efficacy and potential audibility for marine mammals in tidal-stream sites. This examination showed that the deployment of off-the-shelf acoustic devices developed for other applications, would be inappropriate in a tidal energy context. If the range of warning is too small, as appears to be the case for equipment known as Acoustic Deterrent Devices (ADDs), then animals are not be given sufficient time or space to avoid a turbine encounter. In contrast much louder equipment such as Acoustic Harassment Devices (AHDs) are likely to be detectable at ranges far greater than the sphere of influence of an individual turbine or even an entire array. Accordingly, there is the risk of significant habitat exclusion. Furthermore, habituation is a concern for any equipment, especially if a single source is used to mark an array of turbines.

Given the discrete point source of threat (i.e. individual turbines and the rotors in particular) coupled with the investment and infrastructure associated with tidal-stream developments, then more sophisticated acoustic warning devices would not be out of place to help mitigate a collision issue, should one prove to exist. If a warning system were to be built then this report describes seven attributes that should be considered. These were that: (1) the signal must elicit an appropriate response (2) emission rates must suit approach velocities (3) emission frequencies must be audible for target species (4) amplitudes must be appropriate for detection ranges and sites (5) signals must be directionally resolvable (6) the warning should be co-ordinated with the threat and (7) the location of the sound sources at a turbine or within an array must facilitate appropriate spatial responses.

Finally, this report emphasises that in the face of a potentially attractive mitigation option, any active acoustic warning also represents a new source of sound pollution, specifically intended to alter the behaviour of marine mammals in tidal-stream habitats. While it is unknown whether there is actually a real (rather than perceived) mammal-turbine collision problem, we should consider carefully whether or not it is appropriate to deliberately add extra-noise to the sea as a precautionary measure. Nevertheless, while further information on the collision issue is likely to emerge as turbines are deployed over the next few years, the acoustic warning option should continue to be explored and not shelved pending that outcome. The use of acoustic warning equipment, if appropriately designed, could prove a valuable mitigation tool should a collision problem become apparent.

Introduction - Is there a collision issue?

The incidence of marine mammals colliding with man-made objects is well-known and has received considerable attention in recent years. Collisions with fishing gear and entanglement is a now well quantified global problem (Read et al. 2006) and has elicited substantial research and mitigation efforts (Kraus et al. 1997). Similarly, impacts between marine mammals and vessels ranging from small boats to ships is sufficiently wide-scale and frequent to merit attention from global bodies such as the International Whaling Commission (IWC) and the International Maritime Organisation (IMO 2008). Investigations of these and other physical interactions have shown that in addition to the most obvious scenarios (animals swimming into nets or being struck by moving propellers) other less obvious contacts also occur. These include examples such as whales ensnaring themselves in marker buoy lines (rather than actual fish-capture equipment) and fatal collisions with the bows of ships rather than their propellers (Laist et al. 2001).

It is therefore a possibility that marine mammals might collide with marine renewable energy devices, with tidal-stream energy devices presenting the most obvious scenario (with potential parallels to birds and bats being struck by wind turbines, Barclay et al. 2007). The rotational motion of turbine blades (vertical and horizontal) coupled with the relatively rapid passage of water past devices, presents a conceivable collision scenario for species manoeuvring in the same water masses (Wilson et al. 2007). This possibility has been raised as an area requiring attention by a variety of fora when considering the potential environmental impacts of marine renewable energy devices (Linley et al. 2009).

At this time, it is unknown whether injurious mammal-turbine collisions will actually occur with sufficient regularity to be a significant concern. This is primarily because of the embryonic status of the industry with a limited number of full-scale deployments, the limited range of installation sites, the diversity of species so far exposed and their own spatial responses to the devices. However, with the imminent deployment of multiple full scale devices in several parts of the British Isles (The Crown Estate 2010) the issue of collision and its frequency or absence is likely to become clearer in coming years.

To consider the issue of collision in advance of the construction of commercial scale arrays, some basic interaction modelling has been carried out (Wilson et al., 2007). This suggested the spatial co-incidence is sufficient in that if marine mammals do not take appropriate swimming manoeuvres then physical interactions may be common enough to be of concern. However, with marine mammals being both mobile and agile, it is likely that some degree of avoidance (long-range) or evasion (close-range) will occur. This is only possible however if animals are able to accurately perceive the location of the turbines as they approach. For marine mammals coming from upstream (i.e. on a relatively rapid closing course), two of their primary senses: vision and mechanoreception (Dehnhardt 2002) are likely to be useful only at short ranges (tens of meters or less) such that they would only be relevant for close-range evasion. It is therefore more likely that they will gain their information on the presence, motion and three dimensional underwater extent of turbines from their auditory senses (Carter 2007; 2013). For odontocete cetaceans (i.e. toothed whales, dolphins and porpoises), echolocation (if used at the time) is likely to provide information out to greater than 100 m (Goodson et al. 1988; Au 1993) though it is unclear how/if echolocating animals might perceive and respond to long but thin and sweeping structures such as rotor blades using this directed and intermittent sense. It is otherwise likely that information on the presence of submerged energy devices will come from the machinery's own acoustic emissions (rotors, gearing, flow noise etc.). As mysticete cetaceans (baleen whales) and pinnipeds (seals) do not use active sonar (Dehnhardt 2002) their long-range awareness of turbines is likely to come entirely from auditory detection of device noise alone.

Modelling work carried out to calculate how far coastal marine mammals are likely to be able to detect tidal turbines (Carter 2007), showed that detection distances (and times) were highly variable depending upon the interplay of four variables in particular. These were:

1) the frequency specific acoustic output of devices,
2) the ambient noise at the site,
3) the site-specific propagation characteristics and,
4) the acoustic sensitivity of the species of concern (see Figure 1).

Other variables such as signal to noise detection thresholds were also important but less critical.

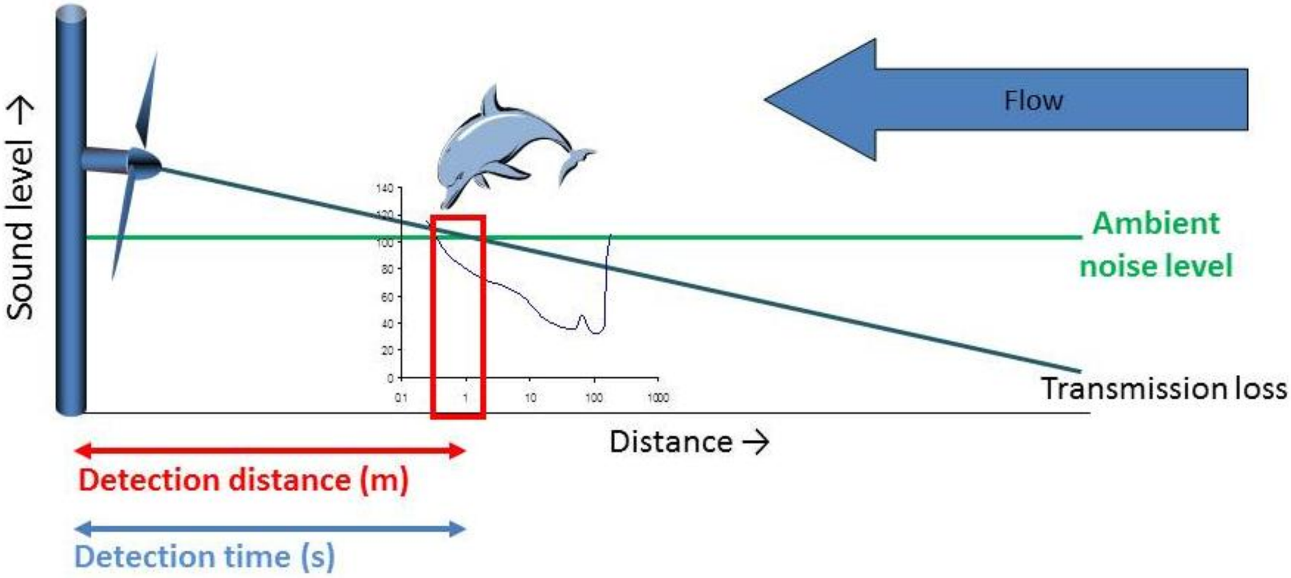


Figure 1. Schematic of the key parameters required for acoustic detection of a tidal-turbine. Sound emanating from a turbine (left) propagates away from the device while experiencing transmission loss (black line slope) and at some point drops below the site's ambient noise floor (green line). An approaching marine mammal (with its own frequency specific audiogram, thin wavy line), will only be able to acoustically detect the turbine when the turbine noise exceeds a threshold relative to ambient noise. This provides a minimum detection distance and based on the swimming speed and water flow rate provides an indication of the amount of time that the animal has to respond. This scenario assumes that the ambient noise floor exceeds the minimum hearing thresholds of the species of interest which is reasonable in tidally-energetic sites.

Of the four main variables, device noise is currently known only for a few (primarily prototype) devices, but is likely to become more readily available in the immediate future as commercial-scale turbines are deployed, particularly at test sites. Though there is little direct information on propagation in tidal-stream sites, there are sufficient published data to make useful estimates. Animal audiograms are also available for only some species but provide reasonable information on what odontocetes and seals in Scottish waters should be able to perceive. Information on baleen whales hearing is very limited (Richardson et al. 1995) and therefore they are not considered further here. The final variable, ambient noise, is relatively well known for the open sea (Richardson et al. 1995) but there is little tidal-site relevant information available. However, it can expected that both the lateral and vertical water motion and sediment transport will produce levels of ambient sound greater (or considerably greater) than in the more commonly studied environments.

Using available information (and appropriate assumption envelopes) on the acoustics of tidal sites, propagation, devices and animal audiograms coupled with known swimming speeds, Carter (2007), in a modelling study, calculated a series of distance-to-turbine detection scenarios. Because of the uncertainties associated with the input data, there was considerable variation in the outcomes but for many likely scenarios, the detection distances were short (500 m or less) and these became even shorter (100 to 10 m or less) when ambient noise levels were elevated by factors such as surface waves equivalent to Beaufort sea state 6 or greater.

Though this work was preliminary, it illuminates the possibility that while acoustic detection will be a primary cue for approaching marine mammals, under many of the likely circumstances, detections ranges will be too short for animals to effectively avoid close-range encounters with tidal turbines. One obvious solution to this detection issue would be to add further acoustic cues to turbines for them to be more detectable to marine mammals in their vicinity (Figure 2). This report therefore better explores:

1) whether or not there is actually a need for acoustic warning devices,
2) whether acoustic warning devices developed for other applications (e.g., seal scarers or bycatch reducing pingers) might prove valuable in a tidal-stream context,
3) what risks there may be of using such devices and
4) what characteristics purpose-built versions would need.

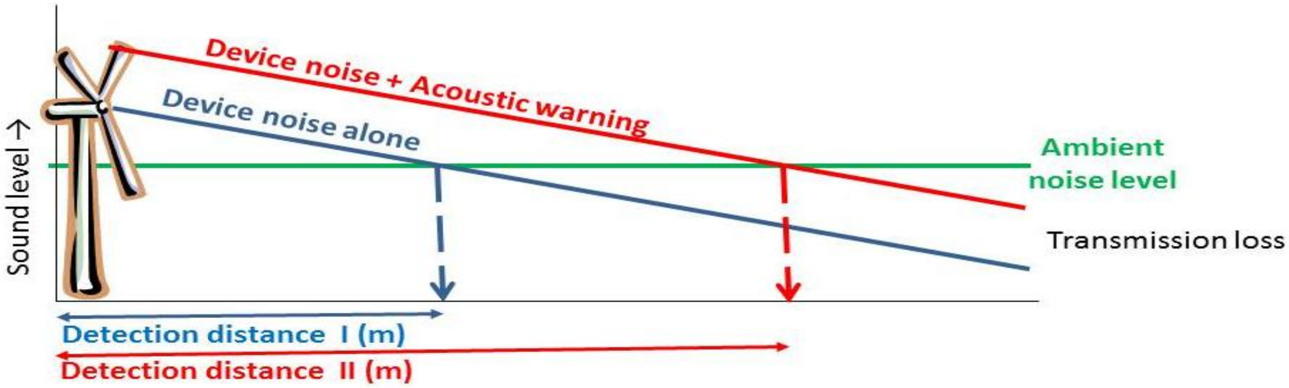


Figure 2. A development on Figure 1, where additional acoustic cue(s) are added to a turbine to increase the distance (and time) over which approaching acoustically sensitive animals can detect and potentially respond to the renewable energy device.

Is there a problem to fix?

Though most full-scale turbines have not yet been constructed it is likely that they will generate sufficient noise to be audible to marine mammals (Carter 2007; 2013). The range over which these devices will be audible will be subject to the efficiency of sound propagation in tidal sites and, crucially, the ambient noise already present in these locations. If ambient noise is high then device audibility would be reduced to ranges such that additional acoustic cues could prove necessary (i.e. ADDs, AHDs etc.). Of the variables stated above (propagation, device and ambient noise), ambient noise in tidal-stream sites is poorly known to the extent that there is too little information from other locations to generalise with any degree of certainty. Therefore, to generate real information on the acoustic properties of tidal sites we investigated the ambient soundscapes of three tidal-stream sites on the west-coast of Scotland. Two were sites that are of immediate interest to tidal-stream developers (the Sound of Islay and Kyle Rhea) and the third has received a little tidal-stream developer interest but represents a lesser resource and is subject to highly turbulent flows (Falls of Lora).

To record ambient sound in tidal sites we utilised the SAMS-European Marine Energy Centre's (EMEC) “Drifting Ears” method which uses drifting acoustic recorders to document ambient sound (Wilson et al., In press). The autonomous drifters each consist of a subsurface hydrophone suspended within a drogue which itself is attached to a surface float and dan-buoy fitted with batteries, preamplifiers, a sound recorder and GPS unit. The units are self-contained and waterproof such that they can be released into the water upstream of a site and allowed to drift through it, recording ambient sound as they go. The use of drifters allows recording in strong tidal streams without the artefacts associated with flow noise past the hydrophone (which troubles fixed recorders) and also the unwanted noises associated with hydrophones deployed from a boat.

For this study, four drifters were deployed in a line-abreast formation using a 6m RIB upstream of the site of interest then retrieved after they had drifted over the site, forty to sixty minutes later. During deployments the chase boat was kept at least 500m from the drifters with the engines silenced. Ambient underwater sound was recorded from 5 m below the surface and sampled at 96 kHz (16 bit). The hydrophone and recording equipment in each drifter was calibrated against a B&K 8104 reference hydrophone itself calibrated at the Aberdeen University Oceanlab test facility and then at the National Physical Laboratory, London.

Site 1: The Sound of Islay (55° 50’N 06° 06’W)

The Sound of Islay lies between the Islands of Islay and Jura and is subject to strong tidal-flows in excess of 3 $m.s^{-1}$ at springs. At its narrowest, the sound is around 700 m wide, is 20 km long with the deepest point exceeds 60 m deep. On account of the glaciated bottom topography and straight sides, the flow through the sound is relatively laminar. The sound is regularly crossed by a ferry transiting the narrowest part (Port Askaig to Feolin) about half way along its length. Scottish Power Renewables have consent for a ten 1MW turbine array immediately to the south of Port Askaig.

We collected ambient acoustic data in the site over five days between neap and spring tides in September 2009. Deployments were carried out on both ebb (south-going) and flood (north-going) tides in daylight. A car ferry also regularly traverses the narrows between Port Askaig and Feolin during daylight hours. Because this and other more sporadic vessels (ferries to the mainland, coasters, fishing boats etc.) produce considerable noise that would swamp the longer-term but lesser known ambient soundscape, we avoided times when these vessels were traversing the narrows. Weather during the study was generally favourable with sun and cloud and only short periods of light rain. Beaufort sea-states ranged from 0 to 5 but were predominantly 2 or less. Sampling was carried out along the whole length of the sound from the mouth in the north to the Black Rocks in the South (Figure 3). We sampled six ebb tides with four independent drifters generating 24 acoustic tracks and seven flood times generating 28 tracks. Sampling was carried over a period from late-neap into full spring tides. Because the drifters were passive we could not record in predetermined locations. Instead they were deployed across the current so that as they drifted they would generate a swath of recordings along the length of the sound.

In subsequent analyses we divided the Sound of Islay into a series of lines of latitude 150m apart and then used the drifters' on-board GPS logs to calculate at which point in the acoustic recordings each gateway was passed. A sixty second sound segment was then extracted from the recordings to characterise the soundscape at each line of latitude and the particular line of longitude from which the recording was made. The sound-sample duration of sixty seconds was chosen (from previous trials at EMEC) as an optimum compromise between the instantaneous variability in ambient noise and characterising a discrete location during a drift. In total, 596 of these sixty second samples were extracted and are shown with the dots in Figure 3.

Broadband Sound Pressure Levels (SPL) for all of the recordings ranged from 114.5 to 130.9 dB re 1μPa. Analysis of SPL against local flow speed (derived from each drifter's on-board GPS) suggested that there was a weak relationship between sound intensity and flow speed. In general, as the flow speed increased, so the ambient noise increased. When stratified to greater or less than 2 $m.s^{-1}$ underwater sound levels were found to be significantly different (ANOVA General Linear Model using fixed factors of flow rate and direction, P<0.001, Figure 4.).

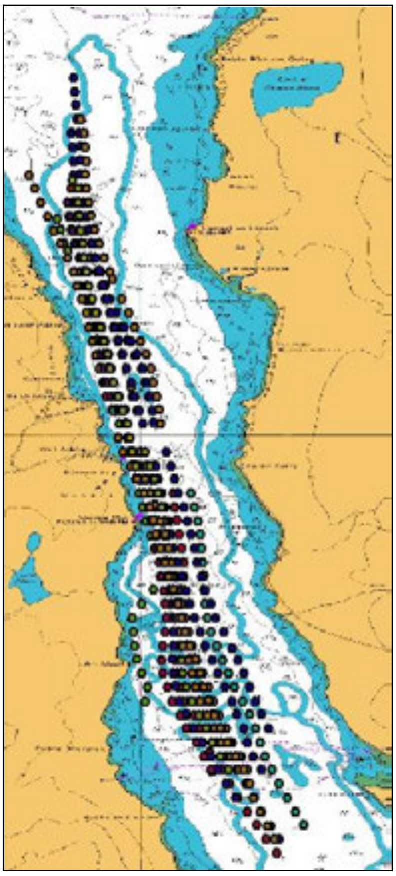


Figure 3. Sound sample locations in the Sound of Islay derived from 52 drifts. The dots represent the central location of each 60 second sound segment used to characterise the ambient soundscape of the site.

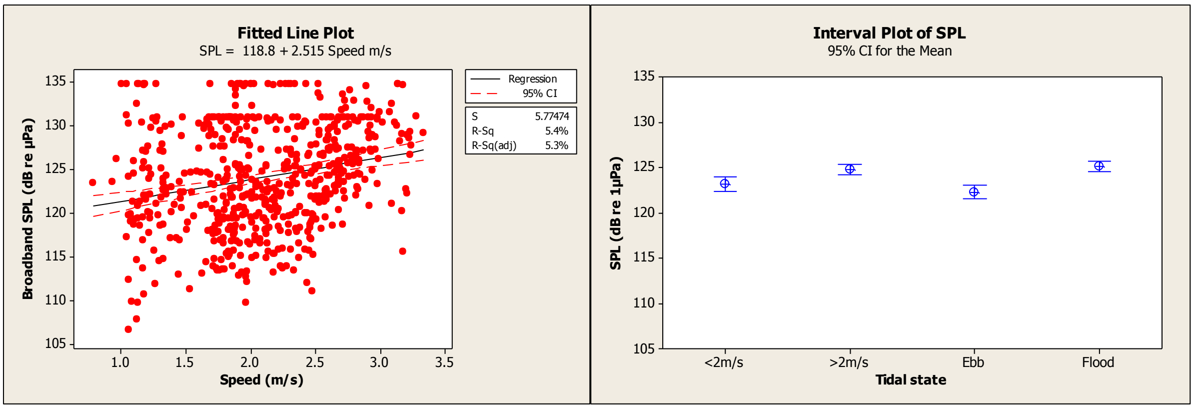


Figure 4. Left panel: Comparison of tidal flow speed against underwater noise which demonstrated a tendency for sound to increase with water speed. **Right panel**: Significant differences between greater or less than 2 $m.s^{-1}$ and also between ebb and flood tides.

When mapped it was clear that as well as rate of water flow influencing sound levels, location also made an important difference to ambient underwater noise. There were distinct patches of high and low sound intensity (Figure 5). In particular, the waters at the narrowest part of the sound (off Port Askaig) experienced the highest levels of underwater ambient sound while areas where the strait opened out (particularly to the south east - off Black Rocks) were subject to less intense underwater sound levels. The reasons for this “sound-topography” are unknown but a variety of factors may be at play, particularly any flow-generated sediment transport over rock, patches of “snapping shrimps” and turbulence in the water itself and associated surface disturbances (tide generated waves, ripples and so on). Though we attempted to survey when the ferry was not crossing the sound, at times its engine was left in idle when the vessel was tied up and this may have further contributed to the intensified background around Port Askaig.

As described earlier, we attempted to avoid the sound produced by operating ferries, transiting ships and other vessels from contaminating the sampling of non-anthropogenic ambient noise. Nevertheless these vessels contribute substantially to the ambient noise budget of these and other coastal sites. However, because their output is sporadic, somewhat predictable and present only a small fraction of the total time, we excluded them from our consideration of ambient sound here. Being better quantified in the literature than natural ambient sound and a point source of sound, it is however possible to retrospectively add their signature to such sites.

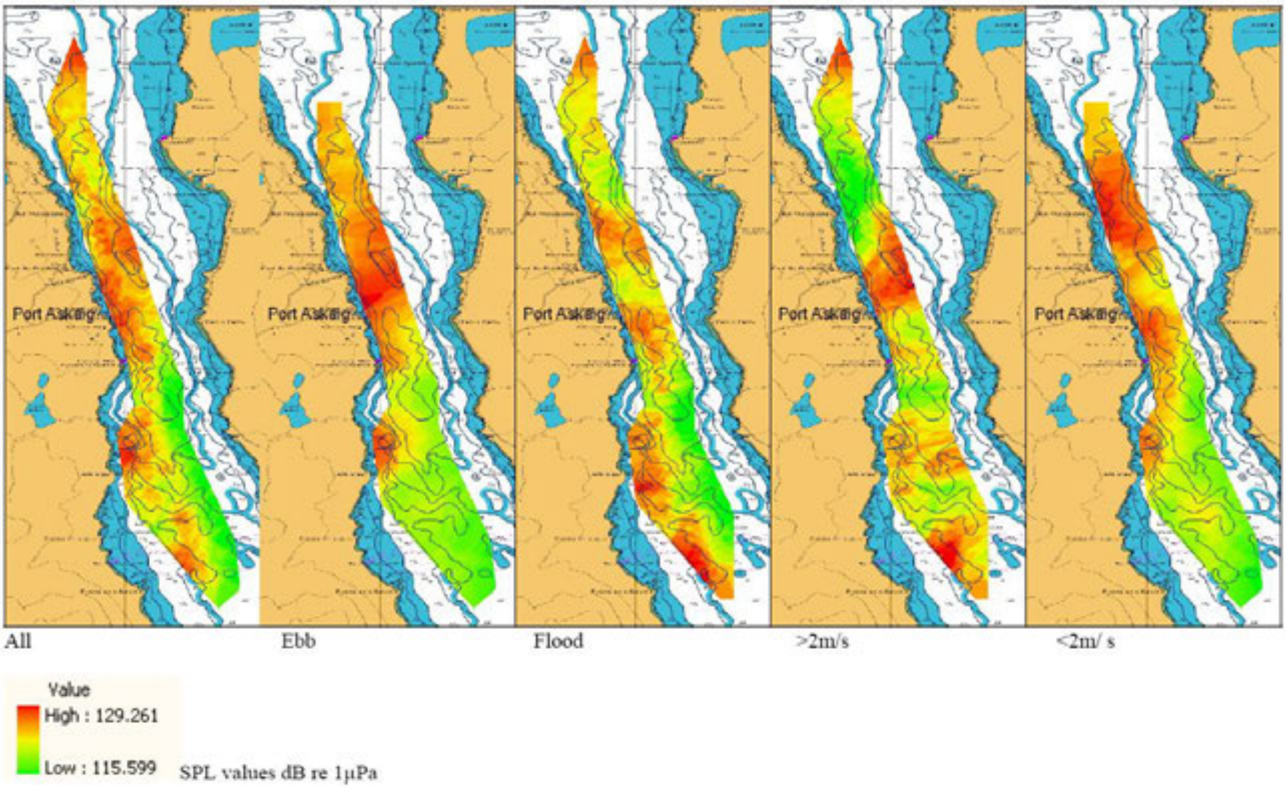


Figure 5. Underwater sound maps of the Sound of Islay summed (left) and divided by tidal direction (middle) and rate of flow (right). The lowest observed intensities are represented by shades of green and the highest in shades of red.

Site 2: Kyle Rhea (57° 14’N 05° 39’W)

Like the Sound of Islay, Kyle Rhea was chosen in this study as it is an inshore site experiencing substantial tidal-streams and of immediate interest to tidal energy developers. The site is a narrow strait between the Isle of Skye and the Scottish mainland. The narrows are approximately 3.5 km long and slightly tapered from the north (700 m wide) to the south (350 m at the narrowest). The waterway is bounded by Loch Alsh to the north and the Sound of Sleat to the south. Tidal streams flow northwards on the flood and southwards on the ebb and reach rates in excess of 2.3 $m.s^{-1}$ at springs. Again because of the glaciated and smoothed out rock shape of the strait, the flow through the site is relatively laminar. The Kyle Rhea is crossed by a small ferry at its narrowest point in the south. Several companies have expressed interest using this site to develop tidal-stream energy, notably Marine Current Turbines who are exploring the potential to generate around 8 MW from the site (MCT press release, April 2011).

We collected acoustic data from the site in the early summer of 2011 (17th May). Several attempts at data collection prior to and after this date were abandoned due to unsuitable weather conditions, primarily heavy rain and strong winds. The sampling period fell during spring tides and the inclement weather was dry with some heavy rain and light to moderate winds from the southwest (3.5 - 16 $m.s^{-1}$), which in combination with the tide created agitated sea conditions particularly in the northern Sound of Sleat and southern Kyle Rhea. It was calmer elsewhere. Being summer, the small car ferry ran almost constantly during the surveys and being broadband its acoustic signature was impossible to extract from recordings.

For the analyses, the drifter tracks were separated into latitude bands 150 m apart and a sixty second sound segment extracted from the acoustic file to represent that site. This generated 228 sound samples (Figure 6). As with the Sound of Islay work, the individual drifters were calibrated during the study using a B&K hydrophone, itself calibrated by the National Physical Laboratory (London)

Figure 6. Kyle Rhea and northern Sound of Sleat and 228 acoustic sampling stations (separated in latitude by 150 m). The ferry track is also shown (dotted line) where the strait is narrowest (300 m).

Broadband Sound Pressure Levels (SPL) for all of the recordings ranged from 116 to 137 dB re 1µPa. Overall, therefore, the lower sound levels experienced were very similar to the Sound of Islay (116 cf 115 dB) but the upper extreme was considerably higher (137 cf 129 dB). Analysis of SPL against local flow speed again found a weak positive relationship between sound intensity and flow speed. When stratified to flow rates greater or less than 2 $m.s^{-1}$ and also compared to ebb and flood tides underwater sound levels were found to be significantly different (ANOVA General Linear Model using fixed factors of flow rate and direction, P<0.001, Figure 7.). In contrast to the Sound of Islay, the ebb tide recordings were louder than the flood, most probably because of the south westerly wind conflicting with the south-going flow of the ebb tide and associated tidally derived surface waves particularly in the Sound of Sleat (Figure 8). In addition, the inclusion of sound files recorded during ferry movements would have contributed to the increased sound levels. When mapped, the higher intensity sounds in the southern portion of the area are clearly apparent. This is particularly clear in the tide against wind (ebb: south-going ebb, wind: north-east going) and converse flood tide with wind scenarios (Figure 8). Though wind/waves and the ferry may explain some of the spatial structuring of the sound field it does not explain it all. Other factors such as sediment bed-load and snapping shrimps are likely to impinge on the sound field. The observation of discrete sound patches in the upper Kyle Rhea (Figure 8, extreme right panel) suggests that such other factors are also present.

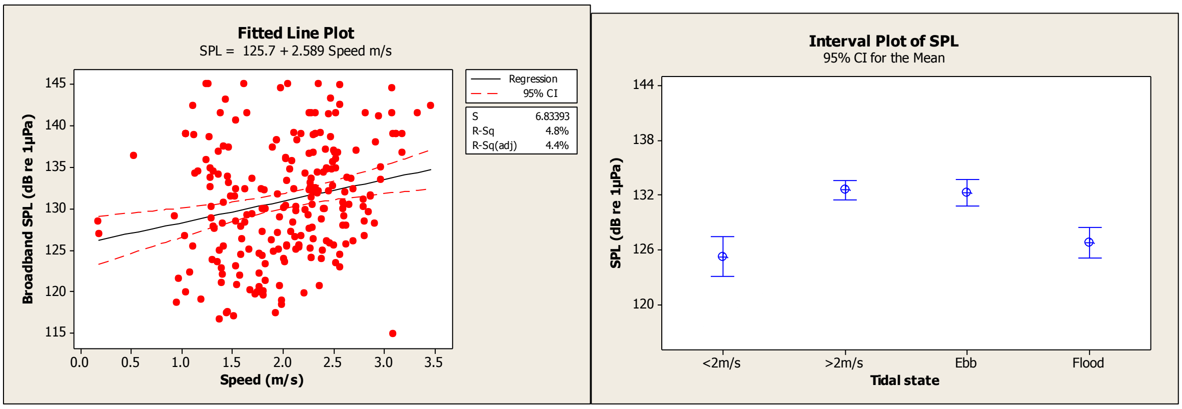


Figure 7. Left panel: Comparison of tidal flow speed against underwater noise in the Kyle Rhea which demonstrated a tendency for sound to increase with water speed. **Right panel**: Significant differences in sound intensity between greater or less than 2 m.s^{-1} and also between ebb (more) and flood (less) tides. Together tidal speed and direction explained 18% of the variation.

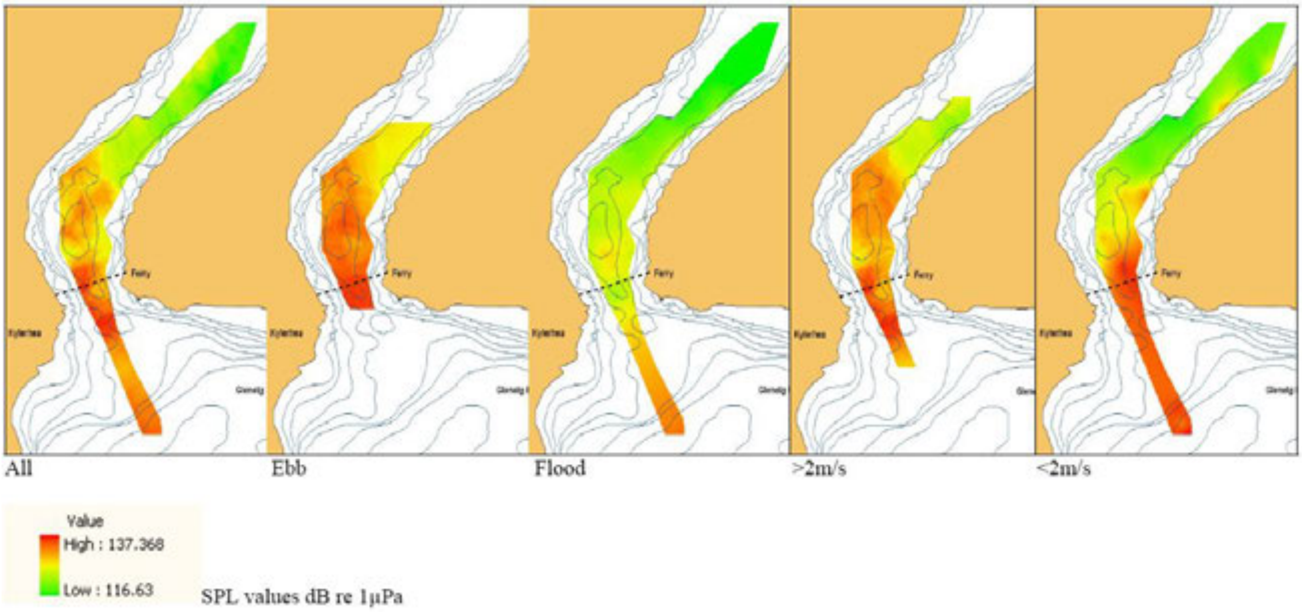


Figure 8. Underwater sound maps of the Kyle Rhea and upper Sound of Sleat. **Left**: summed **Middle**: divided by tidal direction, **Right**: rate of flow. The lowest observed intensities are represented by shades of green and the highest in shades of red.

Site 3: Falls of Lora (56° 27’N 05° 23’W)

In contrast to the other two sites studied, the Falls of Lora is at the mouth of a sea loch (Loch Etive) where the tide is forced to move over a shallow, narrow sill. The irregular bottom topography and constriction generates a turbulent flow with standing waves and extensive vertical mixing. Though there used to be a ferry crossing at this site, there is now a single span bridge. Flow rates range up to 4 m.s^{-1} on springs and the falls at their narrowest are around 170 m across. The site has been discussed as a potential site of tidal-energy extraction but only in terms of a site for prototype devices or small scale local deployment (Argyll and Bute Council 2011).

We collected acoustic data from the Falls of Lora in mid-June 2011 on an ebb tide (i.e. tide flowing out of the loch). There was no rain during the survey and only light winds (≤1.5 m.s^{-1}). We could not set sample points in the usual manner as the extreme turbulence introduced periods of self-noise among the recording equipment (hydrophone-bumping into the drogue). Instead, any sound segments with this self-noise were excluded and only clean 60 second segments used.

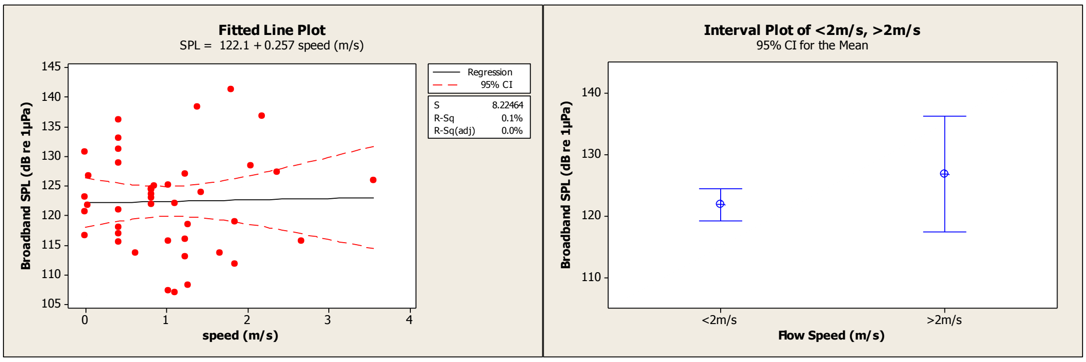


Figure 9. Left panel: Comparison of tidal flow speed against underwater noise in the Falls of Lora which demonstrated the large variation in sound levels at speeds greater than 0.5 m.s^{-1} and a very weak tendency for sound to increase with water speed. **Right panel**: Differences in sound intensity between flow rates less and greater than 2 m.s^{-1}.

The sound levels encountered in the Falls of Lora showed the greatest range of any of the three sites, fluctuating from 106 to 141 dB and presenting both the quietest and loudest levels encountered in this study (Figure 9). Mapping these levels demonstrated that the most turbulent flow at the narrows and immediately downstream generated the highest sound levels and that lower intensities were encountered in the less confused waters at greater distance from the narrows (Figure 10). The highest flow rates were experienced to the south side of the channel and in the immediate vicinity of the areas of the most intense ambient sound.

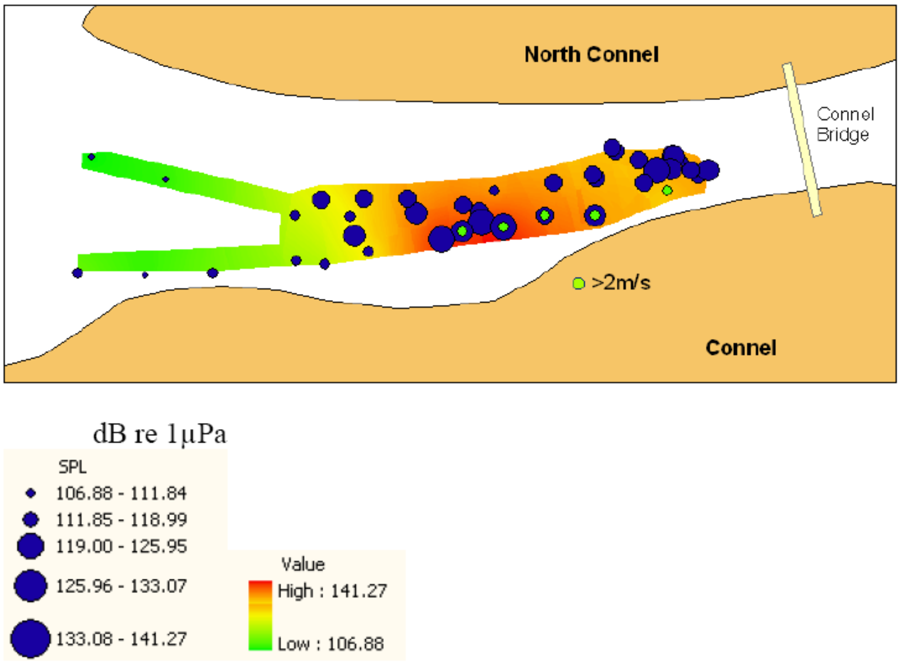


Figure 10. Underwater sound maps of the western Falls of Lora. The lowest observed intensities are represented by shades of green (and small circles) and the highest in shades of red (larger circles). The recordings made in water moving faster than 2 m.s^{-1} are shown with green dots.

Comparing sites

When the three sites are compared (Table 1) all experienced broadly similar ranges of flow speeds, ranging from near still patches of water (usually near the shoreline) to strong flows with upper speeds from 3.3 to 3.5 $m.s^{-1}$ (~6 to 7 knots). However, while all three experienced similar ranges, both the Sound of Islay and Kyle Rhea experienced average speeds that were alike (around 2 $m.s^{-1}$), while the Falls of Lora experienced around half these speeds at its average. This is likely because of the substantial discontinuities in the flow of the Falls of Lora site with large areas of confused water and wide back-eddies to either side of the main flow. Measured ambient sound levels were equally variable, with the Sound of Islay and Kyle Rhea showing broadly similar sound levels and the Falls of Lora showing the greatest variability both above and below the levels experienced elsewhere. The elevated levels of the Kyle Rhea compared with the Islay site are likely a result of the poor weather during surveying and the near-continuous operation of the small ferry.

Table 1. A comparison of the three sites monitored.

	Sound of Islay	**Kyle Rhea**	**Falls of Lora**
SPL range (dB re 1 μPa)	114-131	116-137	106-141
Depth (m)	0-60	0-36	0-30
Flow speed: range ($m.s^{-1}$)	0.79-3.34	0.18-3.47	0-3.56
Flow speed: average ($m.s^{-1}$)	2.10	2.02	1.02
Survey time of year	September	May	June
Weather conditions	Good	Poor	Good

In terms of what we can learn from measuring sound in these three sites, it is informative for the wider ambitions of this study to discover that the ambient underwater sound levels experienced in both sites of immediate commercial interest were broadly similar and ranged from 114-137 dB re 1 μPa.

Since the Kyle Rhea recordings were subject to site-specific boat traffic and a time limited recording window, for this generic study it is most appropriate to use the Sound of Islay as a model site for considering how far the acoustic output from warning devices may propagate under natural conditions. From there we can consider how much spatial warning additional sounds may provide animals manoeuvring in the vicinity of turbines.

Of course, most tidal sites are also subject to vessel traffic (whether crossing ferries, transiting or fishing). Furthermore, once turbines are installed, increased vessel movements for maintenance are likely. These anthropogenic sound sources will sporadically dominate the soundscapes of these sites and should also be considered alongside the more continuous ambient soundscapes in more detailed site-specific modelling.

Existing acoustic warning equipment

The bulk of marine mammal–human interactions that have involved the purposeful introduction of acoustic energy (e.g., ADDs/AHDs) have been related to fisheries and aquaculture. As such, a variety of devices have been developed primarily to deter mammals from approaching and interacting with fishing gear or cages. Modern devices generally fall into two categories. Acoustic Harassment Devices (AHDs, sometimes Commercial Aquaculture Acoustic Devices CADDs) which produce intense sounds (above 185 dB re 1 μPa) with the general intention of discouraging or excluding animals from proximity to a resource such as a fin-fish cage. Acoustic Deterrent Devices (ADDs), on the other hand, produce less intense sounds (below 185 dB re 1 μPa) with the aim of reducing bycatch in fishing equipment. That these devices may work is well known (Fjalling et al. 2006; Kraus et al. 1997) but why they only sometimes work and how they work are more mysterious. The acoustic pulses, tones or sweeps that these devices produce are variable across the brands and versions but most emit synthesised sounds of entirely artificial origin without known biological significance (Gordon et al., 2007). AHDs (also known as 'seal scarers/scrammers') are thought to work primarily by emitting sound levels so powerful that they are painful or unpleasant for a listener at close range. ADDs (also known as 'pingers') operate at lower sound pressure levels (usually <150 dB re 1 μPa) and are therefore unlikely to cause discomfort. Instead it is thought that they promote more local avoidance behaviour (Cox et al., 2003). By presenting an unusual sound, pingers may also prompt animals to proceed with greater caution and therefore detect an actual threat (such as a fishing net) more readily. Though ADDs have been shown to reduce bycatch in a wide variety of fisheries (Reeves et al., 1996), they have also been found to increase depredation (prey removal) in others (Bordino et al., 2002). This is perhaps because animals, once alerted, can choose to do different things with the information. The so called 'dinner bell' effect is one such example, where animals (e.g. sea lions) appear to learn to associate the introduced sound with the presence of nets and prey-fish caught in them (Bordino et al., 2002). The use of potentially painful sounds used by AHDs are intended to counter the dinner bell effect by using unpleasant stimuli to discourage animals from actually getting close enough to cause damage to fish, cages or themselves.

A variety of AHDs and ADDs have been developed for application in a wide variety of fisheries or aquaculture applications. Though the precise characteristics of several of these remain in commercial confidence, key features of many were summarised by Gordon et al. 2007 and have been outlined in Table 2.

Table 2. Characteristics of selected acoustic warning devices. Adapted from Gordon et al. 2007; Lepper et al. 2004; McKinley et al. 1988; Ace Aquatec promotional material (AA-03-037) and Gerstein et al. 2007.

Category	Target			Manufacturer	Device name	Frequency (kHz)	Source level (dB re 1μPa @1m)	Transmission duration (s)	Pulse duration (ms)	Duty cycle
	Seals	Cetaceans	Other							
AHD	■			Airmar	dB Plus II	10.3	192	2.25	1.4-2	~1:29
	■			Ace Aquatec	Silent Scrammer	8-20	165	0.33-0.48	1.4-14	1:1+
	■	■		Ace Aquatec	MMD*	10-20	194	2	250	1:7-80
	■			Terecos	DSMS-4	1.8-3.8	146-178	15 -120	8-16	1:1&random
ADD		■		Dukane	Netmark 1000/2000	10	130-150		300	1:13
		■		Aquatec Sub-Sea	AQUAM*ark* 100-300	10-160 tones & fq sweeps	145		300	1:13-100 regular or random
		■		Fumunda Marine	FMP 332	10	130-134		300	1:13
		■		Lien	L2/L3	2.5-3.5	110-132		300	<1:7
		■		STM	DDD02/02F	1-500	≤ 150		~100	1:2400+
		■		Airmar	Gillnet Pinger	10	132		300	1:13
Boat approach			Mantees	Gerstein et al., 2007	Manatee Alert Device	10-20 kHz	120		variable	variable
Water intake exclusion			Fish	Fishdrone	**	0.02-1	160–175		3000	1:1.3
				'Speaker system'		≤2	n/a		variable	variable
				The Hammer	Fishpulser**	Impulsive			200	

* Promotion includes tidal turbine acoustic warning
** Low-frequency mechanical sound generators

In contrast to the use of artificial sounds, several studies have investigated the use of biologically meaningful sounds, principally killer whale calls, for deterring marine mammals (Anderson and Hawkins 1978). Seals and cetaceans are particularly sensitive to killer whale vocalisations because they are one of their primary predators and their calls are likely to elicit responses over and above any specifics of absolute sound intensity or novelty. Trials to gauge how marine mammals (seals and small cetaceans) respond to playbacks of killer whale calls, have however returned mixed results ranging from strong avoidance (Fish and Vania 1971) and rapid flight (Anon 2002, as cited by Gordon et al., 2007) to transitory responses (Shaughnessy et al. 1981) and few response at all (Deecke et al. 2002). Perhaps it is unsurprising that use of such a biologically meaningful sound will elicit complex responses from animals hoping to evade a stealth predator. As pointed out by Gordon et al., (2007) it is also worth considering what impact frequent playbacks of killer whale calls might have on the local killer whales in an area.

Acoustic devices have also been used to reduce other (non-fishing related) human-marine vertebrate interactions. For example, a range of devices have been developed to discourage fish from approaching the cooling water intakes of power stations

With 25% of all documented Florida manatees fatalities and almost all living animals exhibiting scars from powerboat collisions (O'Shea et al., 2001; Calleson and Frohlich 2007), efforts at reduction have included studies of the boat-animal acoustic interactions (Gerstein et al., 2001). It appears that while manatees can hear fast moving powerboats and commence avoidance behaviour, they do not perceive the lower frequencies of slower moving boats (Gerstein et al., 2001). This shift in understanding from the assumption that fast moving boats were the problem has prompted a contentious re-think of speed restriction guidelines (Calleson and Frohlich 2007) and the testing of a narrow-beam, bow-mounted acoustic alarm for vessels operating at low speeds (Gerstein et al. 2001). A proposed alarm projects two ultrasonic source frequencies (230 and 250 kHz) that interfere with each other to produce a highly directional 20 kHz sound beam directly in front of the vessel. This emission was not intended to scare or harm manatees but instead to provide a consistent highly directional cue that manatees might learn to associate with boats (Gerstein 2002).

In contrast to a cue that animals might *learn* to avoid, whalers noticed that large whales showed spontaneous strong aversive responses when exposed to primitive sonar (ASDIC emitting short pulses between 10 and 26 kHz). Originally intended to be used to track whales, operators on whaling ships found that their quarry seemed to be irritated or frightened by these signals and responded by bolting away in straight lines which then made them easier to harpoon (Gordon et al., 2007).

In addition to using sound to manipulate marine mammals, there have also been a suite of studies considering fish responses to sound, primarily to reduce their loss in large areas that cannot be easily screened such as power station water intakes and irrigation channels. In a review, McKinley et al. (1988) considered several devices and documented wide variations in the nature of fish responses to the low frequency devices on the market. Overall, they found that fish could be made to avoid water-intakes with sound but that no devices were completely effective. Instead they excluded considerably less than 100% with a maximum of 85% of individuals reacting to the most successful sonic device tested (McKinley et al. 1988; Anon, 2006). It is perhaps unsurprising (on account of different auditory abilities) that they observed wide variation between species, especially comparing pelagic and benthic ones, however they also saw markedly different responses in closely related species (e.g. sockeye versus Coho salmon). Furthermore some species, particularly predatory ones, were attracted to the noises while others were repulsed. Though fish did respond does not necessarily mean that these devices proved suitable for excluding fish from intakes. In some cases, for example, the fish required several minutes of exposure before they began to take action, furthermore, many of the frequencies tested didn't elicit turning with a relevant directionality to avoid the danger (McKinley et al. 1988). Overall, the use of low frequency transducer-based sound systems and those focussing on producing substantial particle motion, did not appear to be viable alternative for protecting fish at water intakes. However, high-frequency, transducer-based systems were effective in generating avoidance and exclusion for “hearing-specialist” species such as clupeids (shad and herring) and alewifes at intakes. High frequency systems have shown mixed and partial success with salmonid species (salmon and trout) guidance and exclusion (EPRI 1999).

In addition to absolute exclusion, acoustic methods have also been used to steer fish movements so that they didn’t approach a danger. For example, a prototype *sonic barrier* was installed and evaluated at the confluence of Georgiana Slough and the Sacramento River in the USA (Figure 11, Anon 2006). The barrier consisted of a series of acoustic devices positioned at a bend in the river’s flow to encourage migrating Chinook salmon smolts to use the opposite side of the river and so transit the area without encountering the area of danger (Anon 2006). In addition to physical screens, ladders, louvres and sonic methods to move fish away from danger, a variety of other natural and artificial ideas have been tested including: 1) *natural* - ambient light, flow velocity, depth, channel shapes and temperature and 2) *artificial* - vertically hung chains, electromagnetic fields, strobe lights, bubble curtains, water jets and even chemicals. Of these methods the non-acoustic artificial ones have generally proved ineffective with little or no success (Anon 2006).

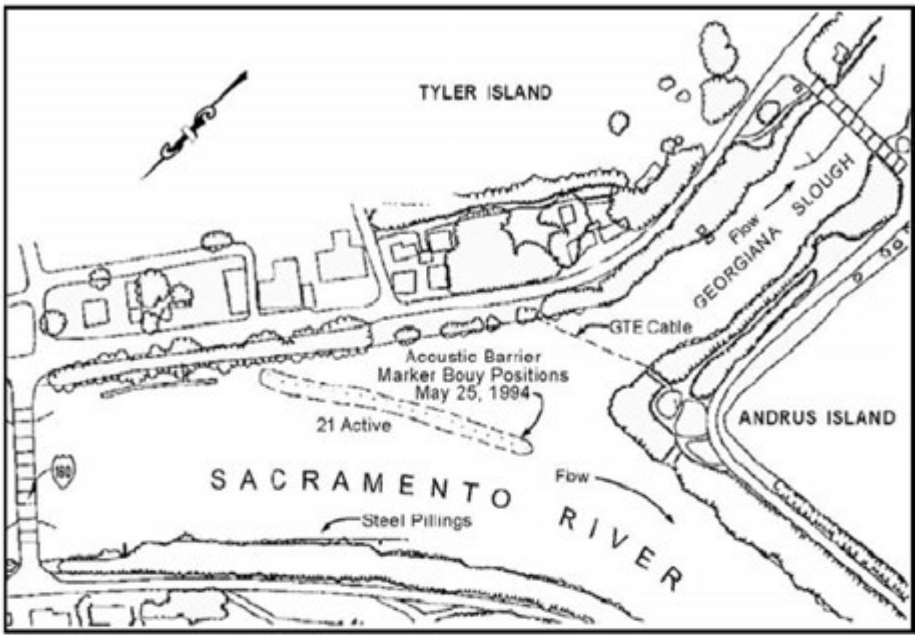


Figure 11. Acoustic barrier deployed to divert Chinook salmon from entering Georgiana Slough in California, USA. The sound system consisted of a 250 m long linear array of acoustic transducers suspended from buoys that were placed approximately 300 m upstream from the slough entrance and generated sounds at 300-400 Hz. The acoustic barrier angled out from the slough-side shore with the objective of deflecting the out-migrating fish to the far side of the river, away from the slough entrance (Anon 2006).

In this section, we have briefly described previous applications of acoustic devices intended to influence the movements of mysticetes, odontocetes, pinnipeds, sirenians and fish. Though there are a wide variety of stimuli and outcomes it is clear when looking across these studies that *it is possible* to use sound to influence marine vertebrate behaviour and movements in relation to potentially dangerous human activities. The majority of devices make somewhat arbitrary, artificial sounds at a range of amplitudes and also elicit a variety of responses. These responses range from fright and bolting (ASDIC-whales), through to wide- and narrow-scale avoidance (AHDs and ADDs, fish-alarms) and even attraction (pingers-sea lions, fish alarms-predatory fish). Some devices might result in learning with intended useful outcomes (boat alarms-manatees) while others result in deleterious consequences (pingers-sea lions). Though less studied, most could suffer some degree of habituation (Cox et al., 2001). However, probably the most striking result was that, despite wide-scale efforts to develop acoustic devices, there remains a very poor understanding of why these sounds work at all. Central to this question is what the animals perceive the sounds as, and for them, what an appropriate response would be. Synthesised killer whale calls offer the most obvious path to an intelligible response but the mode of operation of the pings, buzzes, clicks, beeps and whistles of other devices are unknown. Crucially, if the intention of a warning device is to prompt an animal to exhibit a specific behaviour with directional relevance (e.g. safely steer around a turbine) then some notion of what feature of a sound the animal is actually responding to is also required to ensure that the stimulus is optimised and appropriate.

Audibility of existing acoustic warning equipment in tidal-sites

The development of modern acoustic warning equipment has primarily been to either keep marine mammals out of fishing nets (ADDs) or away from aquaculture interests (AHDs). These sites are typically in open coastal or sheltered inshore waters which are not subject to the elevated natural noise levels of tidal-sites. To investigate what impact this alternative setting would have on the audibility range of these acoustic devices we compared the minimum and maximum ambient sound levels measured in the Sound of Islay (114-131 dB re 1 μPa) against the output intensity of these devices.

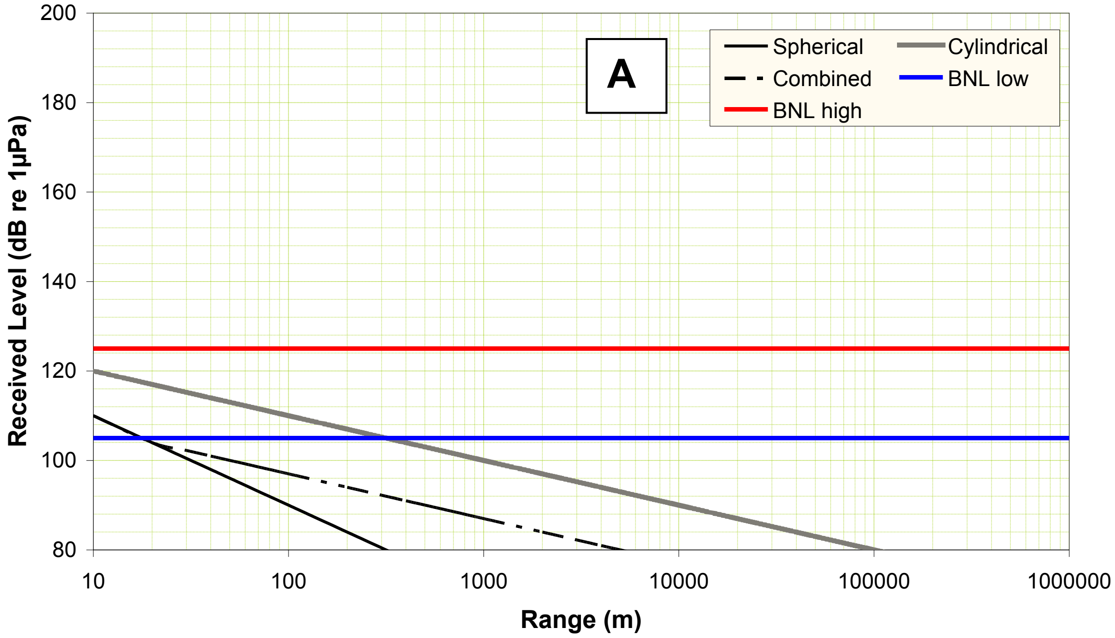
To compare sound levels with typical ADDs such as the Dukane Netmark 1000 pinger and its successors, we first referenced the Sound of Islay ambient noise to the specific frequency band used by most of these devices. They typically emit signals around 10 kHz (with less intense harmonics) so we filtered the recorded ambient sound down to a third octave around this fundamental frequency (Erbe 2011) using a Fast Fourier Transform filter (size 4096, hamming window). From this we derived upper and lower levels for an ambient noise third octave band (8.9 to 11.3 kHz) corresponding to an animal audition window within which the acoustic warning signal will sit. We used an ADD signal strength of 130 dB re 1μPa as a generic level (Table 2). AHDs, in contrast produce louder signals and are more variable in their frequency components (5-30 kHz) between both brands and models (Table 2). The responses of different taxa (particularly odontocetes and pinnipeds) towards this diversity of AHD devices are less well understood (other than the fact that they are much louder), so we considered the audibility of the better known ADD-like signal at a strength equivalent to the upper extent of marketed AHDs (200 dB re 1μPa, Table 2).

To assess how far these generic ADD and AHD signals might propagate in tidal sites we considered several variants of simplistic but standard transmission loss equations. Three types of geometric spreading were used: 1) *Spherical spreading*, where the energy from a sound source can propagate uniformly in all directions ($TL = 20log_{10}(R)$ with TL being transmission loss and R the range from the acoustic source); 2) *Cylindrical spreading, which applies to* shallow water and spreading occurs in two dimensions only ($TL = 10log_{10}(R)$) and 3) *Combined spreading loss;* where near the source the sound propagated spherically then at some range (H) where the range is greater than the water depth (in the sound wave propagates cylindrically ($TL = 20log_{10}(H) + 10log_{10}(R/H)$). For simplicity we considered the sound to be a point source at turbine hub height and positioned slightly deeper than mid water column in a 50 m site to allow for surface vessel clearance (i.e. 22 m from the bottom).

To consider acoustic warning device propagation distances we combined the information on the upper and lower levels of ambient sound (1/3rd Octave around 10 kHz from Sound of Islay) with generic ADD and AHD signal strengths (130 & 200 dB re 1μPa) and the three propagation scenarios. These generated two plots (Figure 12).

When considering a sound source at levels associated with conventional ADDs, the sound of these devices will not propagate far before dropping below the ambient. For the louder measurements taken from the Sound of Islay, an ADD will drop below ambient before spreading to a 10 m from the device – i.e., less than the likely rotor diameter of a commercial device. In a quieter scenario, the acoustic warning device will have wider audibility but even then it would only propagate three hundred meters under the most generous sound spreading scenario. However, given that the most likely spreading scenario in such a site will be the combined measure, the potential acoustic audibility range will be less than
20 m.

For the much more intense sound associated with an AHD, itself capable of causing hearing damage in marine mammals (Southall et al., 2007), propagation distances are much more substantial. Under all three propagation models and two background noise levels, the signal may be audible to beyond 1.4 km before nearing ambient in the unlikely case of spherical spreading. In the more likely case of depth-relevant combined spherical-cylindrical spreading the modelled sound will exceed background out to many tens of kilometres and well beyond the relevant confines of current tidal-site interests.



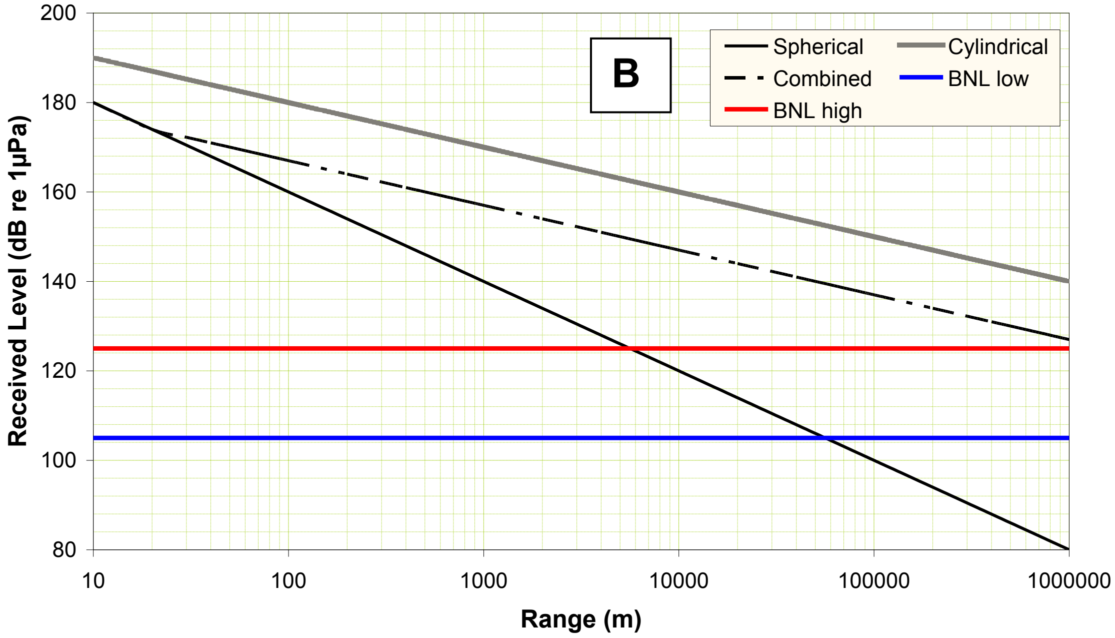


Figure 12. Combining the parameters in this study to determine how far acoustic warning devices will propagate in tidal-stream sites before dropping below ambient background noise levels. Top graph A: 130 dB re 1µPa, 10 kHz signal typical of an Acoustic Deterrent Device. Bottom graph B: 200 dB re 1µPa source at 10 kHz of a simplified Acoustic Harassment Device. Red and blue horizontal lines denote the upper and lower levels of ambient noise recorded in the Sound of Islay. Black sloping line is propagation assuming circular spreading, grey line is cylindrical spreading and the dashed line is a combination of the two for a 50 m deep site with a sound source at 22 m.

Clearly this examination of how acoustic warning devices may propagate in tidal-stream sites is basic and generalised beyond the specifics of individual acoustic devices and site-specific propagation scenarios. However, it shows that the deployment of off-the-shelf acoustic devices developed for other applications, is unlikely to be appropriate for a particular tidal-stream site. If the range of warning is too small, as appears to be the case for ADDs then animals may not be given sufficient time or space to avoid an individual turbine. Furthermore the exact placing of an ADD on a turbine (hub or blade tips etc.) would be highly important. In contrast a much louder device such as an AHD is likely to be detectable at ranges far greater than the sphere of influence of an individual turbine or even an entire array. Accordingly, if such a device influences animal movements then it will be at ranges capable of causing significant habitat exclusion or discourage animals from using passageways or passing headlands. For a more graded behavioural response (as is probably the case for AHDs) habituation is a concern, especially if a single source is used to mark an array of turbines. Furthermore, if the sound is intermittent (as is the case for many seal-scarers) then fright responses may lead to inappropriate behaviour relative to the actual threat of the turbines themselves. So in terms of a sound source, what might be appropriate?

Requirements on an acoustic warning system

It is clear from this basic consideration of underwater sound in tidal-sites and existing acoustic devices that using existing off-the-shelf equipment to warn marine mammals of turbines would be an unsatisfactory and simplistic approach. However, given the discrete point source of threat (i.e. individual turbines and the rotors in particular) coupled with the investment and infrastructure associated with tidal-stream developments, then more sophisticated acoustic warning devices would not be out of place to help mitigate a collision issue, should one prove to exist. If formulating warning systems, the following paragraphs outline seven attributes that should be considered. These are not intended to be a recipe for designing an acoustic warning system but rather outline the operating requirements that such a system would need to satisfy.

Attribute 1: The signal must elicit an appropriate response: To keep animals away from a discrete point of extreme danger, knowing the precise mode and extent of exclusion resulting from an acoustic warning is not essential. On the other hand, for more complex scenarios the way animals respond and the spatial extent of those behaviours are more critical. This is particularly the case for tidal turbine developments. Subsequently to test-devices, commercial-scale turbines are unlikely to be deployed singly but instead be placed in arrays of tens or ultimately hundreds in spaced-grid or more complex configurations (Bai et al., 2009). Thus, animals' reactions around a single turbine are highly relevant particularly if those responses take them towards the path of neighbouring turbines. Acoustic warnings that elicit startle responses and rapid flight, for example, may suit a single turbine but become inappropriate for multiple turbines. Furthermore, marine mammals, particularly odontocete cetaceans are social and their movements are often coordinated among individuals (Gibson 2006). Accordingly a response such as fright and flight by one animal on the periphery of a school can be propagated to more distant individuals (a phenomenon evident and well documented in fish, Domenici and Batty 1997; Gerlotto 2006). For species forming large or fast moving schools (e.g. common dolphins), their communication and coordination has the potential to be over ranges relevant to multiple turbines simultaneously. An extreme and inappropriate response to the warning sound associated with one turbine could therefore steer more distant individuals towards another.

One of the more obvious options for a warning stimulus would be to use the sounds of a natural predator. Killer whales prey to a greater or lesser extent on all coastal marine mammal species and can be highly vocal. Given that most marine mammals appear to have an innate fear of killer whales and their vocalisations, playbacks of their calls (or a proxy) would seem like a reasonable approach. However, mimicking a natural sound may have unintended consequences. For example prey species, such as seals, may eventually learn to associate playback killer whale sounds with turbines rather than the original predators and so show inappropriate responses on encountering real whales. Also the killer whales themselves may respond to these sounds by approaching as if they were interacting with real conspecifics. Furthermore, the responses of prey to predators are often sophisticated and vary depending on context and may range from flight or extreme avoidance to concealment or no outward response at all (Deecke et al., 2002). Mimicking the sounds of a predator may therefore turn out to be inappropriate when used in the context of fixed turbine(s).

Acoustic Harassment Devices, such as seal scarers, use amplitude as the primary feature, where the sound is sufficiently loud and unpleasant that animals elect not to approach the source and therefore the resource being protected. However, with water being an excellent sound conductor, these emissions will also propagate beyond the area of concern and can introduce acoustic energy (pollution) well outside of the footprint of a tidal stream development. Depending on the circumstances this may sometimes be appropriate (see other Attributes) or simply ensonify otherwise suitable habitat or movement corridors.

Other acoustic devices (ADDs in particular, Table 2) emit lower amplitude sounds that are entirely artificial in nature and usually not intended to emulate the sound of anything in particular. Despite this, they are known to elicit responses either through directional avoidance or more simply, by providing novel sound encouraging animals to switch to a more spatially alert status. Our understanding of precisely which components make these sounds effective is limited, but there is good evidence that they do work (e.g. Kraus et al., 1997; Carlström et al. 2002; Culik et al., 2001; Cox et al., 2003). Therefore, the use of abstract artificial sounds (i.e. pure tones, frequency sweeps etc.) may be appropriate in a renewables context so long as the other Attributes listed below are met. In addition, refinement of the signal to maximise their aversive properties through features such as 'roughness' (i.e. bandwidth and frequency modulation, Götz and Janik 2010) may strengthen the responses.

An alternative to creating artificial sound would be to tune the self-noise generated by the turbine itself, for example by influencing the vibration of the rotor tips or the gearing. This would have the added advantage of the sound scaling with the motion of the turbine. Though an attractive prospect, adjusting variables such as blade design for their sonic properties would be logistically challenging and costly especially once turbines are deployed. This would be particularly so as our thinking on the potential mammal-turbine collision issue is likely to develop as more information comes to light and refinements become available.

Finally, the complexity of finding an appropriate warning stimulus should not be underestimated. A terrestrial equivalent is the development of warning sounds of hybrid and all-electric cars for humans. Running on electricity these can be near-silent during operation and pose a collision risk for pedestrians (Simpson, 2008). Despite all we know about human hearing and acoustic perceptions (Tandy and Lawrence 1998), urban soundscapes and the ease of directly questioning people, there still remains uncertainty over what added sound(s) would be most effective in this context (as exemplified by the on-going ELVIN study, University of Warwick).

Attribute 2: Emission rates must suit approach velocities: The timing that sounds are issued is also important whether near-continuous, intermittent-regular or intermittent-random. Aquaculture or fishery related AHD and ADD emissions tend to be pulsed with either regular or sporadic duty cycles (Table 2). However, unlike nets or cages, the rate at which animals approach tidal turbines are likely to be more rapid and the duration of interactions much shorter. Thus while random signals may discourage habituation in a fisheries context they have less relevance in a renewables one where animals have the potential to rapidly approach a discrete point of danger by swimming within a mobile water mass. Similarly for a regular signal, the cues must come frequently enough to give an approaching animal sufficient spatial warning. Calculating the closing animal-turbine speeds along with the distance thresholds and the number of pulses required to elicit an appropriate response should help define appropriate inter-pulse intervals of a warning emission.

One way to optimise pulse rates and minimise unnecessary site ensonification would be to link an acoustic alarm with an active-detection sonar. Thus an acoustic warning signal would only be triggered upon the detection of a mammal-like target on a strike trajectory. However, while such devices are being developed for detecting upstream targets (e.g. MCT 2010) they cannot yet pick up all approaching animals due to the technical challenges of covering the entire water column. False detections triggering unnecessary warning sounds however are likely to have fewer implications than the alternative of the sonar being used to trigger a turbine shut-down.

Attribute 3: Emission frequencies must be audible for target species: Though it may appear obvious, any warning signal needs to be audible to the animals of concern (McKinley et al., 1988). This, however, is not as straightforward as it may seem because the hearing capabilities of marine mammals span an extremely wide and differing range of frequencies and for many species, particularly baleen whales, their precise sensitivities remain unknown (Richardson et al. 1995). Furthermore, our understanding of how hearing abilities vary among individuals in wild populations is limited even for the best known species. Coupled with hearing acuity, sound frequencies themselves propagate to different extents in water and to be effective in this context must exceed often frequency specific ambient noise.

Most previous attempts at acoustic warning have targeted a broad (but not comprehensive) range of species whether deliberately or not and have not been tuned to local conditions. However some recent developments (e.g. Götz and Janik 2010) have considered the choice of precise frequencies with a particular recipient species in mind. To be effective in a renewable energy context, the choice of the frequency(ies) chosen for a warning stimulus require consideration of the species targeted, any collateral species (including hearing-generalist or hearing-specialist fish) and the ambient conditions through which the sounds are intended to propagate.

Attribute 4: Amplitude must be appropriate for detection range and site: The warning signal must be sufficiently loud to be audible to the intended recipient species at a long enough range that they can take either avoiding or evasive manoeuvres. In addition to hearing sensitivity, development of the correct intensity also requires knowledge of the background noise in the site as well as propagation characteristics.

A pragmatic (and common) approach to sound intensity is to simply err on the generous side and produce overly loud stimuli. This however ensonifies more of the environment than is necessary and elevates the risk of animals (motivated to stay in the area for foraging or breeding) habituating to the stimulus. Two potential refinements that could improve on this simple approach would be to: firstly, make the signal itself directional so that inappropriate areas (particularly off to the sides) are not needlessly ensonified. And secondly, link the signal to a monitoring hydrophone so that the signal strength can be varied to keep it at an appropriate level above ambient noise. Should background noise be particularly high for some reason (storm conditions, passing ship, maintenance vessel operating on site etc.) then the signal can be emphasised and conversely in quiet circumstances it can be reduced.

Attribute 5: Signal must be directionally resolvable: Whether or not an animal can determine the direction of a stimulus impacts how it responds (Blaxter and Hoss 1981). This may or may not be important depending on the type of warning sound and desired outcome used. However, this feature should be considered particularly because of the critical need for animals to make directionally relevant responses to turbines or their arrays.

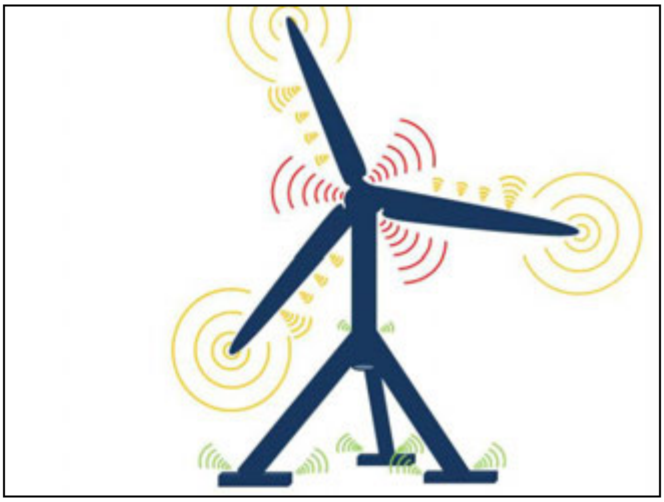


Figure 13. Fictitious diagram to illustrate how the acoustic signature of a turbine will originate from multiple sources and locations around a device. For example, the machinery's gearing and power conversion equipment (red), the rotors (yellow) and general flow noise around the device and substructure (green). Thus at close-range there will not be a single acoustic stimulus from a device and furthermore, the sound emanating may not clearly indicate the parts posing the greatest risk for an approaching animal.

Attribute 6: Warning should be co-ordinated with threat: Introducing artificial sound to the marine environment comes at the risk of introducing additional noise pollution. If the mammal-turbine collision issue turns out to be real, then collision risk is likely to scale to tidal flow because 1) water flow increases the closing speed for any animals approaching from upstream 2) manoeuvring options are constrained by the directional flow and 3) because the flow drives rotor motion at velocities greater than the water speed itself. Should warning sounds be used, then scaling them to the flow rate (as well as ambient noise, see above) may be appropriate particularly so that unnecessary or habituating sounds are not produced at inappropriate times such as slack water.

Attribute 7: Location of sound source must be suitable: The sphere of acoustic warning, by whatever means, can operate over a wide range of scales. At the closest range, a warning may simply prompt attention and provide more precise spatial information to an animal so that it could evade (i.e. dodge) a particular part of a single device as it passes. The flux of water and the various operations of a turbine will produce an assortment of acoustic outputs (Figure 13) with high spatial resolution. Acoustically sensitive animals with directional awareness have the potential to respond to this, though it is currently unclear whether at close-range they will perceive the entire structure of the turbine or simply parts of it. Furthermore it is unclear whether they will appropriately prioritise these stimuli to avoid the parts that pose the greatest risk (e.g. rotor tips more than the nacelle). Given the size of currently commercial scale turbines (12-20 m diameter) relative to marine mammals (0.3-4.4 m diameter) it may be possible to promote appropriate evasion by highlighting close range cues and accentuate the more dangerous parts, whether through local acoustic warning, visual stimuli (colour or lights) or other means (e.g. echolocation reflectors).

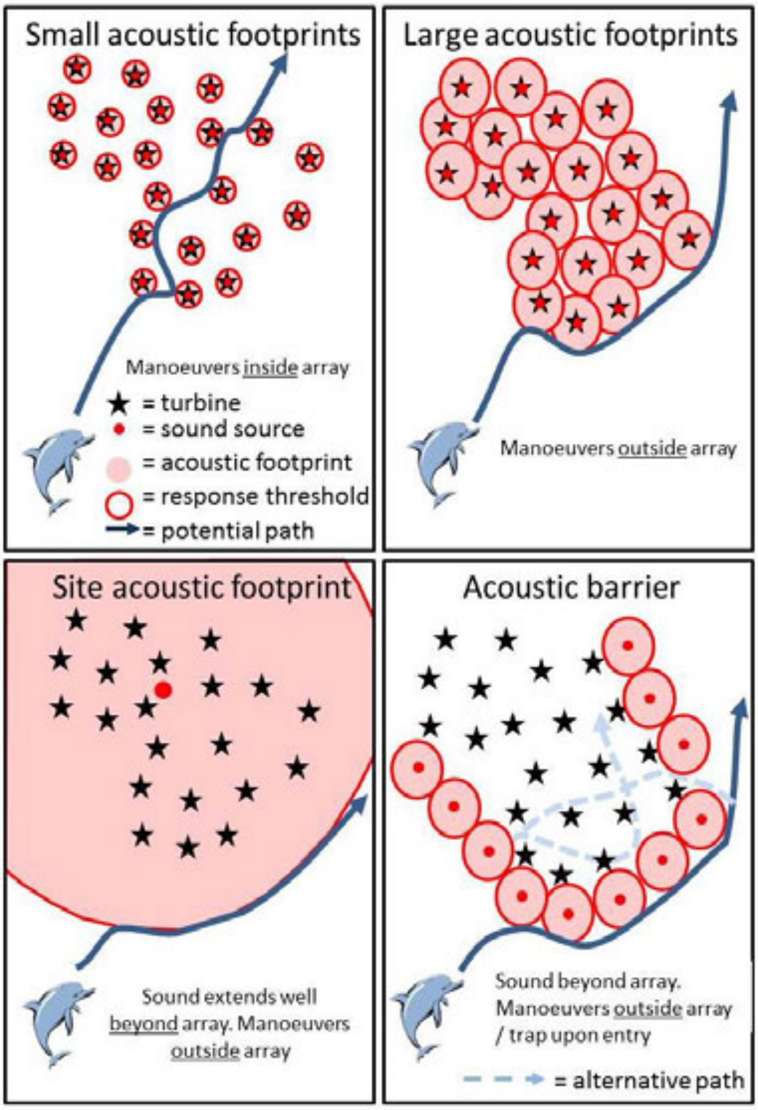


Figure 14. Spatial scenarios for turbine array acoustic warning (plan view). **Top left panel**: Acoustic footprint only extends to immediate vicinity of each turbine. Acoustically sensitive species navigate in response to individual turbines. Array entry and interaction with multiple turbines is likely. **Top right**: Acoustic footprints abut or overlap so approaching animals can perceive multiple turbines at once and have the opportunity to skirt an array without entering it. Fewer turbines are likely encountered. **Bottom left**: Warning sound created from inside the array and independent of individual turbines. Response threshold extends beyond

turbines. Animals can skirt array without nearing turbines but also excluded from additional habitat. **Bottom Right**: Warning sounds created independent of turbines at array perimeter. Animals can skirt array without approaching the turbines. However, if that perimeter is breached (pale blue) then the acoustic warning may encourage animals to stay within array.

At a larger scale - avoiding entire turbines - there is a wide-range of acoustic warning possibilities (Figure 14). These could range from a simple scale-up of the scenario discussed above to encourage avoidance of an entire turbine rather than specific parts of it. If this acoustic footprint only extends to immediate vicinity of each machine (Figure 14, top left) then acoustically sensitive species are likely to navigate in response to approach of individual turbines themselves.

With this scale of information, opportunities for animals to perceive an array are limited – akin to a person coming across a tree trunk in thick fog, there is no opportunity to know that that tree is part of a forest. For a marine mammal, therefore, array entry and interaction with multiple turbines is likely. However, if the acoustic footprints around turbines are larger and extend to either directly abut or overlap one another (Figure 14, top right), then there is potential for multiple devices to be perceived simultaneously and thus animals can both avoid individual devices and skirt around an array. Depending on the array shape, extent and the animal's approach angle, this will ultimately lead to fewer animal-device interactions.

An alternative to equipping each turbine would be to locate a single, longer range warning sound centrally within a development site, independent of the turbines so that its reach covers the area of concern (Figure 14, bottom left). Again, if responding to a threshold value of noise intensity, animals have the opportunity to skirt an array and directly interact with fewer (or no) actual turbines. One disadvantage of this over the turbine-based noise sources is that animals are less likely to ultimately associate the warning noise with turbines and also there is greater danger of areas of suitable habitat (not associated with an array) being ensonified. This is particularly important for sites in or spanning potential movement corridors such as straits or fjord/bay mouths.

Finally, given the likely literalised nature of tidal-stream sites and the parallels with fish movements in rivers, there is the possibility to construct something akin to an acoustic barrier outside of an array (Figure 14, bottom right). Again this would have the advantages of reducing the number of turbines responding animals would need to interact with to potentially zero but ensonify much less water than the whole-site scenario (bottom left). Externalising the noise source from an array, does however run the risk of responding animals being trapped within the site. However (and depending on array shape and animal behaviour), only the side facing upstream could be turned on to reduce this effect.

Summary

Given the current pace, diversity and magnitude of tidal turbine developments in Scotland, there is a place for forward thinking about our options to address a mammal-turbine collision problem should one prove to exist within the deploy and monitor strategy. Though there are currently no commercial sonic devices on the market specifically designed for this context, an existing Acoustic Harassment Device (Ace Aquatec MMD, Table 2) is already being marketed with this as a potential application. Furthermore, there are a wide variety of different devices developed, tested and applied for other applications with the intention of changing the behaviour of marine mammals and fish, particularly in aquaculture or fisheries contexts.

It is clear, however, from the current study that tidal-stream sites present specific differences to other marine habitats particularly in terms of the high (temporally and spatially) variable levels of background underwater noise that they experience. Off the shelf acoustic warning devices are therefore unlikely to function as they might elsewhere. If acoustic warning is deemed to be an appropriate mitigation tactic worth exploring, there are many options available for tuning existing sonic equipment or designing something from scratch. These options range from simply providing animals with a heads-up warning that they are approaching an obstacle, to providing enough information to allow them to successfully manoeuvre around the operating structure, to encouraging them to avoid the footprint of a device or even an entire array. Within this diversity of options, this report outlines seven key attributes that should be considered as requirements in the design envelopes of any warning device(s).

As this topic moves forward, and as with fisheries and aquaculture related acoustic device application, it is likely that several companies will progress ideas in parallel. Inevitably they are likely to pick different combinations of sound characteristics for their products. However, if we want marine mammals to also learn from any near-miss experiences, then some level of stimulus standardisation is required. Administrative organisations with appropriate oversight will need to take this lead.

Ultimately, and in the face of a potentially attractive mitigation option, it must not be forgotten that any active acoustic warning also represents a new source of sound pollution that is specifically intended to alter the behaviour of marine mammals. Given that we do not yet know whether there is actually a real (rather than perceived) mammal-turbine collision problem, we should consider carefully whether or not it is appropriate to deliberately add extra-noise to the sea simply as a precautionary measure. Nevertheless, while further information on the collision issue is likely to emerge as turbines are deployed over the next few years, the acoustic warning option should continue to be explored as it would be immediately needed if a problem becomes apparent.

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