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Tests of acoustic signals for aversive sound mitigation with harbour seals

Sea Mammal Research Unit
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Contents

1 Executive Summary

Some anthropogenic activities that produce intense sound in the marine environment present a risk of causing injury to the body tissues and auditory systems of sensitive marine life. It is an offence to kill or injure a seal under the Marine (Scotland) Act 2010 and in addition both grey and harbour seals are on Annex II of the Habitats Directive and are qualifying features for Special Areas of Conservation set up to promote their conservation. For these reasons, mitigation measures to minimise the risk of causing damage or injury are often a requirement when licences are issued to carry out risky activities in the marine environment. The traditional approach to mitigation is for observers to search for marine mammals (including seals) using visual and acoustic techniques, within a mitigation zone and to delay or halt risky activities if animals are detected. (A mitigation zone should be defined as an area within which animals are at an elevated risk of suffering damage. Joint Nature Conservation Committee (JNCC) guidance suggests that mitigation zones around piling should have a radius of at least 500m.) Such monitoring mitigation is unlikely to be fully effective when animals are difficult to sight at the surface and are rarely vocal, when mitigation ranges are large and when operations are required to continue in poor sighting conditions and at night. Mitigation monitoring can also be very costly to achieve at offshore sites. Aversive sound mitigation is a promising alternative or complimentary approach which would involve moving vulnerable animals out of the mitigation zone before activities such as pile driving commence, using appropriate aversive acoustic signals. In this project data was collected to assess how effectively aversive sound mitigation could be applied to harbour seals by conducting a series of controlled exposure experiments (CEEs).

Three sound sources (a Lofitech ADD, an Airmar ADD and broadcast killer whale calls) were assessed as potential sound sources for aversive sound mitigation. The findings suggest that, of the devices tested, the Lofitech ADD is the most effective at eliciting behavioural responses from harbour seals which should be useful for mitigation.

Our results show that out to a range of around a kilometre, all seals might be expected to show a readily identifiable change in behaviour. However, not all responses resulted in straight forward movement away from the sound source. Response also varied between CEEs in ways which may reflect the particular circumstances of the experiment as well as the motivation and status of the subjects.

Three observations from this work are particularly pertinent to those planning to use aversive sound mitigation. The first is the propensity for seals which are close to shore at the start of a CEE to move very close inshore and then move along shore in very shallow waters. This may well be a general and effective anti-predator response but the extent to which it would protect animals from exposure to intense sound needs further investigation. The second is the observation that animals that were traveling when faced with a CEE ahead of them would rarely reverse their tracks. More commonly they would “swerve” around the sound source, passing closer to it than the range at which avoidance behaviour was first noted and on occasion passing within a few hundred metres of it. Clearly, if this occurred during a mitigation exercise then animals might experience higher sound exposure. Studies should be carried out to investigate how animals respond to multiple sound sources in the field which could inform how they should be spaced to achieve effective mitigation. A final important observation is that animals apparently foraging within an area would often start to return to that area soon after a CEE. An implication of this for aversive sound mitigation is that the potentially damaging activity should start immediately after (or during) the mitigation broadcast.

It will be extremely difficult to measure behavioural response of seals to pile driving because any individual tagged animals would be unlikely to be close to pile driving when it started and it is not feasible to use or replicate pile driving as an experimental sound source. However, the observations made during this study of animals responding to what were clearly aversive signals may provide insights into how seals might react to pile driving. Although seals showed an increase in speed during CEEs this was only modest. This limited response probably reflects energetic constraints on maximum sustainable swim speed which would also limit their escape speed from pile driving. The mean “escape” swim speeds observed during CEEs were lower than those assumed in some exposure models and, in contrast to the assumptions in most models, seals did not always swim directly away from the sound source. These considerations emphasise the desirability of moving animals to a “safe range” using a mitigation sound source whose characteristics can be controlled and measured beforehand using field CEEs.

2 Introduction

Some anthropogenic activities in the marine environment carry with them the risk of causing damage to body tissues and to the auditory systems of sensitive marine animals. Marine mammals, which have especially sensitive hearing, are believed to be particularly vulnerable. Activities that raise these concerns in Scottish waters include seismic surveys, the use of explosives (which is diminishing as alternative underwater cutting technologies are developed) and pile driving (which is likely to increase dramatically as major wind farms are consented and developed). Clearly, it is important that no sensitive animals should be within a range at which they could be damaged when these activities take place. It is an offence to kill or injure a seal under the Marine (Scotland) Act 2010 and in addition both grey and harbour seals are on Annex II of the Habitats Directive and are qualifying features for many Special Areas of Conservation set up to promote their conservation. All cetaceans are European protected species and are thus protected from disturbance and injury. Currently it is usual for regulators to require mitigation monitoring of impact sites before pile driving commences. However, such monitoring is both very expensive to provide at offshore sites and also rather unlikely to be effective in substantially reducing risk (Gordon *et al.*, 2007). An alternative approach , which might be more pragmatic, cost effective and also ultimately more efficient, is to move animals out of a mitigation zone before pile driving commences using appropriate acoustics signals. This concept was reviewed in a report for COWRIE in 2007 (Gordon *et al*., 2007) and concluded that there were good reasons for believing that this approach could be successful but that extensive testing to show that animals responded to putative mitigation signals in an appropriate manner would be necessary if regulators were to rely on them to provide appropriate levels of protection. Since then, the German consultancy company Bioconsult have carried out an extensive series of efficacy trials for one particular device, an acoustic deterrent device made by Lofitech. The results for moving porpoises out of both inshore and offshore marine areas were encouraging (Brandt *et al*., 2012; 2013).

In this project, data was collected to assess how effectively aversive sound mitigation could be used for harbour seals by conducting a series of controlled exposure experiments (CEEs) to wild seals in representative field conditions.

3 Methods and field work

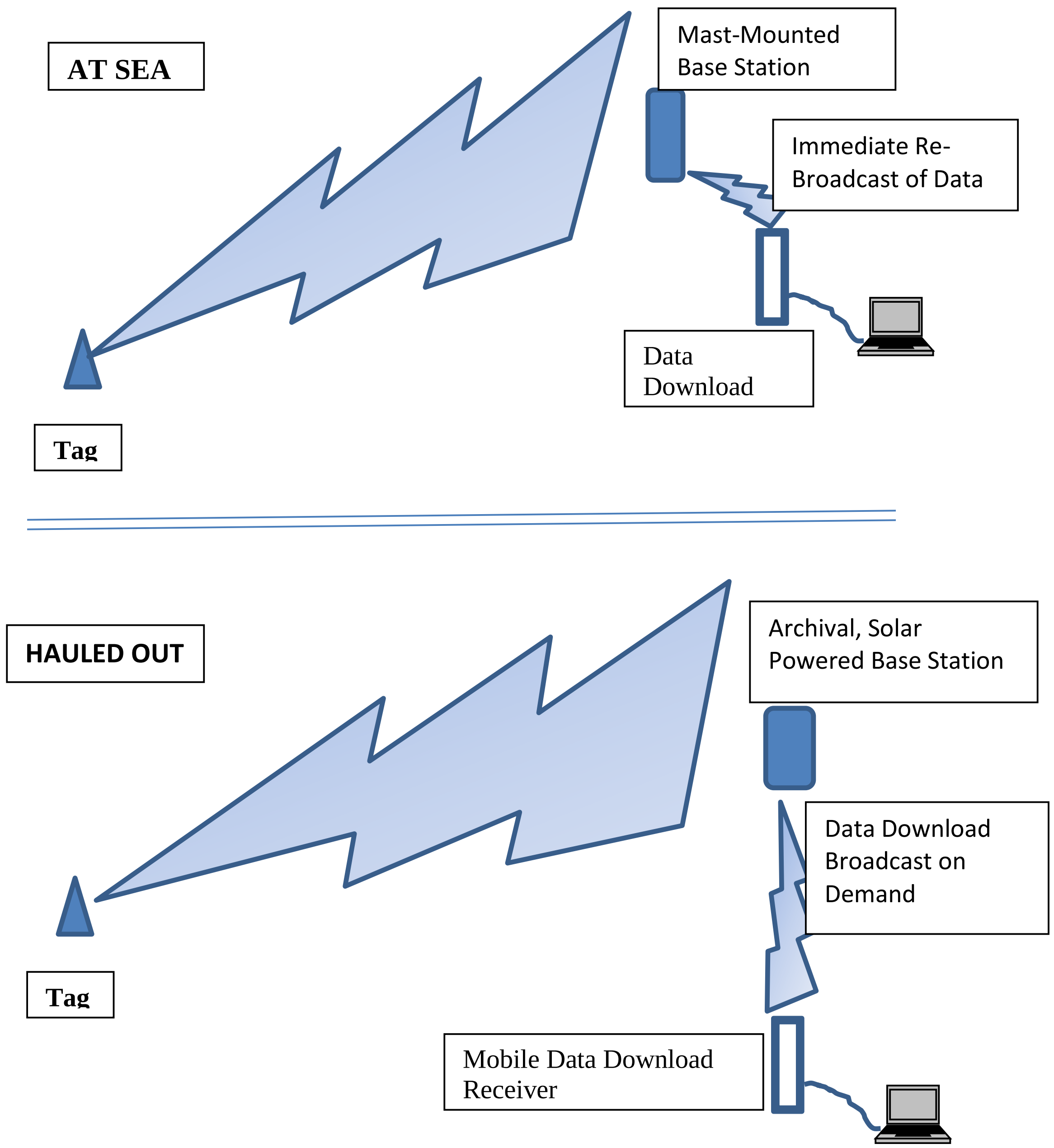
3.1 Telemetry system

Seals are difficult animals to observe at sea and are also effectively silent so an effective way of collecting data on seal responses was to use a telemetry system providing real time localisation information to a playback vessel at sea. No suitable telemetry system was available commercially and an attempt in 2012 to adapt Argos tags to allow this was not successful. Thus a collaboration with Pathtrack™ was set up to develop a new system specifically for this application.

A telemetry system that combined the capacity to provide near real-time at-sea positioning of animals with data storage and periodic transmission to archival base stations on shore, was developed for SMRU by Pathtrack™. Animal-borne tags captured GPS data which is processed by the tag using the Fastloc™ algorithm. UHF telemetry (in the 869.4-869.65MHz frequency band) was then used to broadcast these Fastloc™ data at the first opportunity when animals were at sea. These data were also stored in the tags so that they could be downloaded by UHF to fixed base stations once animals had hauled out ashore and were within range of a station for a pre-determined period (Figure 1).

When an animal surfaced at sea the tag first captured a "snapshot" of GPS data and then immediately broadcast the previously collected good GPS Fastloc™ information from memory using UHF. This broadcast information, which usually related to the location for the previous surfacing, was thus available to be received in real-time on the tracking vessel. A computer on the vessel was running software to immediately decode the GPS data using the Fastloc™ algorithm to provide an accurate location. The pre-processing of the GPS data on the tag before it could be broadcast typically took around 20 seconds. Therefore, unless the seal remained at the surface for a period greater than this, the location that was broadcast was that of the seal's previous surfacing. The semi-processed GPS data were also stored on the tag to be downloaded to base stations at a later date.

On the tracking vessel, transmissions from tags were received via a cluster of four directional UHF base stations set at 90 degrees to each other. These base stations re-broadcast information as soon as it was received and a UHF data receiver connected to a laptop computer at the instrument station on the tracking vessel captured this information from the directional base station array. This system allowed location information to be determined in two ways. Good quality signals could be decoded by a Fastloc™ decoding program running on a laptop in real time to provide an accurate GPS location. If signals were detectable but too weak to be decoded, a comparison of the signal strengths from the four directional base stations could be made to provide an indication of the approximate direction to the animal. This allowed the tracking vessel to move in an appropriate direction to close with the animal and eventually receive a stronger signal.



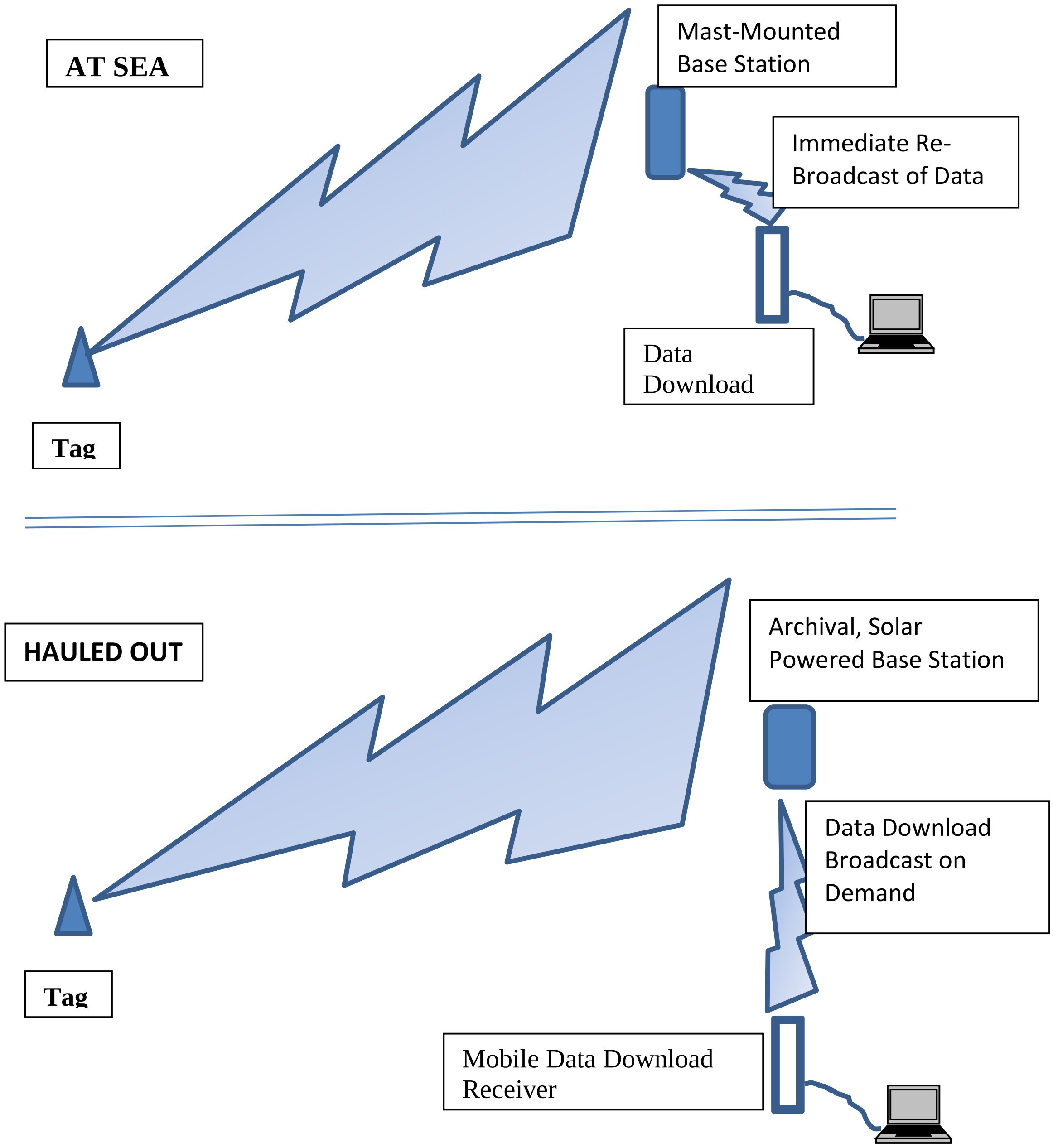


Figure 1. Schematic of telemetry system showing at sea and shore based data download options

Decoding the partially processed Fastloc™ data received from the tag in real time on the boat required up to date ephemeris parameters for the GPS satellites (i.e. providing the positions of the relevant satellites at the appropriate times). These were recorded from a U-Blox LEA 6T GPS receiver and retained on the laptop until required.

Tests of the system in good weather conditions suggested that with the direction finding aerials mounted at ~6m, signals could be reliably decoded at ranges of up to 16 km.

Maps of up to date information on seal locations helped the field team to follow individual seals and to manoeuvre the vessel into appropriate locations before initiating controlled exposure experiments (CEE) with tracked animals. GPS locations that had been calculated using Fastloc™, together with the vessel's current position, were viewed in near real time using Google Earth. As there was no access to the internet, static datasets (maps) covering the study site were preloaded and cached on the laptop. KML network links were then set up to regularly trigger a copy of Google Earth to poll a webserver running on the same machine. A specially written Zend Framework PHP application, christened "LiveLocs", was deployed on that server. Whenever LiveLocs received an appropriate request it would convert the most recent seal and vessel locations into a new set of dynamic KML "files", which were then streamed back to Google Earth, which could then update its 3D display to show the latest data.

Data stored on the tags were collected by data archiving base stations which had been placed at vantage points overlooking haul out sites likely to be visited by these animals. The base stations were fully autonomous, being powered by internal batteries charged by solar panels. When seals hauled out within range (line of sight) of a base station, stored data were transferred from the tags. When the base station signalled that data had been successful transferred, the data pointer in the tag would be advanced to a new section of memory; data were never deleted from the tags. Data were downloaded from the base stations periodically either by connecting them to a laptop using a USB cable or by wireless transfer through a hand held mobile wireless receiver. The tracking vessel could also interrogate the shore mounted base stations for recent data on seal locations if required without removing these data from the base station's memory.

The combination of two-way communications between the tags and the base stations and multiple methods for retrieving data from base stations and tags resulted in a system that was flexible and adaptable. Two way communications also allowed memory to be reallocated once data had been successfully archived in base stations and for tags on seals to be reprogrammed if necessary. Furthermore, data could be retrieved from base stations through a number of different devices and the stations could be readily moved to new locations if seals changed their haulout patterns.

The full datasets eventually recovered from the base station archives was more complete than those collected on the tracking vessel. This was because only a subset of seals were ever within range of the tracking vessel at any one time and even for these animals, data might be lost because the UHF transmission was not received clearly or because transmissions from other seals overlapped and interfered with it.

A complete and coordinated database of all the telemetry data was assembled once all the tags had detached during the seals' annual moult.

3.2 Tagging

Ten harbour seals (*Phoca vitulina*) were captured at haul-out sites in 2013 and 13 in 2014. Once captured the seals were anesthetised with Zoletil™ or Ketaset™. The tags were attached to the fur at the back of the neck using Loctite™ 422 Instant Adhesive. A series of morphometric measurements and biological samples were also taken at the time of capture (Table 1).

Table 1. Summary parameters for seals tagged in this project

2013 Kyle Rhea

UHF tag number	Tagging Date	Sex	Mass (kg)	Length (cm)	Girth (cm)	Flipper tag no.
65	17/05/2013	F	78.4	141	107	73320
55	17/05/2013	F	76.2	140	102	00473
54	17/05/2013	F	82.6	138	102	00474
59	19/05/2013	M	80.2	143	112	00475
56	19/05/2013	M	81.6	154	106	00476
62	21/05/2013	M	68.2	143	99	00492
64	21/05/2013	F	76		93	00480
63	21/05/2013	M	87.2	160	106	00478
57	21/05/2013	M	89.4	151	112	00491
61	21/05/2013	F	86.4	140	108	00494

2014 Moray Firth

UHF tag number	Tagging date	Sex	Mass (kg)	Length (cm)	Girth (cm)	Flipper tag no.
180	18/05/2014	M	77.8	144	104	00503
184	18/05/2014	M	81.8	148	103	00504
183	20/05/2014	M	29.4	99	81	00506
185	20/05/2014	M	88.8	151	109	00507
181	22/05/2014	M	83.6	143	109	00508
186	22/05/2014	F	90.2	145	106	00509
187	22/05/2014	M	60.6	133	98	00511
170	22/05/2014	M	74.8	149	103	00512
189	22/05/2014	M	56	134	89	00513
196	26/05/2014	F	74.2	134	100	00514
194	26/05/2014	M	90.6	134	107	00515
198	26/05/2014	F	82	135	100	00516
190	26/05/2014	M	51.8	123	91	00517

3.3 Controlled exposure field experiments

3.3.1 Research vessel

The research vessels used for the CEE trials were motor sailing vessels chartered commercially and run by the research team. The vessel in 2013 was a 44 foot long motor sailing vessel (Jeanneau Sun Odyssey 439), while in 2014 the vessel was a slightly larger 49' Jeanneau Trinidad. The necessary UHF tracking and acoustic monitoring equipment were temporarily fitted to the vessel and temporary science stations were established in the saloon. There were a number of advantages to using vessels of this type. They were large enough to carry the full complement of personnel required to carry out the CEE trails which allowed flexible and effective round the clock operation but were sufficiently simple to be run by the (suitably qualified) research team members. They were also quiet (especially under sail) and manoeuvrable making them ideal for playback. Finally, they proved highly cost effective.

The research vessels were available on site between 18th June and 29th of June in 2013 and the 1st and 25th of June in 2014.

3.3.2 Sound sources

Three sound sources were employed.

1. **A commercial ADD device, the Lofitech Seal Scarer** (http://www.lofitech.no/en/seal-scarer.html). It was decided to use this model as a sound source because the German consultancy, Bioconsult, had already tested the efficacy of this device for pile driving mitigation with harbour porpoises, and obtained encouraging results (Brandt *et al*., 2012; 2013). Clearly it will be beneficial to be able to use a single device that has been shown to be effective with several different species. This is one of the most powerful ADDs commercially available producing 14.5kHz acoustic blasts lasting 550 msec. on an irregular schedule with intervals between pulses ranging from 0.6sec to 90 and a duty cycle of 0.12. Measurements of a Lofitech made in the North Sea by (Brandt *et al.*, 2012; 2013) at a series of ranges from 100- 4000m best fitted a model with a 197dB (RMS) source level a propagation loss of -20log(Range) + 1 dB per km and the field measurements within this study are somewhat similar (see Section Sound Levels). The Lofitech was powered by a 12v leisure battery. The unit's transducer comes on 15m of cable and it could be easily deployed over the side of the drifting vessel for broadcasts. A unit was made available to the project on loan by Lofitech AS, Leknes, Norway.

2. **A second commercial ADD device, an Airmar DB plus II** was also available for the final week of the field season in 2014 on loan from the UK distributor, Mohn Aqua UK, Forres, UK, (http://www.mohnaqua.com/Aquaculture-Sea/Aimar-Predator-Deterrents/Airmar-DB-Plus-II-Acoustic-Deterrent.aspx). The Airmar produces a 2.25 sec "blast" consisting of 57-58 short (1.4ms) tonal pulses, each separated by 40msec. Blasts occur at regular intervals, with a quiet period approximately every 2 seconds (Lepper *et al*., 2004). Lepper *et al*. *loc. cit.* measured a source level of 192 dB re 1µPa @ 1m for an Airmar dBII. The unit used in this study was a 24v version (Lepper *et al.*'s unit is believed to have been powered at 12v). In-house calibration trials indicated a slightly higher source level.

3. **The third sound source was an underwater speaker (Lubell, LL91262T) broadcasting killer whale vocalizations**. The speaker manufacturer's specifications claim a frequency range of 250Hz-20kHz for this unit. The speaker was driven by a 1000w 12v power amplifier (Sony XM2200GTX). Signals were played from a Tascam DR40 solid state recorder. The signals that were broadcast were based on sequences of calls kindly provided by Dr Volker Deker. These were recorded from a group of 15 members so of the seal hunting community off Shetland. These sequences were mixed digitally and repeated to provide a playback sequence with a high call density lasting for 15 minutes. The field measurements indicated that source levels for the loudest calls range between 176 and 187db re 1µPa RMS. However, such loud calls were only intermittently present in the recording.

3.4 Mitigation

The areas in which CEEs were carried out in 2013 (Sound of Sleat and Kyle Rhea) are known to be areas where harbour porpoise (*Phocoena phocoena*) are commonly encountered (Embling *et al*., 2009; Booth *et al*., 2013), while the Moray Firth has a resident bottlenose dolphin (*Tursiops truncatus*) population as well as relatively high densities of harbour porpoises. To minimise the risk of disturbing these animals at short range, mitigation procedures were carried out before activating either of the sound sources. Between 2 and 4 observers searched for marine mammals from the deck of the research vessel before CEEs while another dedicated operator monitored a towed hydrophone system (provided by Vanishing Point Marine) using a computer running the PAMGUARD porpoise detection and localisation modules and spectrograms in real time. A CEE was only initiated if there had been 15 minutes of monitoring without any detections or if the boat had moved at least 500m from the last porpoise detection. In addition, in the Moray Firth, no CEEs were conducted if any dolphin watching vessels could be sighted and no CEEs were carried out within 3km of two well-known dolphin hot spots, the Souters and the Chanonry Narrows or within the upper Moray Firth.

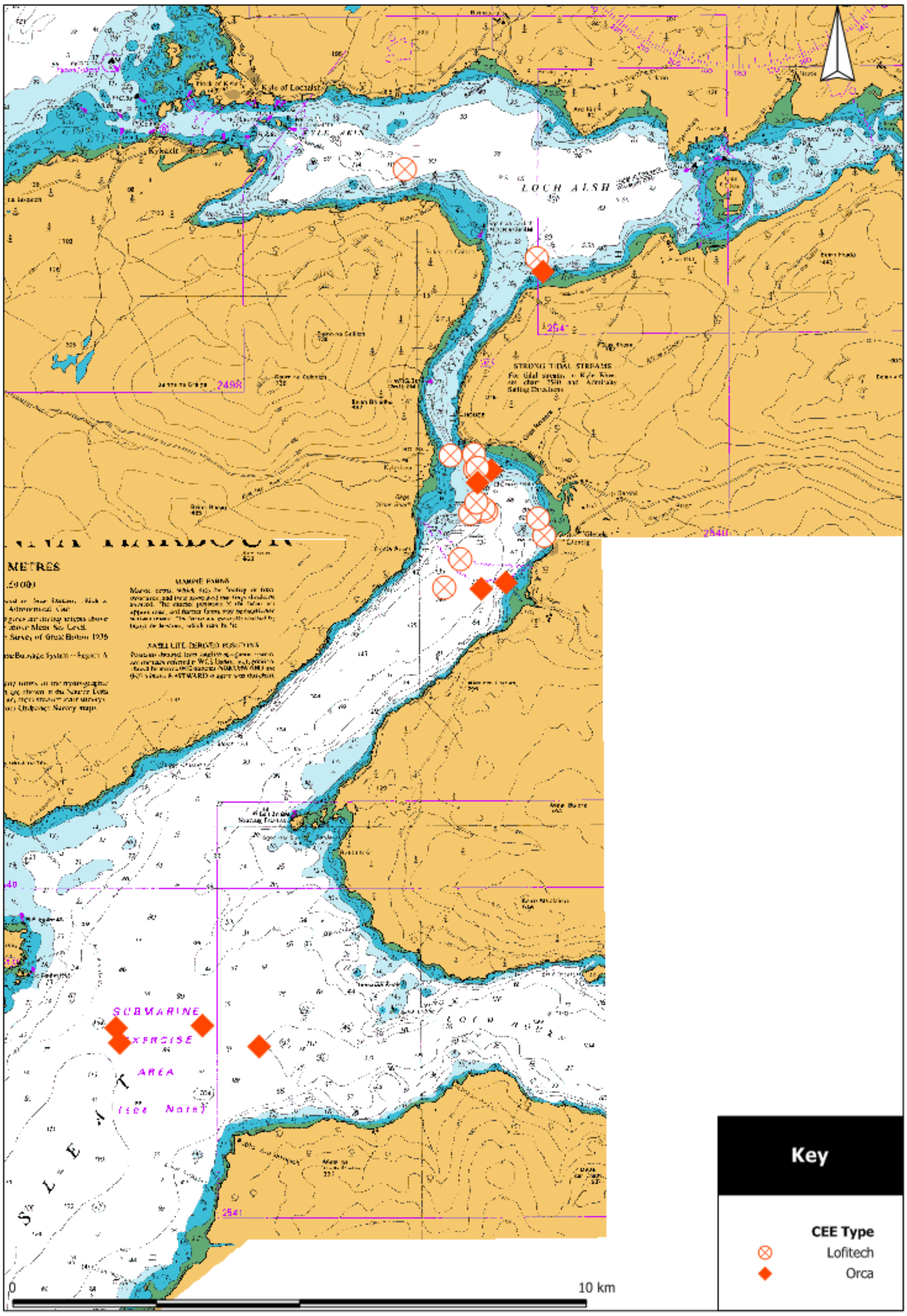


Figure 2. Kyle Rhea study area in 2013 and the location of all attempted CEEs.

3.5 Field sites

Field work was carried out in the Kyle Rhea and Upper Sound of Sleat in 2013 and in the Moray Firth in 2014. Figure 2 and Figure 3 show the study sites and the locations of CEEs carried out there. The field sites were chosen primarily because they were locations at which significant numbers of seals had been tagged for two other projects: for the NERC funded RESPONSE project in Kyle Rhea and for the SNH and Marine

Scotland funded Ardersier harbour seal project in the Moray Firth. The current project was able to make use of these tagged animals.

Kyle Rhea is a narrow channel between Skye and mainland Scotland which links the Kyle of Lochalsh to the north and the Sound of Sleat to the south. The channel is characterised by very high tidal currents (as high as 8 knots). In the summer months high densities of seals are found within Kyle Rhea, which seems to be a favourable foraging area for them (Thompson, 2013). Seals spent the majority of their time within Kyle Rhea itself, either hauled out or active and apparently foraging, in the water. They showed a marked tidal cycle, being most active, especially at the southern end of Kyle Rhea, during the flood tide and hauling out or resting during the ebb tide (Figure 4).

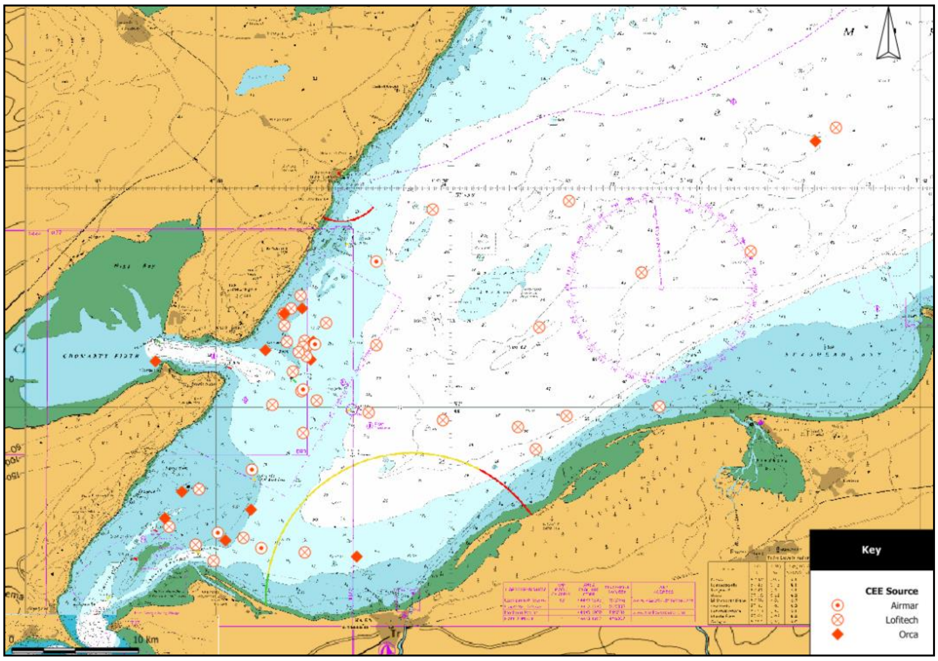


Figure 3. Moray Firth study area in 2014 and the location of all attempted CEEs.

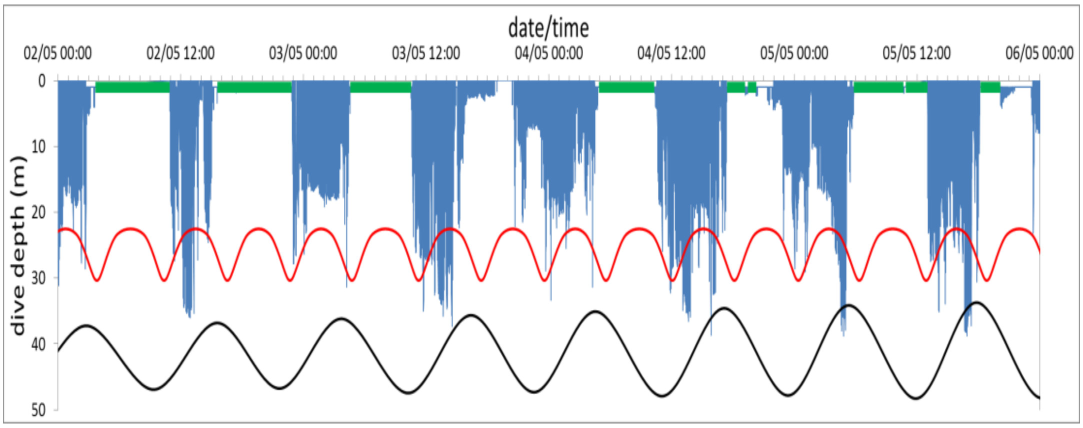


Figure 4. An example of dive profiles for an adult male harbour seal swimming in the tidal rapids at Kyle Rhea. Blue lines represent time depth profiles, green bars along the top axis represent haulout periods, black sine waves are an index of tide height and red lines are an approximate index of flow speed.

Attempts were not made to carry out CEEs within Kyle Rhea itself for several reasons. In the first place, it was clearly a highly preferred foraging location for a large number of harbour and grey seals at this time of the year and it was desirable to avoid disrupting their use of this important habitat. In addition, this highly spatially constrained location is very unlike the areas in which pile driving mitigation would be likely to be required, thus, any results obtained here might not be transferable. The strong currents in Kyle Rhea also posed practical difficulties for setting up CEEs and finally, playbacks within Kyle Rhea would have been likely to compromise another research project (the NERC RESPONSE Project) which was using the same seals to investigate responses to underwater playbacks of tidal turbine noise.

Most playbacks were carried out to the south of Kyle Rhea in the Upper Sound of Sleat when animals made brief excursions out of the narrows. The limited availability of seals and the relatively confined topography made this a less than ideal study location. There was also concern that this location was topographically dissimilar to the sites at which wind farms will be constructed.

The Moray Firth is a larger and more open body of water on Scotland's East Coast. The typical pattern of behaviour for seals in the Moray Firth was to move between haulout sites (Findhorn, Culbin Forest, Ardersier, Loch Fleet and the Dornoch Firth) and a series of preferred offshore areas which are believed to be foraging sites. The more open topography provided a greater scope for conducting CEEs in conditions that should be more representative of conditions at offshore wind farm constructions.

3.6 CEE playback protocols

The aim of the CEEs in this project was to assess the effectiveness of aversive sound mitigation. Thus the most relevant behavioural response to assess were movements and the aim was to measure the ranges to which animals could be induced to respond and move away from each sound source in a variety of scenarios and behavioural states. The sound source was always deployed from the tracking vessel.

To conduct a CEE, attempts were made to position the vessel at an appropriate range from the test animals (typically between 500 and 1500m) as quietly as possible to minimise the risk of disturbance. If possible, the vessel was manoeuvred at low speed or, when safe and practicable, under sail. Near-real time telemetry tracking software running on the research vessel allowed this sort of responsive boat positioning. The animal's behavioural state influenced how CEEs were initiated. When animals were moving in a non-directed manner (assumed to be foraging) the attempt was made simply to position the boat as quietly as possible at the desired location. If, as was often the case, several animals were being tracked at the same time, the vessel was positioned to try have useful CEEs carried out on more than one animal with a single set of transmissions. When animals were moving in a directed manner, typically when travelling between haul-out sites and foraging sites, a "cut off" CEE would be attempted. For these attempts were made to position the boat directly ahead of the seal at a range of 2 km or more and then wait for the animal to move within range.

The sound source would not be activated if there was any indication in the animal's track that it was aware of the vessel and was responding to it. CEEs were not initiated if alternative potential sources of disturbance, such as shipping, were detected in the area. CEEs were only initiated once the cetacean mitigation protocols had been successfully completed.

Once the vessel was correctly positioned the sound source was lowered to a depth of 5m. The source was usually activated on a whole minute after a seal had dived. This represented a good compromise between starting the CEE source soon after a surface location had been obtained so that range was known accurately and providing a degree of variation in the exact time in the dive when transmissions commenced.

In each CEE the sound sources remained active for exactly 15 minutes. The towed hydrophone system used for acoustic mitigation was monitored and recorded continuously during CEEs both for mitigation and to ensure that the sound source was operating correctly.

The boat would remain hove to and drifting during the CEE and for at least 15 minutes after the source was turned off.

3.7 Field monitoring of sound source outputs

The towed hydrophone system used for acoustic mitigation was monitored during CEEs to check that the sound source was operating correctly. In addition a custom-built self-contained recording buoy was used to record sound levels at greater ranges during CEEs and provide indications of propagation loss and the likely exposure levels for the target animals. The recording buoy consisted of two HiTech HTI 96 Min hydrophones whose output was recorded on a Tascam 40D solid state recorder with sampling rate of 96kHz. The recorder and a Royal Tec RGM3800 GPS logger were mounted in a 2m ABS plastic spar buoy which was deployed shortly before initiating CEEs and allowed to drift freely until the CEE had been completed and the buoy could be recovered. The range between the buoy and the vessel and sound source were calculated comparing time-referenced GPS locations collected on the vessel and at the buoy.

The sensitivity of the recorder was measured using a signal generator and oscilloscope. Measures of RMS power and peak-peak levels were made from individual Lofitech pulses and from the loudest calls within the killer whale signal using Raven interactive sound analysis software (Cornell, Bioacoustics Program).

3.8 Analysis of telemetry tracks

3.8.1 Software

For analysis ashore the telemetry data and vessel tracks were animated at a fine temporal scale using a second custom built web application. As was the case with the on vessel tracking software, seal telemetry locations, vessel tracks and other associated KML datasets were accessed through a webserver running on the local machine. However, in this case a browser rather than Google Earth was used. This meant that JavaScript could be used to write an interface which offered full VCR-like controls over the animation of the datasets loaded into an instance of the Google Earth Browser Plugin embedded in the main webpage.

Most of the HTML, PHP and JavaScript in these web applications was either adapted from existing code or specially written for this project by Clint Blight at SMRU. The intention is to further develop the functionality and extend the documentation of this system as required. Potentially it could eventually form the basis of a more integrated suite of open source tools for use in other studies using near real time tracking in remote locations and/or requiring very fine temporal and spatial scale control over the visualization of similar datasets.

3.8.2 Analysis

Several simple categories of behaviour could be readily identified by observing animations of telemetry tracks including:

Travelling (TR) - directed movement over several minutes in a consistent direction.

Area restricted movement (AR) - Animals showing a lack of consistent heading resulting in seals remaining in the same location. In many cases these seals may have been foraging.

Avoidance (Av) - change in course away from the sound source. In the most dramatic cases animals might alter courses by 180^{o} and reverse their swimming direction. More subtle responses included temporary diversions with animals then continuing on course.

Inshore movement (IN) **-** animals already close to the shore might move in very close to the shore then often moving along the shoreline in shallow water

Transition between these categories during CEEs was one indication of response.

Efforts to assess and measure a "tolerance range" were undertaken where possible. This was an indication in the track of the closest distance that an animal was willing to come to the active sound source (which might be less than the range at which a response was first shown). Thus, during a "cut off" CEE it was common for the target animal to "swerve" around the sound source before apparently continuing towards its initial goal. The tolerance range would then be the shortest distance between a known location and the boat and sound source at that time. For subjects showing "area-restricted" movements there were cases where individuals initially moved directly away from the source but then, in the course of a playback, started to curve around on a track that would eventually bring them back towards their initial "foraging" location. In such a case the range at which the animals track started to curve around was taken as a tolerance range.

Inevitably, there were limitations on the ability of the experimenters to control events in the field, and this affected the ability to execute planned experimental scenarios. In this study the situation was made more complicated by the fact that the location data available in the field, in nearly real time, was almost always the animal's position for the previous dive and thus several minutes out of date. An additional complication in 2013 was that the seals and the boat were both moving in strong but often different tidal streams. Consequently, the configuration of research vessel and subjects at the start of CEEs was often not ideal.

A preliminary analysis step therefore, was to provide a quality score for each individual CEE (i.e. for each seal in each CEE). This was used to assess whether the trial was "adequate" to inform an assessment of obvious behavioural responses and/or of changes in movement parameters. For example, if a seal was already close inshore or hauled out there was limited scope for it to show additional disturbance response. If an animal was already swimming away from the research vessel then it could not show a change in heading, but changes in swim speed and dive duration could be measured. Whether or not a CEE elicited an observable response should not influence this assessment of "adequacy". Two observers independently viewed the track data and scored "adequacy" for each seal in each CEE on a scale of 1 to 5. CEEs with a score of less than 2 were not considered adequate and were excluded from analysis.

For the analysis, telemetry and vessel track records before, during and after CEEs were carefully observed using the animation program by each of the authors independently. Ranges were measured using the program's cursor tools, assessments of quality were made and animal responses, if any, scored and recorded. Screen shots were captured at the start of playback to show the animal's movements and behaviours beforehand, at the time the playback stopped (to show response over the 15 minute period of sound exposure) and for at least 15 minutes after the end of playback (to show animals' subsequent behaviour).

After independent assessments had been made of CEEs, joint reviews of any instances where the assessment and interpretations differed and, in these cases, an agreed scoring and interpretation process put in place. Ninety-five percent of the independently made behavioural assessments were in agreement.

Parameters were calculated summarising the "steps" between surface locations for all animals that were potential targets for CEEs. For seals at sea, these "steps" would normally represent dives. Parameters extracted were dive duration, distance between the two surfacing points and mean speed between these locations, and mean current corrected speed (2014 data only) and a measure of path directivity (Figure 5).

Steps for seals considered possible targets for CEEs (Table 2) were allocated to four classes

Before - steps with a mid-time within 30 minutes of the start of a CEE.

Start - step during which the CEE actually started,

During - steps, whose start time was within the CEE, and

After - steps, whose mid time was within 30 mins of the end of a CEE.

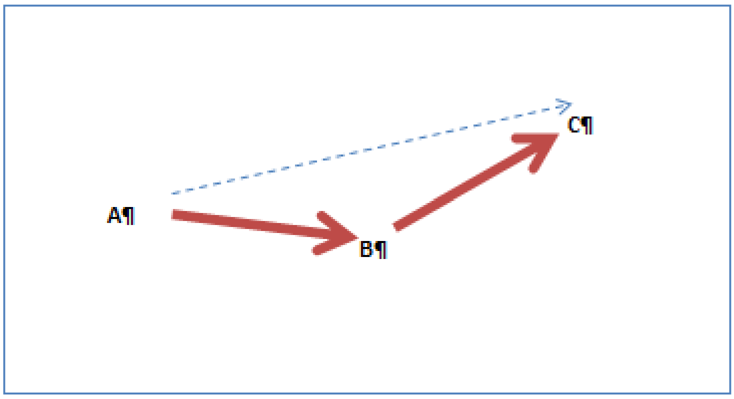


Figure 5. Simple directionality index. For step AB index is (Length AB + Length BC)/ Length AC

4 Results

Table 2 summarises all the CEEs of at least “adequate” quality completed in 2013 and 2014. In total 113 CEEs that were considered adequate were carried out. Of these 73 were with the Lofitech, 11 with the Airmar and 28 with Orca signals.

Table 2. Summary of CEEs of at least “adequate” quality carried out with harbour seals in 2013 and 2014.

CEE	Seal	Start date and time	End time	Latitude	Longitude	Sound source	Range (m)
101	59	19/06/2013 19:43	19:59	57.2222	-5.6468	Orca	369
103	54	22/06/2013 07:52	08:07	57.2223	-5.6516	Lofitech	909
103	64	22/06/2013 07:52	08:07	57.2223	-5.6516	Lofitech	589
104	63	22/06/2013 09:34	09:49	57.2247	-5.6517	Lofitech	218
104	55	22/06/2013 09:34	09:49	57.2247	-5.6517	Lofitech	1022
105	55	22/06/2013 10:12	10:27	57.2225	-5.6511	Lofitech	356
106	55	22/06/2013 11:43	11:58	57.2035	-5.6620	Lofitech	629
107	54	22/06/2013 19:39	19:54	57.2157	-5.6486	Lofitech	524
107	61	22/06/2013 19:39	19:54	57.2157	-5.6486	Lofitech	472
108	65	22/06/2013 21:38	21:53	57.2083	-5.6563	Lofitech	132
108	54	22/06/2013 21:38	21:53	57.2083	-5.6563	Lofitech	520
108	63	22/06/2013 21:38	21:53	57.2083	-5.6563	Lofitech	1376
108	56	22/06/2013 21:38	21:53	57.2083	-5.6563	Lofitech	1717
109	56	25/06/2013 11:33	11:48	57.2154	-5.6486	Lofitech	401
109	59	25/06/2013 11:33	11:48	57.2154	-5.6486	Lofitech	1047
111	59	25/06/2013 12:38	12:53	57.2171	-5.6510	Lofitech	513
111	63	25/06/2013 12:38	12:53	57.2171	-5.6510	Lofitech	439
114	65	26/06/2013 22:36	22:51	57.2116	-5.6317	Orca	304
114	63	26/06/2013 22:36	22:51	57.2116	-5.6317	Orca	1496
114	61	26/06/2013 22:36	22:51	57.2116	-5.6317	Orca	1474
115	65	26/06/2013 23:04	23:19	57.2118	-5.6317	Lofitech	676
115	63	26/06/2013 23:04	23:19	57.2118	-5.6317	Lofitech	1609
116	61	26/06/2013 23:50	00:05	57.2044	-5.6428	Orca	198
116	63	26/06/2013 23:50	00:05	57.2044	-5.6428	Orca	1470
116	62	26/06/2013 23:50	00:05	57.2044	-5.6428	Orca	1205
117	61	27/06/2013 00:17	00:32	57.2144	-5.6332	Lofitech	356
117	62	27/06/2013 00:17	00:32	57.2144	-5.6332	Lofitech	872
117	63	27/06/2013 00:17	00:32	57.2144	-5.6332	Lofitech	1153
117	65	27/06/2013 00:17	00:32	57.2144	-5.6332	Lofitech	364
118	56	27/06/2013 09:41	09:56	57.2035	-5.6502	Orca	1279
118	59	27/06/2013 09:41	09:56	57.2035	-5.6502	Orca	460
118	61	27/06/2013 09:41	09:56	57.2035	-5.6502	Orca	386
123	56	28/06/2013 03:53	04:08	57.2201	-5.6507	Orca	516
1	194	02/06/2014 13:22	13:37	57.6648	-3.8917	Lofitech	3122
1	184	02/06/2014 13:22	13:37	57.6648	-3.8917	Lofitech	844

2	190	02/06/2014 14:56	15:13	57.6728	-3.9393	Lofitech	4342
2	184	02/06/2014 14:56	15:13	57.6728	-3.9393	Lofitech	1252
2	194	02/06/2014 14:56	15:13	57.6728	-3.9393	Lofitech	696
2.1	187	03/06/2014 11:15	11:30	57.6592	-3.7856	Lofitech	139
3	181	03/06/2014 13:09	13:21	57.6903	-3.8860	Lofitech	3518
3	196	03/06/2014 13:09	13:21	57.6903	-3.8860	Lofitech	1395
4	181	03/06/2014 14:22	14:37	57.7091	-3.9399	Lofitech	556
5	196	04/06/2014 08:34	08:49	57.6084	-4.0017	Lofitech	2368
5	194	04/06/2014 08:34	08:49	57.6084	-4.0017	Lofitech	572
6	187	04/06/2014 14:14	14:29	57.6509	-3.7729	Lofitech	644
8	187	05/06/2014 02:03	02:20	57.6973	-3.7708	Lofitech	725
10	186	06/06/2014 09:50	10:05	57.6169	-3.9803	Lofitech	4928
10	196	06/06/2014 09:50	10:05	57.6169	-3.9803	Lofitech	4678
10	194	06/06/2014 09:50	10:05	57.6169	-3.9803	Lofitech	536
11	186	06/06/2014 10:43	10:58	57.6211	-4.0330	Lofitech	3192
11	196	06/06/2014 10:43	10:58	57.6211	-4.0330	Lofitech	719
12	181	06/06/2014 12:21	12:36	57.6354	-4.0119	Lofitech	1174
13	198	06/06/2014 16:59	17:13	57.6977	-3.9512	Lofitech	805
14	186	06/06/2014 17:30	17:45	57.6917	-3.9499	Lofitech	1260
15	186	07/06/2014 09:13	09:29	57.6895	-3.9359	Lofitech	2412
15	194	07/06/2014 09:13	09:29	57.6895	-3.9359	Lofitech	988
16	194	07/06/2014 12:57	13:11	57.6569	-3.9382	Lofitech	222
17	194	08/06/2014 09:36	09:51	57.6803	-3.9452	Lofitech	1198
17	186	08/06/2014 09:36	09:51	57.6803	-3.9452	Lofitech	822
17	198	08/06/2014 09:36	09:51	57.6803	-3.9452	Lofitech	557
18	198	08/06/2014 10:11	10:26	57.6918	-3.9368	Lofitech	1442
20	194	08/06/2014 15:10	15:26	57.6279	-3.9753	Orca	360
20	181	08/06/2014 15:10	15:26	57.6279	-3.9753	Orca	1155
21	186	08/06/2014 17:30	17:45	57.6346	-4.0242	Orca	1627
21	194	08/06/2014 17:30	17:45	57.6346	-4.0242	Orca	2552
21	185	08/06/2014 17:30	17:45	57.6346	-4.0242	Orca	2862
22	185	08/06/2014 19:45	19:59	57.6098	-3.8997	Orca	722
23	194	10/06/2014 09:31	09:46	57.6848	-3.9328	Orca	451
23	198	10/06/2014 09:31	09:46	57.6848	-3.9328	Orca	850
23	181	10/06/2014 09:31	09:46	57.6848	-3.9328	Orca	4592
24	194	10/06/2014 10:26	10:41	57.6860	-3.9360	Orca	1092
25	181	10/06/2014 11:44	11:59	57.7043	-3.9463	Lofitech	1040
25	194	10/06/2014 11:44	11:59	57.7043	-3.9463	Lofitech	3038
26	185	12/06/2014 11:40	11:55	57.7676	-3.5747	Orca	1136
27	185	12/06/2014 12:26	12:43	57.7727	-3.5603	Lofitech	604
28	185	12/06/2014 15:28	15:44	57.7179	-3.6980	Lofitech	1832
29	185	12/06/2014 17:52	18:06	57.6635	-3.7510	Lofitech	454
30	170	13/06/2014 09:12	09:27	57.7418	-3.8464	Lofitech	1116
30	187	13/06/2014 09:12	09:27	57.7418	-3.8464	Lofitech	7075

31	187	13/06/2014 13:06	13:21	57.7451	-3.7492	Lofitech	1029
32	181	13/06/2014 18:45	19:00	57.6986	-3.9219	Lofitech	1424
32	186	13/06/2014 18:45	19:00	57.6986	-3.9219	Lofitech	1173
33	186	14/06/2014 11:31	11:46	57.6897	-3.9384	Lofitech	1992
33	181	14/06/2014 11:31	11:46	57.6897	-3.9384	Lofitech	1514
33	184	14/06/2014 11:31	11:46	57.6897	-3.9384	Lofitech	782
34	181	14/06/2014 13:02	13:18	57.7044	-3.9389	Orca	358
34	184	14/06/2014 13:02	13:18	57.7044	-3.9389	Orca	1394
35	186	14/06/2014 17:45	18:02	57.6143	-4.0142	Lofitech	814
36	184	15/06/2014 11:28	11:42	57.6617	-3.8392	Lofitech	668
37	185	16/06/2014 14:36	14:53	57.6114	-3.9369	Lofitech	490
38	181	18/06/2014 10:24	10:39	57.7023	-3.9519	Lofitech	5974
38	198	18/06/2014 10:24	10:39	57.7023	-3.9519	Lofitech	854
39	198	18/06/2014 11:40	11:55	57.6884	-3.9649	Orca	926
40	187	18/06/2014 15:20	15:35	57.7258	-3.6208	Lofitech	1910
42	186	19/06/2014 12:47	13:02	57.6678	-3.9601	Lofitech	974
43	186	19/06/2014 18:30	18:45	57.6693	-3.9283	Lofitech	2115
43	181	19/06/2014 18:30	18:45	57.6693	-3.9283	Lofitech	730
43	190	19/06/2014 18:30	18:45	57.6693	-3.9283	Lofitech	3289
45	198	20/06/2014 15:15	15:29	57.6243	-4.0360	Orca	100
46	181	22/06/2014 08:51	09:07	57.6908	-3.9299	Airmar	733
46	194	22/06/2014 08:51	09:07	57.6908	-3.9299	Airmar	652
46	186	22/06/2014 08:51	09:07	57.6908	-3.9299	Airmar	2674
47	181	22/06/2014 10:44	10:58	57.6733	-3.9381	Airmar	3733
47	194	22/06/2014 10:44	10:58	57.6733	-3.9381	Airmar	1002
47	186	22/06/2014 10:44	10:58	57.6733	-3.9381	Airmar	1036
47	196	22/06/2014 10:44	10:58	57.6733	-3.9381	Airmar	3750
48	186	23/06/2014 09:10	09:25	57.6429	-3.9742	Airmar	339
49	185	23/06/2014 10:29	10:49	57.6132	-3.9680	Airmar	450
50	196	23/06/2014 11:32	11:47	57.6191	-3.9985	Airmar	566
51	180	23/06/2014 19:10	19:25	57.7783	-3.4307	Orca	888
52	196	24/06/2014 08:51	09:08	57.7220	-3.8863	Airmar	854
53	194	24/06/2014 11:52	12:07	57.7024	-3.9516	Orca	219

4.1 Responses to Lofitech ADD CEE

4.1.1 Qualitative behavioural assessments

Figure 6 to Figure 11 are a series of screen grabs showing seal and boat tracks before during and after two CEEs. The first, CEE number 5 is a "cut off" CEE with a seal travelling towards a haul-out site. The second, CEE number 27, is a CEE to a seal showing non-directed movements on an apparent foraging ground.

Figure 12 and Figure 13 summarise all "adequate" CEEs with Lofitech ADDs showing the ranges and predicted received levels for CEEs at which they did and did not elicit a response from target animals. Figure 14 shows the percentage response rate for groups of ten successive CEEs. To obtain CEE groups all CEEs were ranked by starting range, each successive 10 CEEs were assigned to a group and the percentage responses and mean starting range for CEEs in each group were calculated.

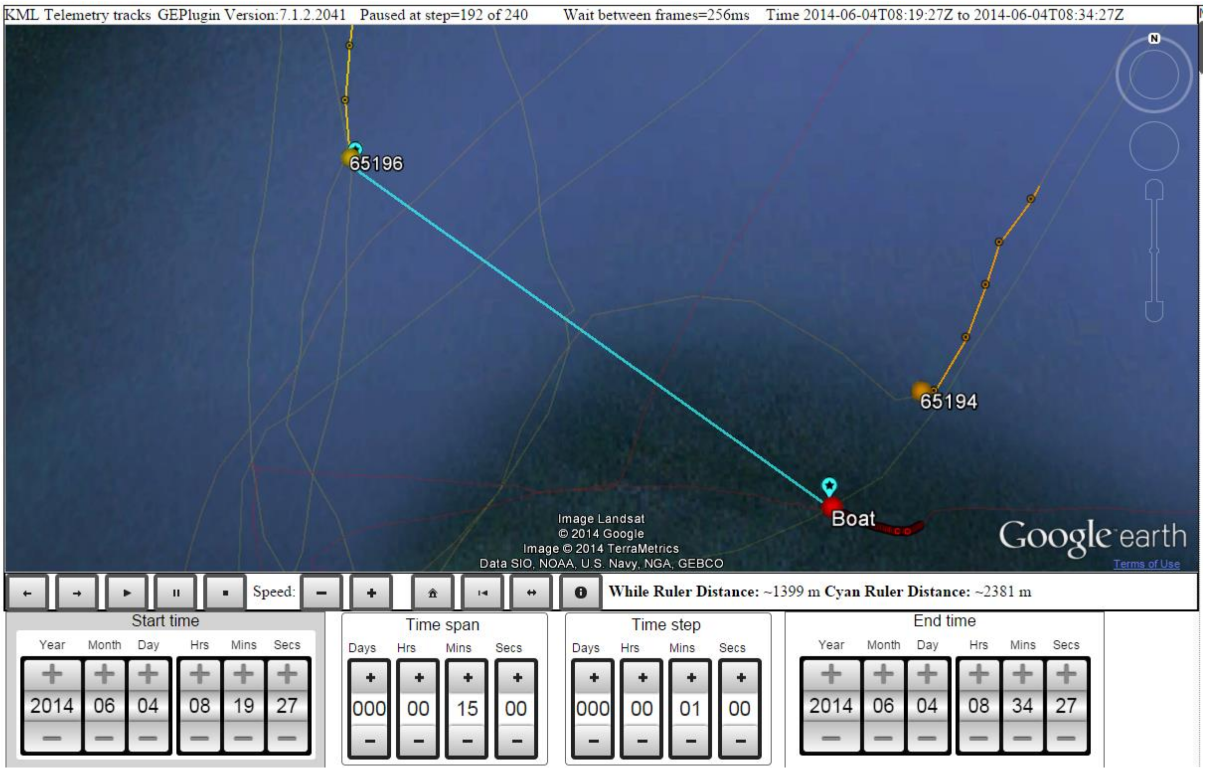


Figure 6. Start of CEE number 5, 2014 showing tracks for 15 minutes before, boat positioned directly ahead of Seal 194 (range 570m) and to the side of Seal 196 (2300m) both seals are heading south towards haul out site.

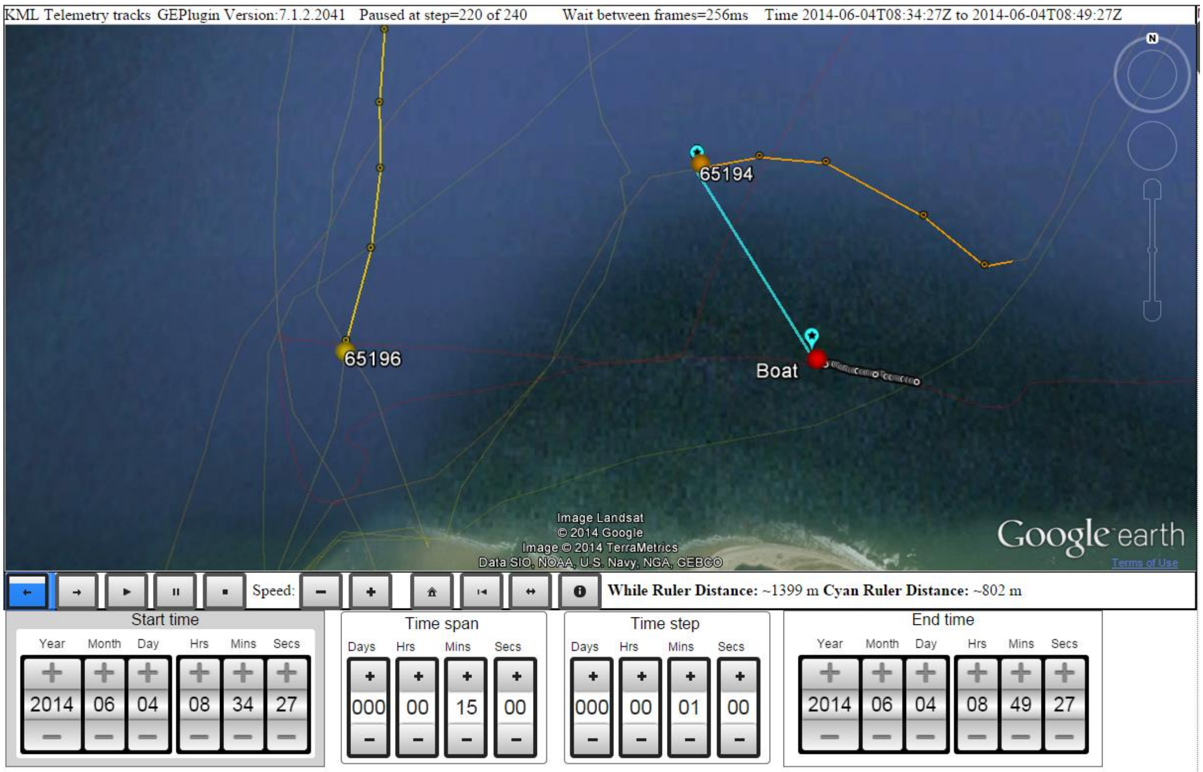


Figure 7. Tracks during the 15 minutes of CEE number 5, 2014. Seal 194 shows a strong avoidance reaction. Beginning to return to track at a "tolerance range" of ~1100m. Seal 196 shows no clear reaction.

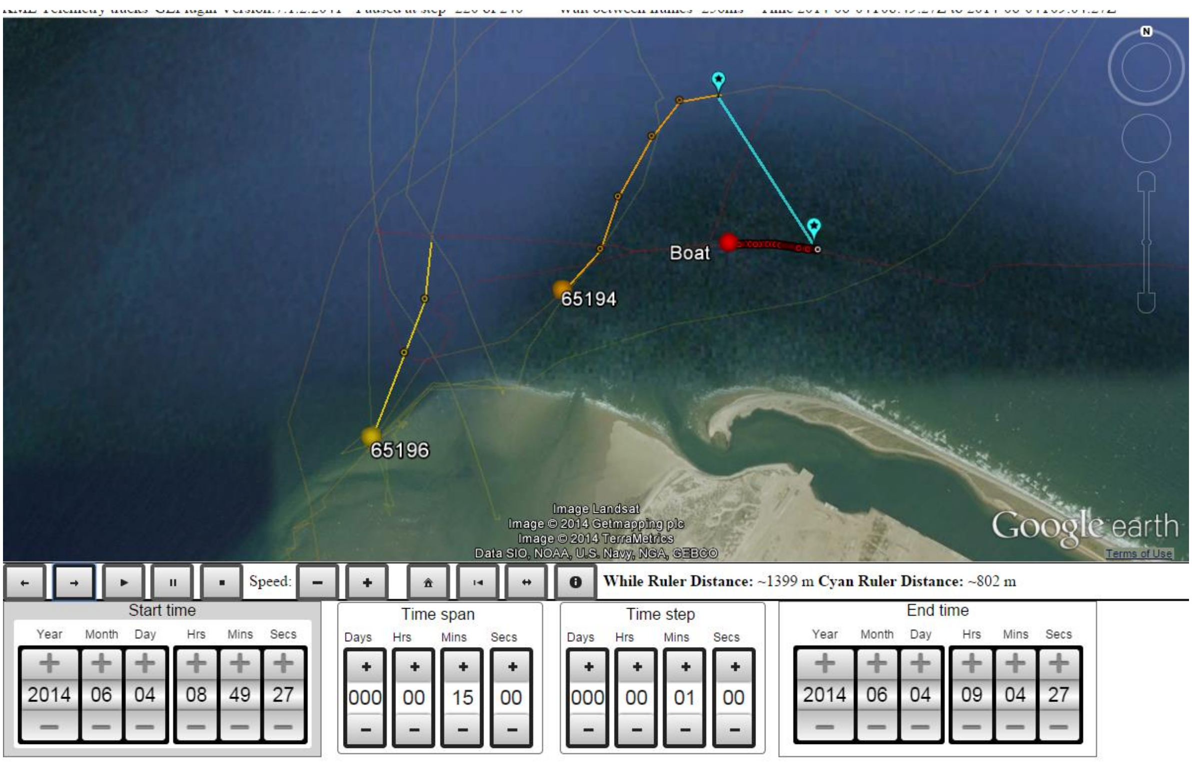


Figure 8. Tracks for the fifteen minutes after the CEE number 5, 2014. Both seals continue towards haulout site at Ardersier and subsequently haul out.

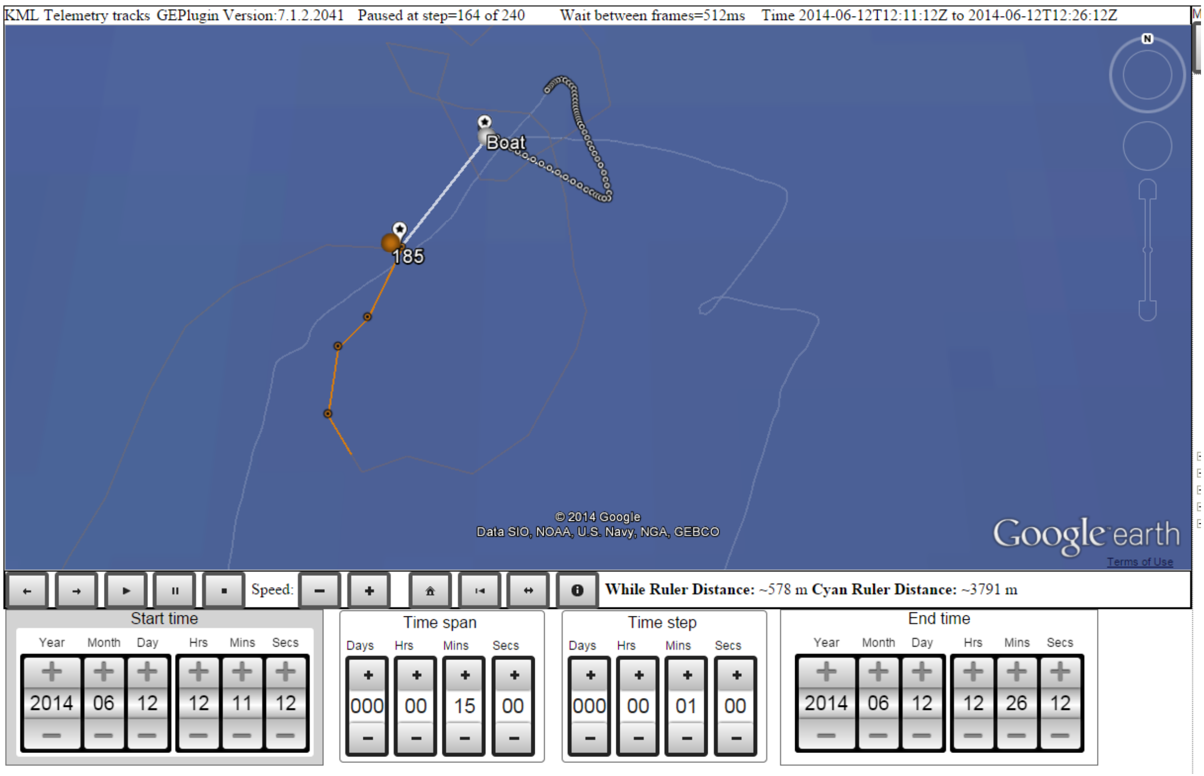


Figure 9. CEE number 27, 2014 to Seal 185. Fifteen minutes before the playback, the seal is moving in a restricted area, on an apparent foraging ground. CEE starts with the seal at a range of 578 m.

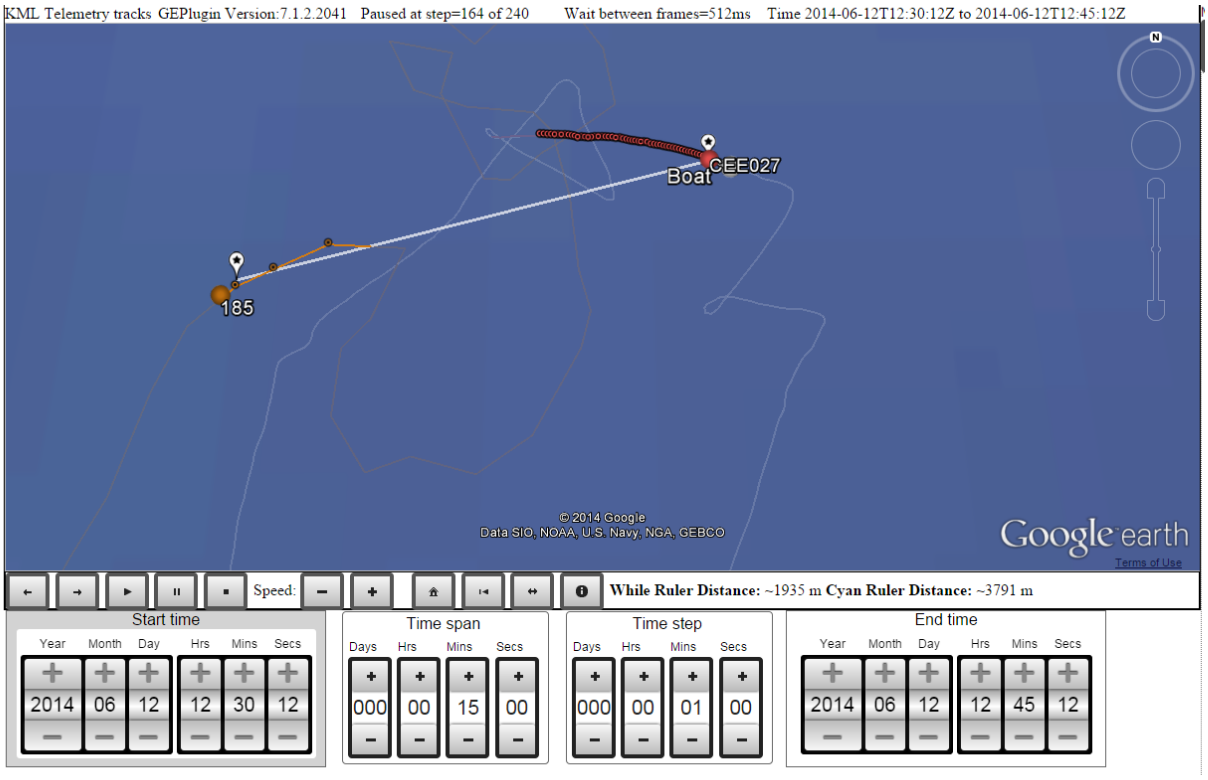


Figure 10 CEE#27 2014. Tracks for the 15 minutes of the playback. Seal moves directly away from sound source

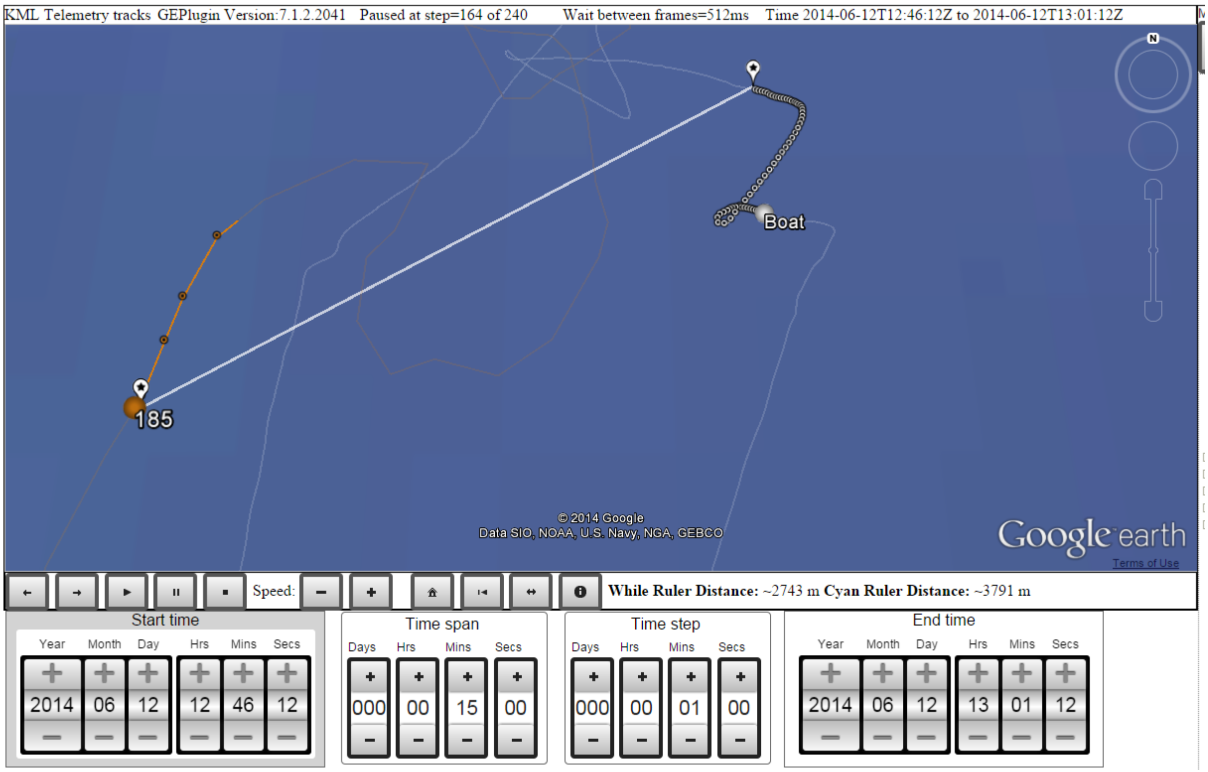


Figure 11. CEE number 27, 2014. Fifteen minutes after the CEE. Seal track bending back towards previous foraging spot. Subsequently returns to restricted area movement and apparent foraging.

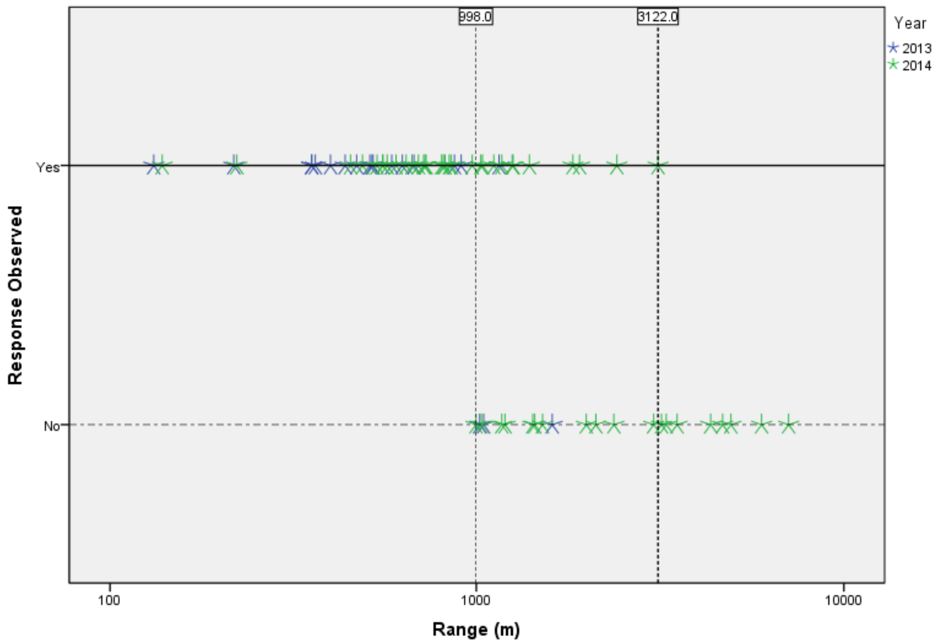


Figure 12. Instances of CEEs which elicited responses and CEEs which did not plotted against range for Lofitech CEEs carried out in 2013 and 2014. The Range of the first closest non-responsive CEE and the most distant responsive CEEs are indicated

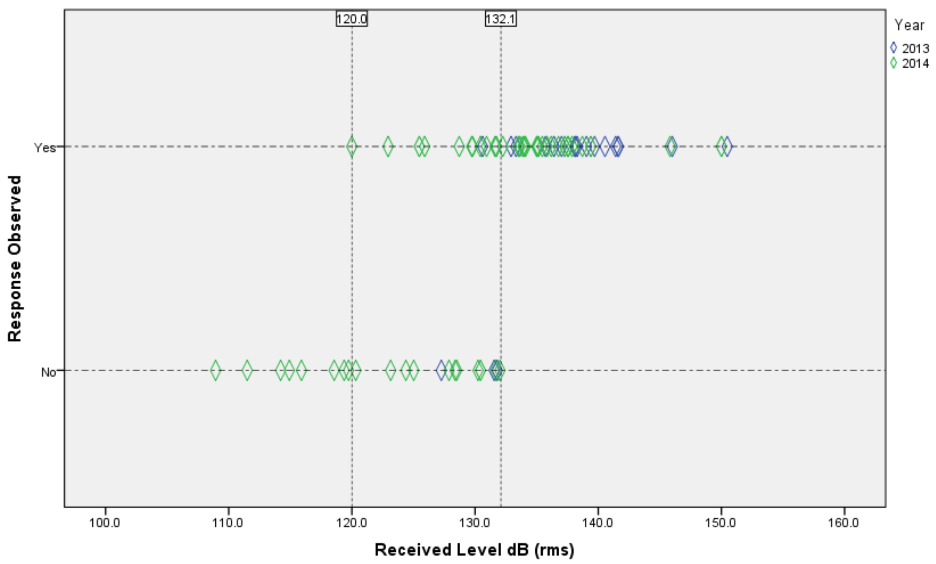


Figure 13. CEEs which elicited responses and CEEs which did not against predicted received level for Lofitech CEEs carried out in 2013 and 2014. The RL of the first closest non-responsive CEE and the most distant responsive CEEs are indicated. Received levels are calculated by applying -20LogR propagation loss to source levels recorded in this study.

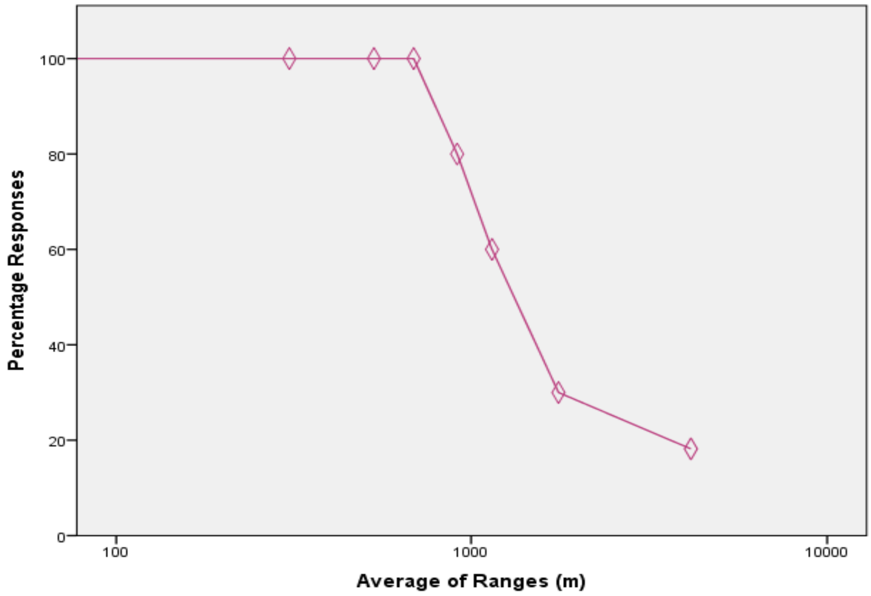


Figure 14. Percentage of Lofitech CEEs eliciting a response and average range for samples of ten CEEs ranked by range.

The shortest range for a CEE that did not elicit a response was 998m (Predicted SL 132dB). A response was scored for all 38 CEEs at closer ranges than this. The greatest range at which a response was recorded was 3,122m with a predicted received level of 120dB (rm) re 1µPa. The percentage of CEEs showing responses remained at 100% out to a range of ~1000m, after which there is a steady decline. The most distant group, with a mean range of 4.1km, showed a response rate of 20%. Typical behavioural changes during responses were from restricted area movement to directed movement away from the sound source. Animals already engaged in directed movements, e.g. travelling animals, would usually show avoidance diverting around the sound source. Average course changes were 72 degrees away from the sound source. Estimated tolerance ranges (assessed for 2014 data only) were often shorter than the start ranges for CEEs showing response. These ranged from 225m to over 2,000m and the average tolerance range was 943m.

4.1.2 Net changes in range

Figure 15 summarises data on the net change in range between target animals and the sound source during Lofitech CEEs. The mean change in range during those CEEs for which a clear behavioural response was scored was -625m (S.D. 590 n=46) while the net change for CEEs for which no response was evident was -36m (S.D.704, n=21). It is worth noting that these animals came closer to the vessel. This difference in change in range was statistically significant (Mann-Whitney U Test, p<0.001). All targeted animals within 1000m were scored as responding moved away, but in some cases the net movement was only in the order of tens of metres. As noted above, seal's "tolerance" or closest approach range during a CEE was often much shorter than the range at which a response could first be seen in the animated telemetry data. This was particularly notable in "cut off" CEES where the sound source had been positioned directly ahead of the subject which then often diverted around the source as it apparently made its way towards its intended destination. Figure 16 is a plot of change in range for animals which were engaged in restricted area movement (probable foraging) at the start of the CEE and which were not subjects of "cut off" CEEs. In these cases, all subjects within 2000m for which a response was scored increased their range from the sound source by ~1km. Clearly, seals did not show a simple flight response. Changes in behaviour and the extent to which they would move away during a CEE likely reflecting a range of factors including the animal's behavioural state and status. As, in the course of the study, it became apparent that occasions when animals were travelling towards a sound source might pose the most difficulties for mitigation applications more effort was focused on these scenarios and "cut off" CEEs are thus likely to be over-represented in the dataset.

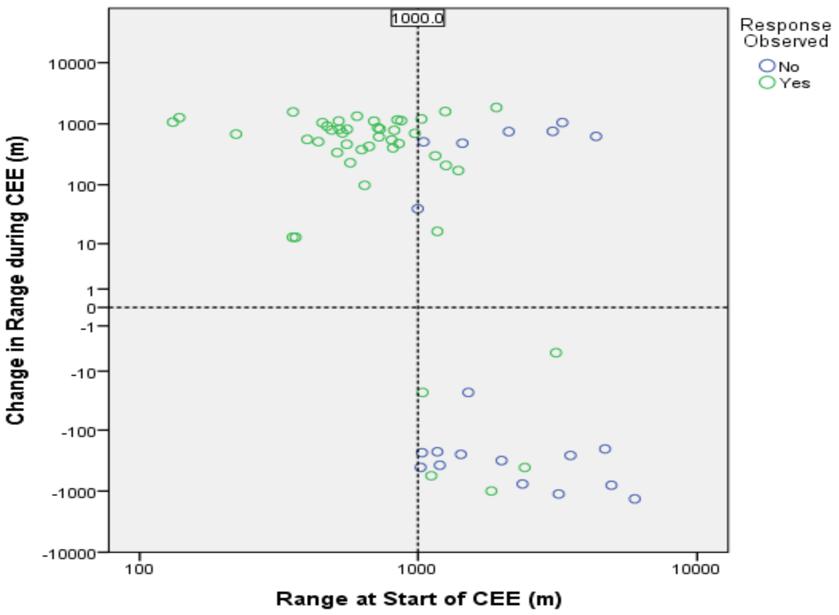


Figure 15. Net changes in range to the research vessel over the course of a CEE for Lofitech ADD which did and did not elicit a clear behavioural response

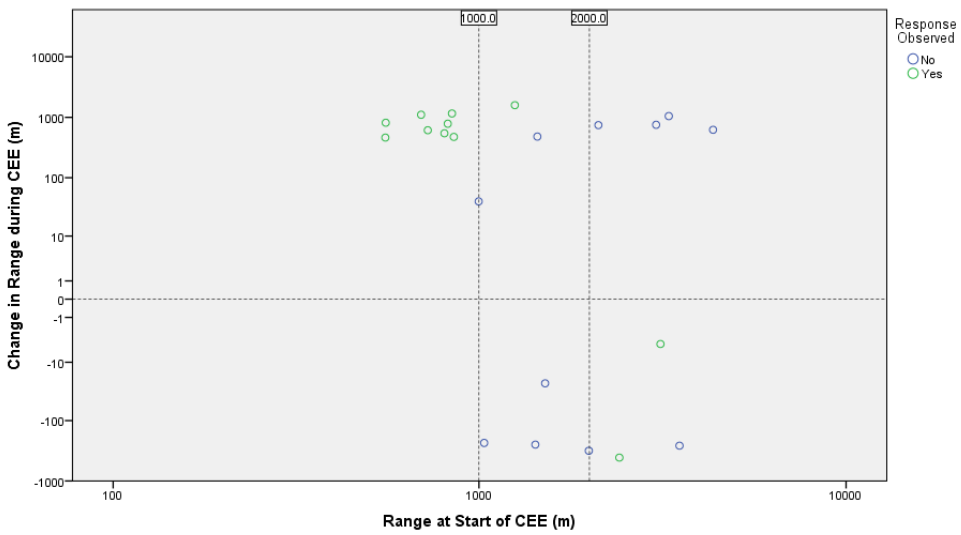


Figure 16. Net change in range to the research vessel over the course of the CEEs for Lofitech ADDs with and without an observed response for non cut-off CEEs, where initial behaviour was recorded as non-directed movement.

4.1.3 Statistical comparison of step parameters

Figure 17 to Figure 20 show plots of mean duration, distance, speed and directivity for steps (dives) before, at the start of, during and after Lofitech CEEs in 2014. Overall, step durations, distances covered and speeds were higher during CEEs than before or after them. Movements were more directional during CEEs but were particularly variable at the start, when a directional response was often evidenced. Net speed was more variable and lower for the steps which included the start of a CEE than for the rest of the CEE. This is probably because this was often the time when the strongest change in direction of movement took place and the net speed between the two surface locations would tend to under-represent the animals' actual swimming speed. Although swim speed increased during CEEs the magnitude of this effect was quite small. Seals often travel at or around their minimum cost of transport speed which represents an energetic optimum speed and any increase in speed would be costly and unlikely to be maintained.

To test the significance of these differences the mean was calculated before, start, during and after values for step parameters for each subject of each CEE and tested the null hypothesis that the distributions did not vary between before, start, during and after conditions using a non- parametric Friedman's two way analysis of variance by rank. The null hypothesis was rejected at significance level of 0.01 for all parameters except step duration (Table 3). Step duration is partly constrained by the tag which was programmed to only attempt to obtain a new location every 3 minutes and this may explain the lack of a significant effect on duration.

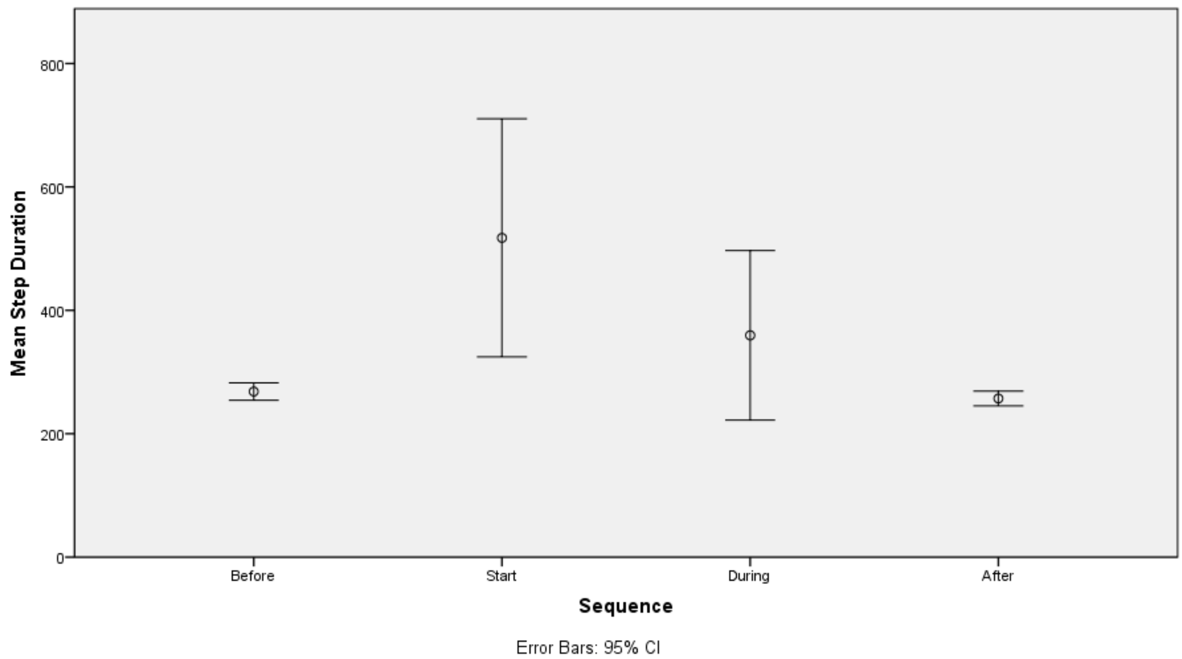


Figure 17. Mean step durations before, during and after Lofitech CEEs

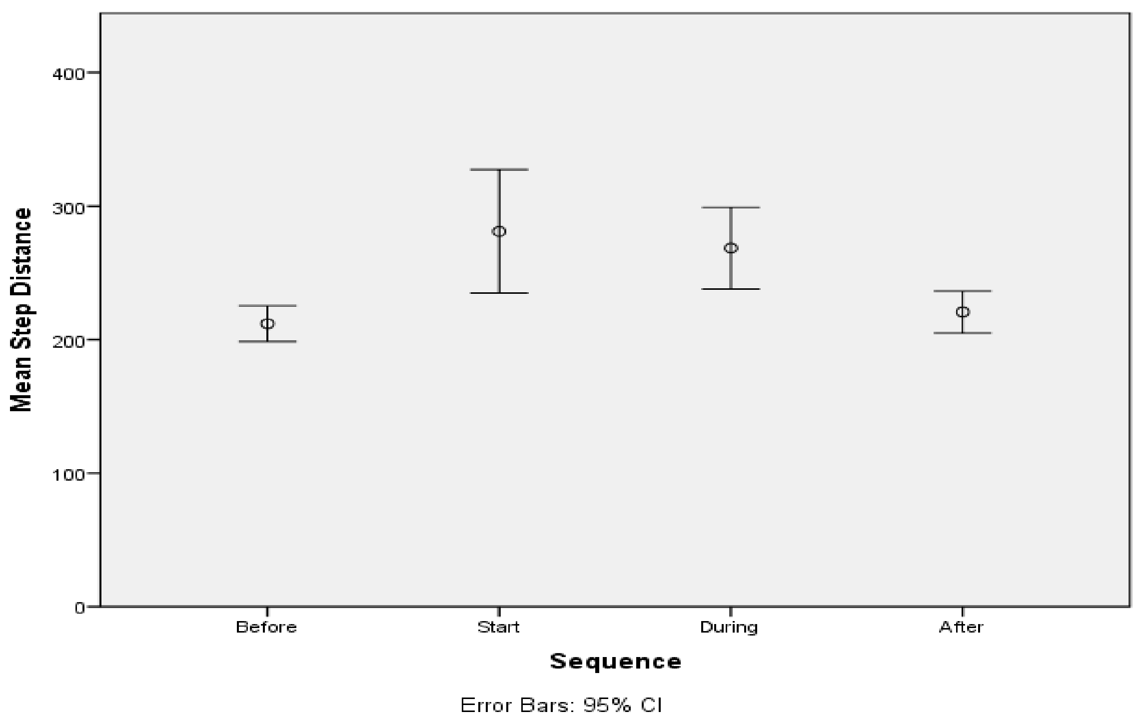


Figure 18. Mean distance covered during steps before during and after Lofitech CEEs.

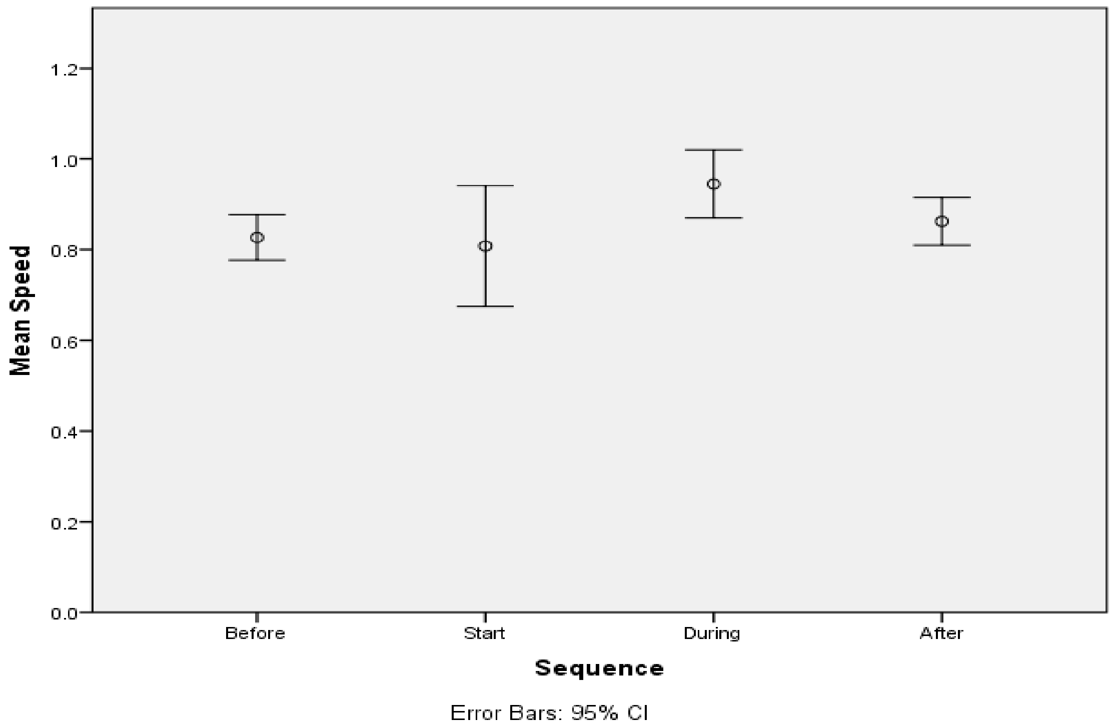


Figure 19. Mean speed during steps before, at the start, during and after Lofitech CEEs

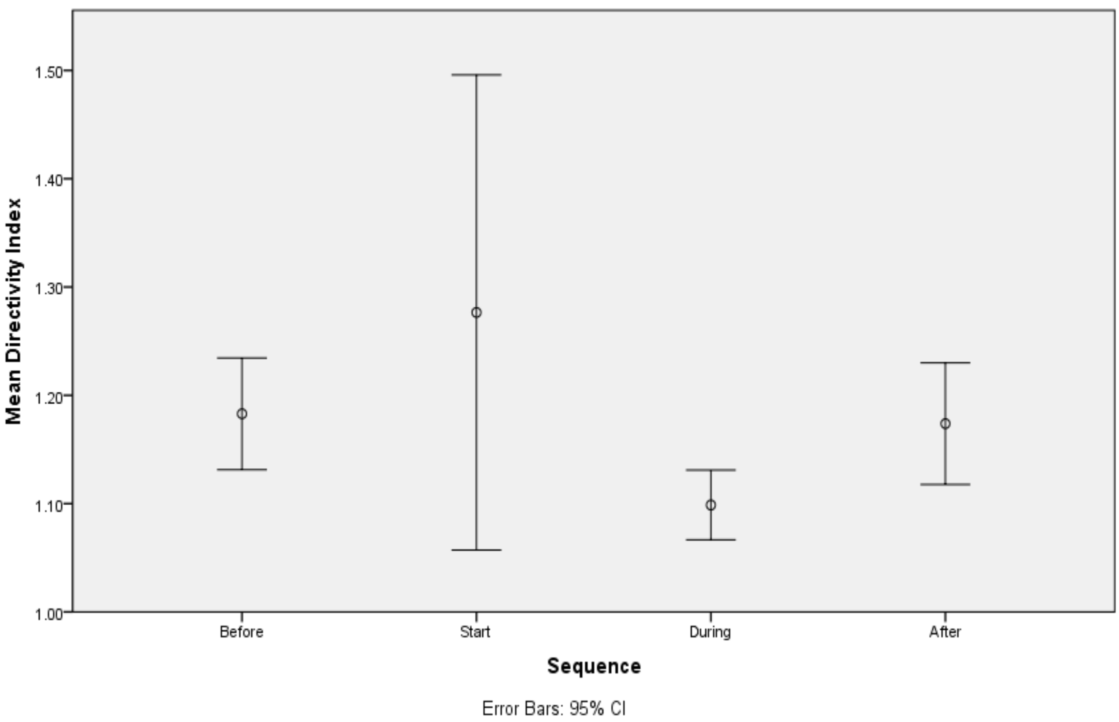


Figure 20. Mean directivity before, at the start, during and after CEEs with Lofitech sound source

Table 3. Average value for step parameter before, at start, during and after CEEs for seals considered targets for CEEs. Significance value for Friedman's two way analysis of variance by ranks tests are shown.

Parameter	CEE sequence	Mean	SD	N	Significance
Duration (sec)	Before	303.3	178.1	83	0.274
	Start	348.3	184.4	83	
	During	326.0	184.3	83	
	After	285.2	99.7	83	
Distance (m)	Before	207.4	101.5	83	0.002
	Start	284.3	188.0	83	
	During	273.4	165.1	83	
	After	212.9	120.0	83	
Speed (m/sec)	Before	0.77	0.38	83	0.006
	Start	0.89	0.47	83	
	During	0.92	0.45	83	
	After	0.80	0.43	83	
Directivity	Before	1.22	0.43	83	0.001
	Start	1.20	0.73	83	
	During	1.09	0.14	83	
	After	1.23	0.72	83	

4.2 Orca Vocalisation CEEs

Figure 21 and Figure 22 summarise information on the ranges and calculated source levels respectively, at which CEEs of Orca vocalisations did and did not elicit clear behavioural responses.

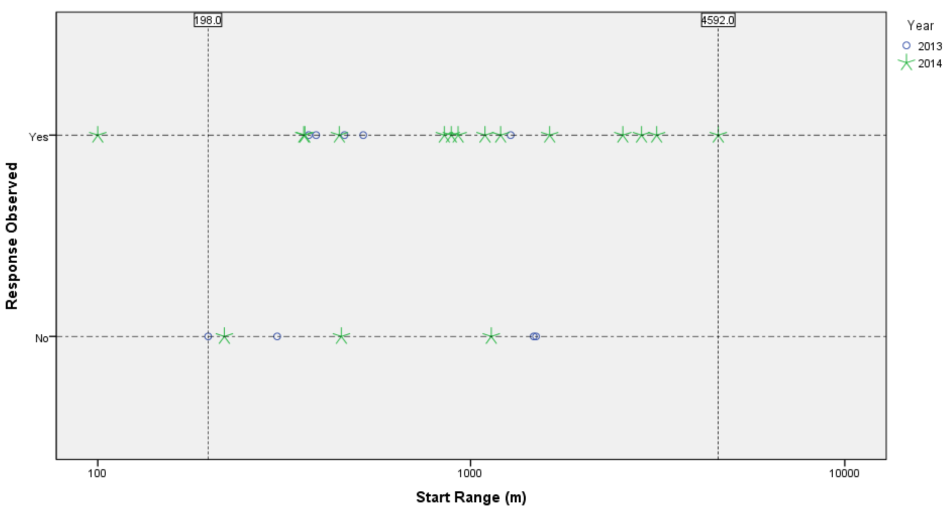


Figure 21. Summary of start ranges for CEEs which elicited responses and CEEs which did not for Orca CEEs carried out in 2013 and 2014. The range of the first closest non-responsive CEE and the most distant responsive CEEs are indicated.

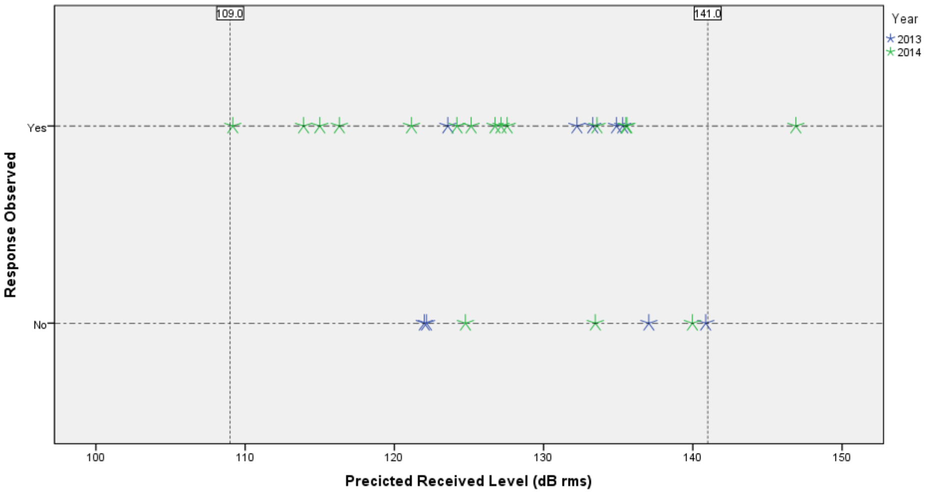


Figure 22. Summary of calculated received levels for CEEs which elicited responses and CEEs which did not for Orca CEEs carried out in 2013 and 2014. The source level of the loudest non-responsive CEE and the quietest responsive CEEs are indicated Received levels are calculated by applying -20LogR propagation loss to source levels of loudest calls measured recorded in this study.

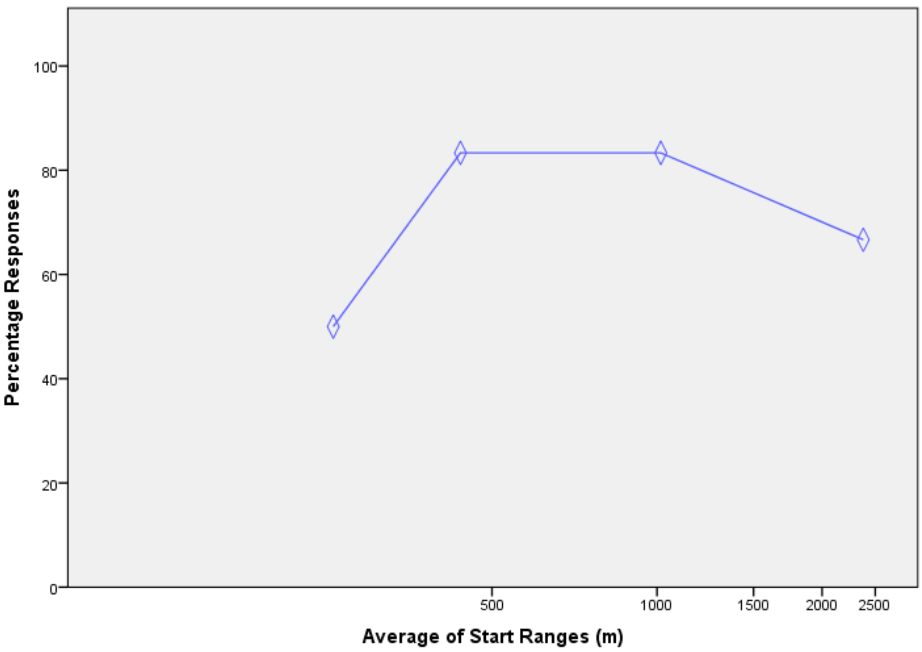


Figure 23. Percentage of CEEs showing positive response against mean range for sequential samples of 5 Orca CEEs.

Figure 23 shows the percentage of animals responding and average start ranges and initial received levels for each successive sample of five CEEs. These plots indicate that generally Orca calls seem to be less reliable in eliciting responses than the Lofitech although apparent responses were identified at range out to ~4600m with predicted received levels of only 109dB. The shortest initial range for a non-responding CEE was just 198m with a calculated received level for the loudest vocalisations of 141 dB re 1µPa RMS. There is little evidence that would allow prediction of the proportion of animals responding with either range or received levels. This matched the qualitative impression of high variability, strong response seen on some occasions even at considerable ranges, while on other occasions no responses were evident even at short range. On two occasions a Lofitech CEE was conducted with an individual after two unresponsive Orca CEEs and in both cases a response was evident during the later Lofitech CEE.

4.3 Controlled exposure experiments with Airmar ADD

The Airmar ADD was available for a short period of time and only nine CEEs were completed using it. The ranges and received levels at which responses were and were not observed are summarised in Figure 24 and Figure 25. With such a small dataset it is difficult to draw firm conclusions but there is no evidence to suggest that the Airmar would be more effective for this application than the Lofitech ADD.

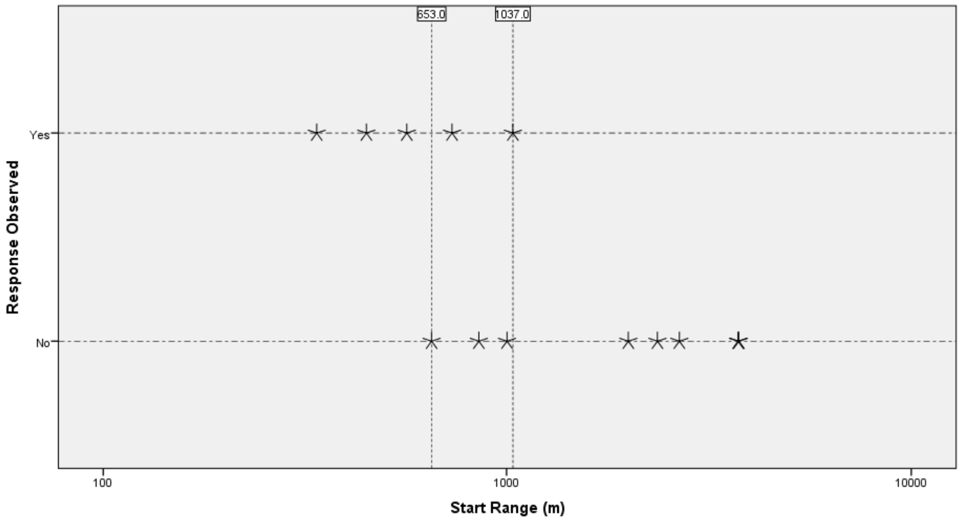


Figure 24. Summary of start ranges for CEEs which elicited responses and CEEs which did not for Airmar CEEs carried out in 2014. The Range of the first closest non-responsive CEE and the most distant responsive CEEs are indicated

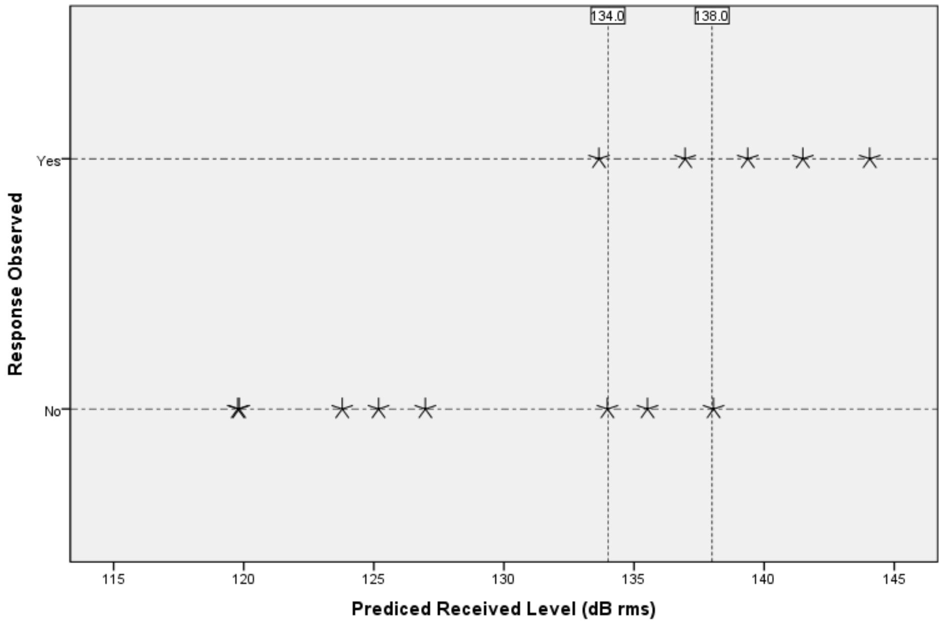


Figure 25. Summary of calculated received levels for CEEs which elicited responses and CEEs which did not for Airmar CEEs carried out in 2014. The source level of the loudest non-responsive CEE and the quietest responsive CEEs are indicated

4.4 Sound source levels

Measurement of sound source levels using calibrated equipment was made in sheltered, quiet waters in Loch Ness and in Loch Oich in 2014. Recordings were made using calibrated hydrophones (Reson TC4033-1 or TC4013) in conjunction with a calibrated amplifier and filter unit (Reson VP200). Data were digitised using National Instruments USB6251 digital acquisition board at a sampling rate of 500 kHz using PAMGUARD software.

Batteries for the sound broadcast equipment were fully charged and battery voltage was checked throughout the trials. Recordings were made at ranges from 25-33m. Distances, measured using a laser range finder and tape measures. Both sound source and recording hydrophones were deployed at a depth of 3m.

Analysis was completed using acoustic measurement tools in Raven Pro v1.4 interactive sound analysis software (Cornell Bioacoustics Research Program). Recordings of ADDs were high pass filtered at 5kHz and recordings of killer whale broadcasts were filtered at 1kHz. Sections of recordings for acoustic measurement were selected by hand using a cursor. Lofitech emissions are a series of 0.5 second tonal pulses and for these the whole pulse was selected for measurement. Airmar emissions consist of a series of short (~1.4msec pulses) with a 40msec spacing which are emitted in blasts lasting 2.25secs. Measurements of Airmar pulses were made using both selections which included the complete blast and selections for each individual 1.4msec pulse within it.

The average and standard deviations of 39 Lofitech pulses recorded in Loch Ness on 28/05/2014 was 193 dB re 1µPa@m RMS with a standard deviation of 1.9, while measurements of 52 pulses made in Loch Oich on 27/06/2014 gave a source level 192.9 dB re 1µPa@m RMS with a standard deviation of 3.45 (Table 4).

Our measurements of source level for the Lofitech align well with those in Brandt *et al.* (2012) who found that a received level model with a source level of 197dB and a 20log(Range) transmission loss provided the best fit to acoustic measurements of a Lofitech made in the North Sea. The source level specified on the Lofitech manufacturer's website is 189dB but they do not specify the units. With a 0.5 sec duration, sound exposure level of 189dB would align well with the RMS measurements.

The mean source level of 17 Airmar pulses measured from recordings made in Loch Oich on 27/06/2014 was 195.3 dB re 1µPa@m RMS with as standard deviation of 0.843. The RMS source level for eight blasts made in Loch Oich was 188.2 dB re 1µPa@m RMS (SD 0.047). Lepper *et al*., (2004) measured a sourced level of 192dB RMS for a standard 12v Airmar. The unit measured here was a 24v model which had twice the voltage of that tested by Lepper *et al*., (2004), which would explain the 3dB higher source level.

The killer whale recordings included a range of call types with different levels. The source levels of the loudest call types are probably of greatest relevance. Measurement of 14 prominent calls with recordings had source levels ranging from 176 to 187 dB re 1µPa@m RMS

Table 4. Means and standard deviations of estimated source levels for the three signals used in the CEEs.

Sound source	Date and location	Number of Measurements	Mean RMS dB re 1µPa@m	SD
Lofitech	Loch Ness 28/05/2014	39	193	3.19
Lofitech	Loch Oich 27/06/2014	52	192.9	3.45
Airmar	Loch Oich 27/06/2014	17	195.3	0.85
Orca	Loch Oich 27/06/2014	14	176-187	NA

4.4.1 Propagation loss and received levels

Recordings made using the spar buoy recorder provide a dataset to indicate propagation loss in the study habitat. However, data were only available over the limited range that the boat drifted to in the course of a CEE. In both 2013 and 2014 attempts were made to conduct dedicated trials to measure received levels at all ranges. These were only attempted at the end of each season to minimise disturbance and on both occasions poor weather compromised the experiment.

Figure 26 shows a plot of received level against range for 415 measurements of Lofitech pulses made from spar buoy recordings in the Moray Firth in 2014. Predictions from the equation that best fitted sound levels in an experiment conducted in the North Sea by Brandt *et al*., (2012) are also shown.

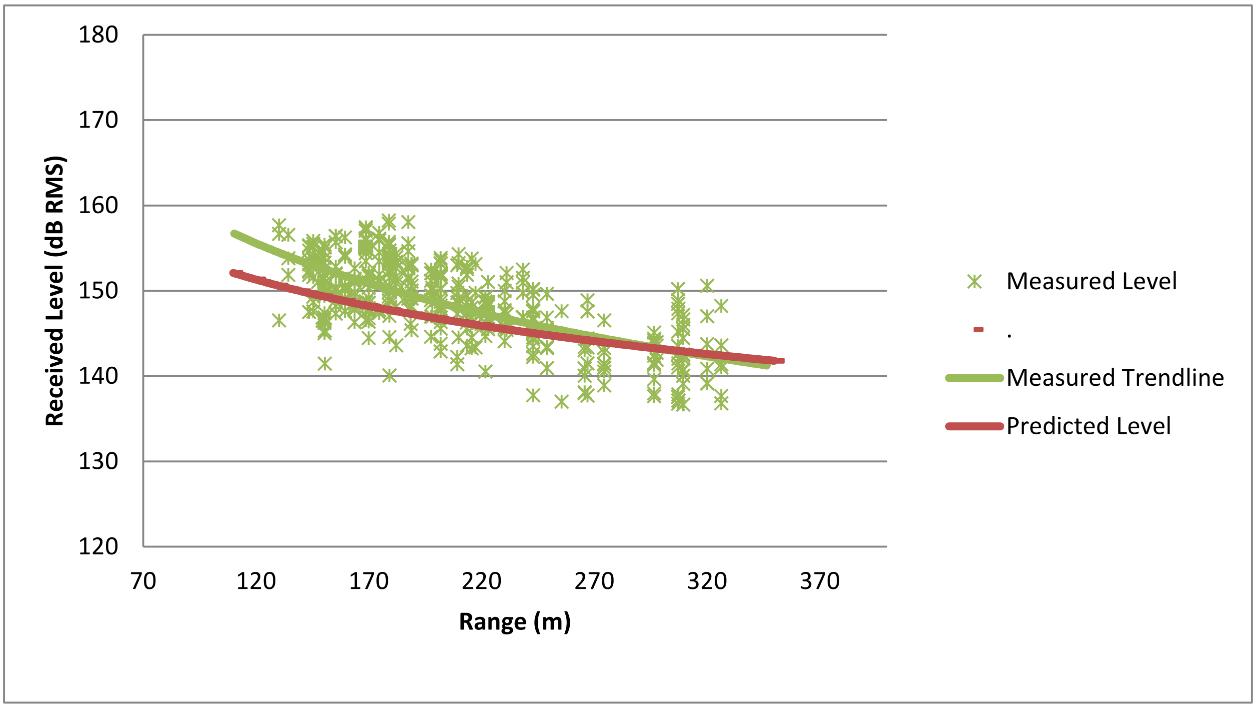


Figure 26. A plot of 415 measurements (dB re1µPa RMS) and logarithmic fitted trendline of Lofitech pulses recorded during CEEs in the Moray Firth using the recording spar buoy. The levels predicted by the equation in Brandt *et al.*, (2012), derived from their field observations in the North Sea, are also shown.

Figure 27 shows a plot of received levels against range for 293 measurements of ADD pulses made in the Sound of Sleat in 2013 at ranges out to 2150m. The absolute value of these levels appears to be ~10dB lower than those measured in 2014. It appears likely that this is a data problem which has not yet been identified rather than a real difference in source level. Even so, these data are useful in showing propagation loss at greater ranges and indicate that the 20LogR propagation loss measured by Brandt *et al*., (2012) can be applied with some confidence in these locations.

Although it was not possible to carry out detailed and well controlled measurements of received levels and propagation loss at the study sites, the source level measurements using calibrated equipment and opportunistic measurements of received levels show good agreement with the equation derived from more formal source characterisation experiments conducted by Brand *et al*., (2012) and therefore their propagation loss equation was used in conjunction with measurements of source level to calculated received levels based on range in this report.

TL = 20 x Log(range) – range/1000

5 Conclusions

5.1 Prospects for aversive sound mitigation

Three devices were tested as potential sound sources for aversive sound mitigation. Because of the work already carried out with the Lofitech showing its ability to move harbour porpoises out of areas by Brandt *et al.*, (2013) this device was considered the "default" option. The findings suggest that this is also the most effective of the devices tested, reliably eliciting behavioural responses from harbour seals.

Our results indicate that out to a range of around one kilometre, all seals might be expected to show a response. However, these responses do not always translate into animal movements directly away from the sound source. Three observations from this work are particularly pertinent to those planning to use aversive sound mitigation. The first is the propensity for seals which are close to shore to move very close inshore and then move along shore in very shallow waters. This may well be a general and effective anti-predator response but the extent to which it would protect animals from exposure to intense sound would need to be considered in the light of local topography and propagation conditions. The second is the observation that travelling animals experiencing a CEE ahead of them would rarely reverse their tracks. More commonly they would "swerve" around the sound source, on occasion passing within a few hundred metres of it. Clearly, if this occurred during a mitigation exercise then animals might suffer an unacceptable sound exposure. A final important observation is that animals which were apparently foraging within an area would often start to return to that area soon after the end of a CEE. An implication of this for aversive sound mitigation is that the potentially damaging activity should start immediately after (or during) the mitigation broadcast.

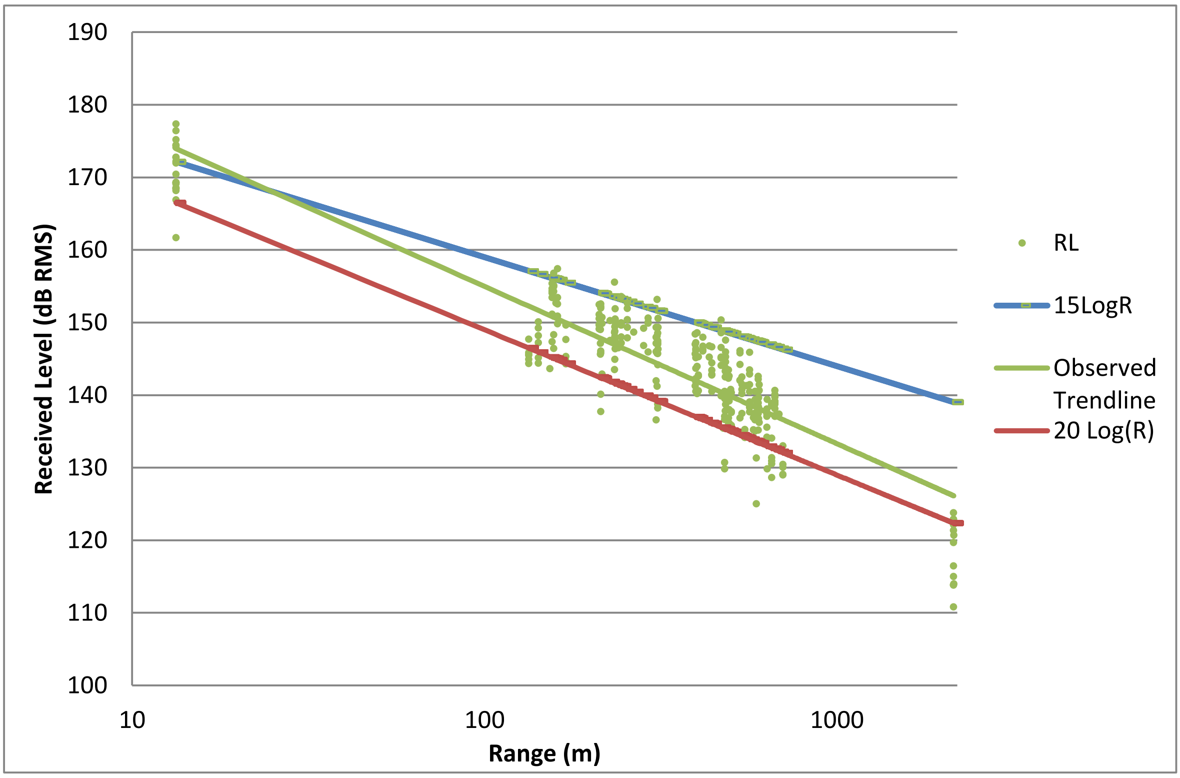


Figure 27. A plot of received levels (dB re1µPa RMS) and logarithmic fitted trendline for Lofitech ADD pulses recording in the Sound of Sleat using the recording spar buoy. The levels predicted by assuming simple geometric spreading at 15 Log (range) and 20 Log (range) are also shown.

It is clear that an observable behavioural response is not an indication that the animal will move to a safe range. As mentioned above, instances where a mitigation sound is deployed directly ahead of a travelling animal are particularly problematic and may require more work. In these preliminary trials only short (15 minute) transmissions were conducted and trials with longer exposures might serve to clarify some of these issues. Other ways of achieving a larger "guaranteed exclusion zone" would be to use a louder sound source or multiple sound sources distributed around the pile driving site. It will be technically difficult to create a louder sound source, and any such device would begin to pose an increasing acoustic risk in its own right. If multiple sound sources were to be deployed it would be most practical if they were self-contained buoy-based units. Studies should be carried out to investigate how animals respond to multiple sound sources in the field which would inform how they should be spaced to achieve effective mitigation.

It will be extremely difficult to measure the behavioural response of seals to real pile driving episodes because the likelihood of an individual telemetered animal being close to an opportunistic pile driving event when it starts will be low and it is not feasible to conduct experimental exposures with such an unwieldy and expensive source. However, the observations made in this study, of animal responses to what were clearly aversive signals, may provide insight into how seals might react to pile driving. The responses observed did not suggest panic leading to a straightforward flight response; rather the seals' behaviour appeared to represent controlled responses which often seemed to be adapted to location and circumstances allowing seals to avoid sound sources while continuing with their existing behaviour with minimal disruption. Although seals showed an increase in speed during CEEs this was only modest. This may well reflect the influence of energetic constraints on maximum sustainable swim speed.

Seals may respond similarly to pile driving, especially during the "soft start" phase. The mean "escape" swimming speeds observed during the CEEs were lower than those assumed in some cumulative exposure models. Such models also assume that animals move directly away from the piling site. The current findings suggest that this is not a precautionary supposition. These considerations emphasise the desirability of being able to move animals to a "safe range" using an additional known sound source and the importance of conducting CEEs so that behavioural responses to such sound sources can be quantified.

5.2 Future work

One of the important outputs of this project is the development of a telemetry system and field protocols which allow data on relevant behavioural responses to be collected from seals in areas representative of those likely to be subject to pile driving.

This work has made important steps towards assessing the likely performance of a mitigation system suitable for harbour seals. However, it also identified areas which require additional attention, including testing longer CEEs and the use of multiple (or louder) devices to achieve a larger exclusion area. So far, no data on grey seals has been collected. The system used here should provide good data from this species though they will be more challenging to work with as their foraging grounds are further offshore and this may require animals to carry an additional small satellite tag so that they can be located at offshore foraging grounds.

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