

Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland





Scottish Natural Heritage
Dualchas Nàdair na h-Alba

All of nature for all of Scotland
Nàdar air fad airson Alba air fad

COMMISSIONED REPORT

Commissioned Report No. 517

Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland

For further information on this report please contact:

Dr Suzanne Henderson
Scottish Natural Heritage
Great Glen House
INVERNESS
IV3 8NW
Telephone: 01463 725238
E-mail: suzanne.henderson@snh.gov.uk

This report should be quoted as:

Lepper, P.A., Gordon, J., Booth, C., Theobald, P., Robinson, S. P., Northridge, S. & Wang, L. 2014. Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland. *Scottish Natural Heritage Commissioned Report No. 517.*

This report, or any part of it, should not be reproduced without the permission of Scottish Natural Heritage. This permission will not be withheld unreasonably. The views expressed by the author(s) of this report should not be taken as the views and policies of Scottish Natural Heritage.

© Scottish Natural Heritage 2014.



COMMISSIONED REPORT

Summary

Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland

Commissioned Report No.: 517

Contractor: Loughborough University, Ecologic Ltd, NPL, SMRU, SMRU Ltd., HWDT

Year of publication: 2014

Background

The aim of the project is to provide the capability to establish potential risks to cetaceans and seals from the use of acoustic deterrent devices in Scottish waters. Acoustic Deterrent Devices (ADDs) are often used on aquaculture sites to reduce predation of seals on fish stocks using acoustic emissions. These acoustic emissions may also have secondary effects on marine mammals (including non-target species) ranging from physical injury, behavioural response and reduced sensory capability.

In this project, an attempt is made to investigate the effects of water depth, seabed sediment type and bathymetry on the propagation and received levels of ADDs. It also examines the implications of simplified modelling approaches and associated prediction of a 'zone of potential risk'. A generalised sensitivity model has been developed to allow prediction of the range to exceed predetermined thresholds (e.g. for hearing injury) based on sound pressure levels and cumulative sound exposure levels for user defined impact criteria based on ADD type, local environments and functional hearing capabilities of species present in Scotland.

Main findings

- A survey of the status of aquaculture sites in Scotland has been conducted indicating that the majority of ADD systems in use are from three manufacturers (Terecos, Ace Aquatec and Airmar).
- Modelling of propagation losses show dependence on water depth, sediment type and seabed slope.
- In relation to determining the sensitivity of cetaceans and seals to noise, the use of dual impact criteria based on zero-peak Sound Pressure Level (SPL) and broadband Sound Exposure Level (SEL) metrics have grown (i.e. Southall *et al.*, 2007). The models developed here were based on combination of criteria drawn from current best peer reviewed data on physiological damage to cetacean and pinniped species including Southall *et al.* (2007) and Lucke *et al.* (2009).
- The dominant frequency components of ADD systems range from 2-40 kHz.
- A generalised sensitivity model has been developed to allow the prediction of received level and ranges to exceed given SEL thresholds for various ADD models. Variant parameters include number of devices, duty cycle and the influencing factors of local

environments, sediment types, the functional hearing capabilities of seals and cetaceans and simplistic assumptions about animal movements.

- Broadband noise was broken into third octave bands. Propagation losses for a range of environments were then calculated for each frequency band using a source-image modelling technique, incorporating water depth, sediment and water column acoustic properties and surface roughness.
- Seabed slope was found to impact the propagation of noise. An upslope was found to generally have lower propagation loss when compared to a flat seabed and so additional functions were added to the model to accommodate this. Down slopes were generally found to have higher propagation loss, resulting in lower or similar received levels compared to flat seabed. A flat seabed case was therefore used as a more precautionary approach.
- Correlations of modelling of broadband noise with measured data were used to give confidence in the application of the noise modelling technique to characterise broadband noise and construct the impact database.
- Poor understanding of the extent to which behavioural change and avoidance are dependent on received levels of sound means that the propagation modelling completed in this project can contribute little (at present) to understanding the extent of habitat exclusion around fish farms with operating ADDs.
- Modelling of the exposure time to exceed injury criteria for seals and porpoises at given ranges from active ADDs suggest that there is a credible risk of exceeding injury criteria for both seals and porpoises. Thus the risk that ADDs at Scottish aquaculture site is causing permanent hearing damage to marine mammals cannot be discounted.

For further information on this project contact:

Dr Suzanne Henderson, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725238 or suzanne.henderson@snh.gov.uk

For further information on the SNH Research & Technical Support Programme contact:

Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725000 or research@snh.gov.uk

Table of Contents		Page
1.	INTRODUCTION	1
2.	MODELLING SOUND PROPAGATION FOR ADDS IN SCOTLAND	3
2.1	Different types / models of ADDs being used	3
2.1.1	Introduction	3
2.1.2	Summary	4
2.2	Review of ADD systems in use in Scottish waters	5
2.2.1	Introduction	5
2.2.2	Airmar (dB Plus II)	5
2.2.3	Terecos (Type DSMS-4)	8
2.2.4	Ace Aquatec (Silent Scrammer)	12
2.2.5	Additional systems	16
2.2.6	Source Characteristics in Third Octave Bands (TOB)	17
2.3	Test case modelling	19
2.3.1	Range dependent modelling	19
2.3.2	Introduction to Source Image Model (ImageTL)	23
2.3.3	Range averaging	25
2.3.4	Surface Roughness (wind speed)	26
2.3.5	Water depth	27
2.3.6	Sediment type	30
2.3.7	Seabed slope	33
2.4	Model validation against measured data	36
2.4.1	Model comparisons	36
2.4.2	Comparison with measured data	36
2.5	Critical analysis of different models	38
2.5.1	Discussion	38
2.5.2	Example of broadband received level estimate	40
3.	EFFECTS OF SOUND ON CETACEANS AND SEALS	42
3.1	Effects of underwater sound	42
3.1.1	Introduction	42
3.1.2	Non Auditory Physical Effects	42
3.1.3	Auditory Injury and Threshold Change	42
3.1.4	Behaviour	43
3.1.5	Behavioural Responses to ADDs	43
3.1.6	Perceptual Effects: Auditory Masking	44
3.1.7	Audiograms	45
3.1.8	Measuring and Predicting Damage and Behaviour: Some Comments	47
4.	DAMAGE RELATED CRITERIA AND THRESHOLDS FOR ACCEPTABLE EXPOSURE	49
4.1	Introduction	49
4.1.1	US Marine Mammal Noise Exposure Criteria for Injury	49
4.1.2	Auditory Sensitivity and Frequency Weighting Applied to Marine Mammal Noise Exposure Criteria	50
4.1.3	Injury Sound Exposure Criteria	52
4.1.4	Behavioural Noise Exposure Criteria	53
5.	ASSESSING DAMAGE RISK FROM ADDS AT SCOTTISH FISH FARM SITES: COMBINING SOUND FIELD PREDICTIONS AND DAMAGE RISK CRITERIA	54
5.1	Introduction	54
5.2	Propagation loss modelling	54
5.3	Received level model organization	56
5.4	Predicting range to pre-determined SEL Contour	59
5.4.1	Seabed slope propagation loss adjustment	60

5.4.2	Frequency Weighting	61
5.5	Models of Influence Zones and Safe Exposure Times for ADDs at Typical Scottish Fish farms	62
5.5.1	Zero to Peak Instantaneous Exposure Criteria	62
5.5.2	Sound Exposure Level v Range	62
5.5.3	Sound Exposure Level Injury Criteria	64
5.5.4	Model outputs	65
5.6	Note on Model Update and Development	72
6.	CONCLUSIONS	74
7.	REFERENCES	75
8.	GLOSSARY	81
	ANNEX 1	82

List of Figures	Page
Figure 1: Map showing aquaculture sites (red and black circles) in the western approaches overlaid against chart data (© Crown copyright 1980).	3
Figure 2: Map showing Scottish aquaculture sites (black dots) and predicted EUNIS (EUNIS, 2010) habitats for Scottish coastal waters using GIS data layers. Different sediment types represented by colours, for example orange is described as deep circalittoral sand, purple as deep circalittoral mud (silt-clay) and brown as circalittoral sandy-mud (sandy silt).	4
Figure 3: Time domain plot of (dB Plus II) Airmar (upper panel shows a 10.3 kHz single tone burst, lower pane shows a sequence of tone bursts).	5
Figure 4: Time versus frequency spectrogram for a sequence for a single Airmar system recorded at a range of 2 m (Lepper <i>et al.</i> , 2004).	6
Figure 5: Effective RMS source level versus time at fundamental frequency. Duty cycle of around 3.5% during a burst sequence.	6
Figure 6: Typical Airmar (dB Plus II) deployment at fish farm cages (Source www.airmar.com).	7
Figure 7: Ten transducer (Airmar dB Plus II) deployment at fish farm cages (Source www.benex.co.uk).	7
Figure 8: Airmar dB Plus II calibration.	8
Figure 9: Airmar (dB Plus II) system (Source www.airmar.com).	8
Figure 10: Spectrogram of the Programme 4. example from the Terecos system.	9
Figure 11: Terecos programme 2 example time domain on various scales.	10
Figure 12: Terecos programme 2 spectrogram.	10
Figure 13: Seq. 2. Fundamental and harmonics.	10
Figure 14: Sequence 1 and sequence 2 peak frequency RMS source level estimates.	11
Figure 15: Effective RMS received level versus time at 4.9 kHz for a programme 4 sequence (DSMS-4 range 2 m).	12
Figure 16: Terecos type DSMS-4 transducer.	12
Figure 17: Terecos type DSMS-4 controller unit.	12
Figure 18: Ace Aquatec Universal Scrammer Unit.	13
Figure 19: Silent Scrammer trigger unit.	13
Figure 20: Time domain plots Silent Scrammer (Ace Aquatec) test sequence.	13
Figure 21: Pulse length variation across all 28 possible pulsed emissions.	14
Figure 22: Frequency time distribution of all possible Universal Scrammer transmissions.	14
Figure 23: Maximum RMS source level estimates for individual Universal Scrammer signal types (1-28) and frequency of major signal component.	15
Figure 24: Effective RMS received level versus time at 10 kHz across all 28 signal types.	15
Figure 25: SEL Source Level integrated across 1 s in third octave band for the Ace Aquatec system.	18
Figure 26: SEL Source Level integrated across 1 s in third octave band for the Airmar system.	18
Figure 27: SEL Source Level 'On period' integrated across 1 s in third octave bands for the Terecos system Programme P1.	19
Figure 28: SEL Source Level 'On period' integrated across 1 s in third octave bands for the Terecos system Programme P2.	19
Figure 29: SEL Source Level 'On period' integrated across 1 s in third octave bands for the Terecos system Programme P3.	19
Figure 30: SEL Source Level 'On period' integrated across 1 s in third octave bands for the Terecos system Programme P4.	19
Figure 31: Shallow water aquaculture site of varying bathymetry.	21
Figure 32: Seabed bathymetry.	21
Figure 33: Extracted seabed profiles surrounding the aquaculture site.	21

Figure 34:	Shows the complex transmission loss profile for a 10 kHz source (Airmar) from a northerly bearing (0°) taken from the shallow water site shown in Figure 31. Source depth 10m.	22
Figure 35:	Shows transmission loss at 10 kHz (Airmar system) taken on a northerly bearing from a shallow water site shown in Figure 31. Source and receiver depth 10 m.	22
Figure 36:	Shows transmission loss at 4 kHz (consistent with the Terecos system) taken on a northerly bearing from a shallow water site shown in Figure 31. Source and receiver depth 10 m.	22
Figure 37:	Image sources to a receiver in a shallow water channel.	24
Figure 38:	Example of range averaging for a sandy sediment in 30 m water depth at 10 kHz TOB centre frequency.	26
Figure 39:	Example of range averaging for a sandy sediment in 30 m water depth at 2 kHz TOB centre frequency.	26
Figure 40:	Propagation loss at a range of 500 m for a 30 m deep site with a sandy sediment versus wind speed.	27
Figure 41:	Range averaged propagation loss versus water depth for a silty (mud).	28
Figure 42:	Range averaged propagation loss versus water depth for a silty (mud) sediment for a 2.5 kHz centre frequency.	29
Figure 43:	Range averaged propagation loss versus water depth for a silty (mud) sediment for a 31.5 kHz centre frequency.	29
Figure 44:	5 kHz TOB propagation loss for different sediment types in 30 m water depth.	31
Figure 45:	10 kHz TOB propagation loss for different sediment types in 30 m water depth.	31
Figure 46:	2 kHz TOB propagation loss for different sediment types in 30 m water depth.	32
Figure 47:	3.15 kHz TOB propagation loss for different sediment types in 30 m water depth.	32
Figure 48:	10 kHz propagation loss versus seabed down slope for a 10 m deep receiver using a sandy sediment.	33
Figure 49:	10 kHz range averaged propagation loss versus seabed down slope for a 10 m deep receiver using a sandy sediment.	34
Figure 50:	10 kHz propagation loss versus seabed slope for a 10 m deep receiver using a sandy sediment in 80 m water depth.	35
Figure 51:	10 kHz propagation loss versus seabed slope for a 10 m deep receiver using a sandy sediment in 30 m water depth.	35
Figure 52:	Sampled measurement points in Loch Nevis (red circles) and Taret aquaculture site (green triangle).	37
Figure 53:	Predicted (using source image model) and measured received level for at a deep water site on Loch Nevis. Received level based on an equivalent RMS source level 175 dB re $1\mu\text{Pa.m}$.	38
Figure 54:	SEL source levels in third octave bands for the Airmar system.	41
Figure 55:	Broadband SEL received levels for a 30 m deep site with a silt-clay sediment using an Airmar system.	41
Figure 56:	Hearing threshold data for a range of cetaceans.	46
Figure 57:	Hearing threshold data of a range of pinniped species.	46
Figure 58:	The M-weighting filters taken from Southall et al. (2007).	52
Figure 59:	Transmission loss profile in a silt sediment for a 2 kHz centre frequency versus depth (all data range averaged as per Harrison and Harrison, 1995).	55
Figure 60:	Transmission loss data for a 5 kHz signal with and without range averaging (Harrison and Harrison, 1995).	56
Figure 61:	Propagation loss data organization within sensitivity model database (source data generated using source-image model).	57
Figure 62:	Cumulative SEL exposure model flow chart.	58

Figure 63: Example of a range of influence estimation for a broadband signal for a 30 m deep site and a 140 dB re 1 $\mu\text{Pa}^2\text{s}$ hypothetical impact threshold.	59
Figure 64: Effect of seabed slope versus received level at 10 kHz for a 30 m deep site with a sandy sediment.	60
Figure 65: Adjusted flat seabed received level to compensate for upslope loss differences at 10 kHz for a 30 m deep site with sandy sediment.	61
Figure 66: M-weighted (Southall et al., 2007) for a low frequency cetacean equivalent SEL source levels in third octave bands for an Ace Aquatec system.	62
Figure 67: Example screen capture of interactive sensitivity model output for minimum range to avoid TTS threshold exposure from 1 second exposure.	63
Figure 68: Received level modelling at a site with significant slope.	64
Figure 69a: Example output for time for exposure to reach the injury threshold of 186 dB re 1 $\mu\text{Pa}^2\text{s}$ for a pinniped for a single Terecos system versus distance for multiple water depths.	65
Figure 70a: Example output for time for exposure to reach the injury threshold of 186 dB re 1 $\mu\text{Pa}^2\text{s}$ for a pinniped for a single Ace Aquatec system versus distance for multiple water depths.	66

List of Tables	Page
Table 1: Other commercially available ADD systems (compiled from Gordon and Northridge, 2002; Ainslie, 2010).	16
Table 2: Water column properties used throughout modelling.	25
Table 3: Sediment properties used throughout modelling (Hamilton, 1980).	25
Table 4: Functional marine mammal hearing groups taken from Southall et al., (2007).	51

Acknowledgements

We would like to sincerely acknowledge the assistance and valuable information provided by and the manufacturers of the ADD systems manufacturers / engineers Baxter Binnie and Maureen Glen (Terecos), John Ace-Hopkins (Ace Aquatec) and Chris Hyde (Airmar) Steve Christensen (Airmar USA) and finally Owen McGrath (SNH) for his valuable feedback on the model and database development.

1. INTRODUCTION

This report is intended to outline the tasks undertaken towards completion of the Scottish Natural Heritage (SNH) funded project entitled “Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland”.

The interaction between aquaculture and seals is a well-documented problem in many areas and acoustic deterrent devices (ADDs) are often used to mitigate this. Harbour seals (*Phoca vitulina*) are considered to cause the biggest problem at Scottish sites (Quick *et al.*, 2004). Such interactions can lead to lower production in a number of ways: as a result of direct mortality to farmed species, from increased fish-stress and/or from damage to nets caused by predation attempts. A number of methods are utilised on fish farms to minimise interactions with seals including net tensioning, provision of additional ‘predator netting’, and lethal removal of individual seals (Ross, 1988).

A commonly applied method for reducing seal-aquaculture interactions in Scotland is the use of high source-level underwater sounds, many of which are targeted at the range of best hearing sensitivity of seals, to deter them from sites (Jefferson and Curry, 1996). These devices are most commonly referred to in the literature as Acoustic Harassment Devices (AHDs) or Acoustic Deterrent Devices (ADDs).

Globally, a wide range of anthropogenic activities introduce sound into the marine environment. Some are incidental by-products of industrial processes, however, some are intentionally produced to warn animals of the presence of fishing gear or to scare predators away from aquaculture sites (Jefferson and Curry, 1996). Underwater noise is generated by commercial shipping, oil and gas exploration, military activities, scientific research, fishing activities, recreational pursuits, marine renewable energy (MRE) installations and acoustic devices deployed on aquaculture sites (Richardson *et al.*, 1995; Shrimpton and Parsons, 2000; Carter, 2007; Linley *et al.*, 2009). Relatively little is known about the impacts of such noise sources on marine fauna, but the consensus is that there is potential for impacts on marine species and a need for better understanding (ASCOBANS, 2006; MMC, 2007). All cetacean species in the UK are protected under Annex IV of the EC ‘Habitats Directive’ (Council Directive 92/43/EC), as “*animal [and plant] species of community interest in need of strict protection*” with two sections of Article 12 being of particular relevance: 12(b) which prohibits “*deliberate disturbance of these species, particularly during the period of breeding, rearing, hibernation and migration*” and 12(d) which prohibits “*deterioration or destruction of breeding sites or resting places*”.

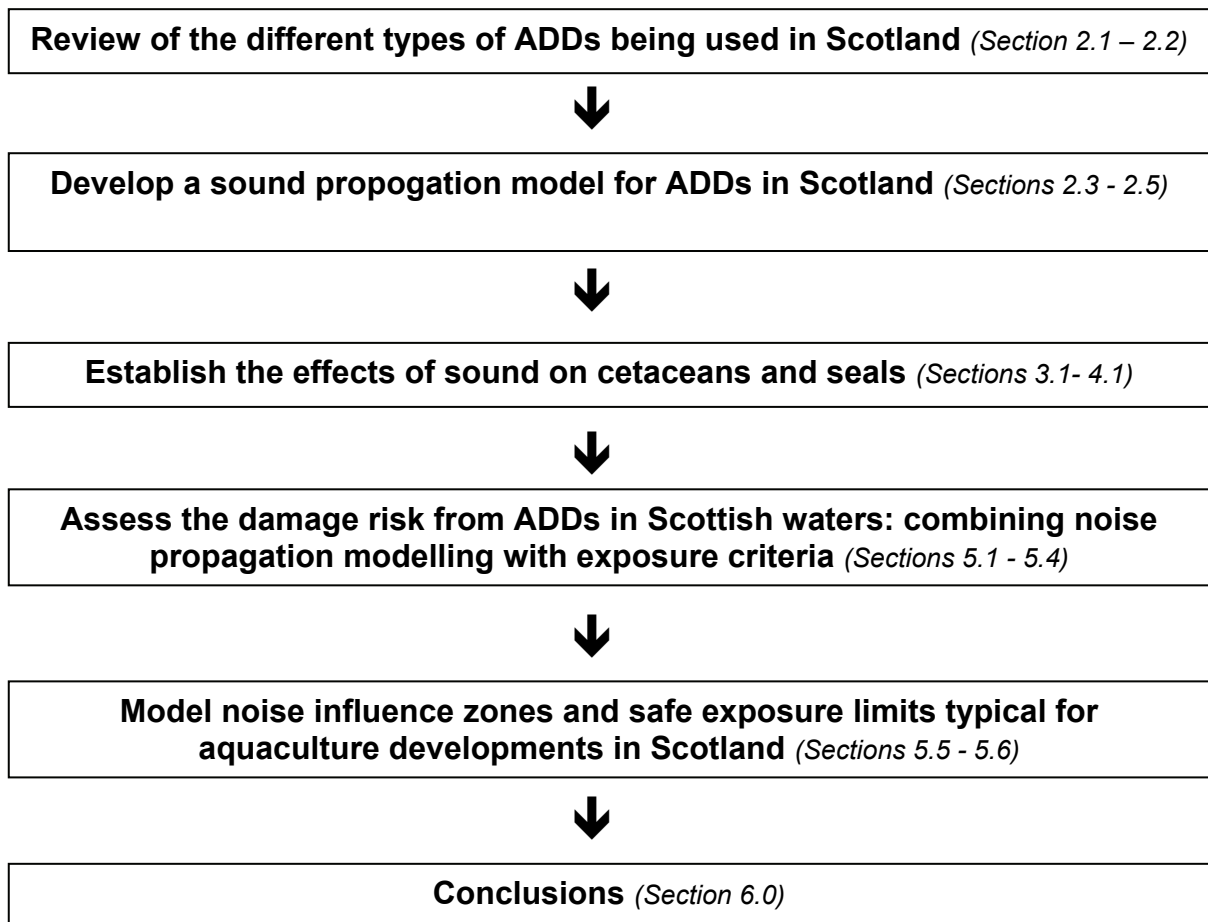
The UK is a signatory to the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) and Resolution 4 of the Conservation and Management Plan indicates that continued effort towards “*the prevention of [other] significant disturbance, especially of an acoustic nature*” must be made (ASCOBANS, 2006). Furthermore, the potential impact of anthropogenic activities on marine species and the need for additional research have been raised in the UK Biodiversity Action Plan.

To assess potential impact due to underwater acoustic emissions a number of marine mammal acoustic impact criteria are currently proposed for example in the Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations (Southall *et al.*, 2007) and observed Temporary Threshold Shift (TTS) (Lucke *et al.*, 2009). Southall *et al.* identify a dual injury criteria based on zero-peak and a cumulative exposure criteria based on Sound Exposure Level (SEL). In the case of SEL this is a weighted broadband metric. Individual frequency components of the broadband signals often show a strong frequency versus propagation loss dependence with varying loss profiles. To reasonably represent the overall broadband propagation loss models are required to estimate the broadband loss for each

system and environment. These loss data can then be combined with source characteristics to give potential received levels surrounding a site.

The SEL-based criteria proposed by Southall *et al.* (2007) is frequency weighted to represent the functional hearing groups of cetaceans and pinnipeds. These are divided into low frequency hearing e.g. minke whale (*mysticetes*); mid frequency e.g. killer whales and many oceanic dolphins and high frequency cetaceans e.g. harbour porpoise (*Phocoena phocoena*) and pinnipeds in water. These weightings can then be applied to the estimated broadband received levels for each device and environment. Comparison of frequency weighted received levels versus range gives estimates of the zone of influence for specific impact criteria, source and environment to best estimate potential impact levels surrounding that site.

This project aims to develop an interactive sensitivity model to allow prediction of the zone of influence for user defined SEL impact criteria site by site. Data from propagation loss models were combined with source characteristics within the sensitivity model to allow the range to an impact level to be estimated for specific sites, devices and functional hearing groups. The steps used to define and the corresponding report chapters are listed below:



2. MODELLING SOUND PROPAGATION FOR ADDS IN SCOTLAND

2.1 Different types / models of ADDs being used

2.1.1 Introduction

Within Scottish waters three commercially available acoustic deterrent systems account for the vast majority of anti-predation systems in use (Northridge *et al.*, 2010). These are the Airmar (dB Plus II), the Ace Aquatec Silent Scammer and the DSMS-4 – Terecos system. Background research during this project suggests that devices such as the Ferranti-Thomson Mk2 Seal Scammer ('multi-tone'), Ferranti-Thomson Mk2 Seal Scammer x4, Ferranti-Thomson MK3 "Seal Scammer" and Simrad "Fishguard" may also be in use in more limited numbers.

In addition to a survey of acoustic deterrent devices in use, an extensive database and interactive GIS (Geographical Information System) has been established with information on Scottish aquaculture sites, bathymetry data (UKHO chart data) and EUNIS data (EUNIS, 2010) for both observed and predicted habitats. The various levels of the GIS are fully interactive allowing direct interrogation of site information, bathymetry and habitat data. In the case of the aquaculture site database, data includes fields such as location, site ID, owner, operational status, licensed operation size, and potential marine mammal species of interest in that location. Figure 1 shows an example of GIS output for aquaculture sites overlaid against UKHO chart data. Figure 2 illustrates an example taken from the GIS output for known aquaculture sites against predicted EUNIS habitat data for the whole of Scotland.

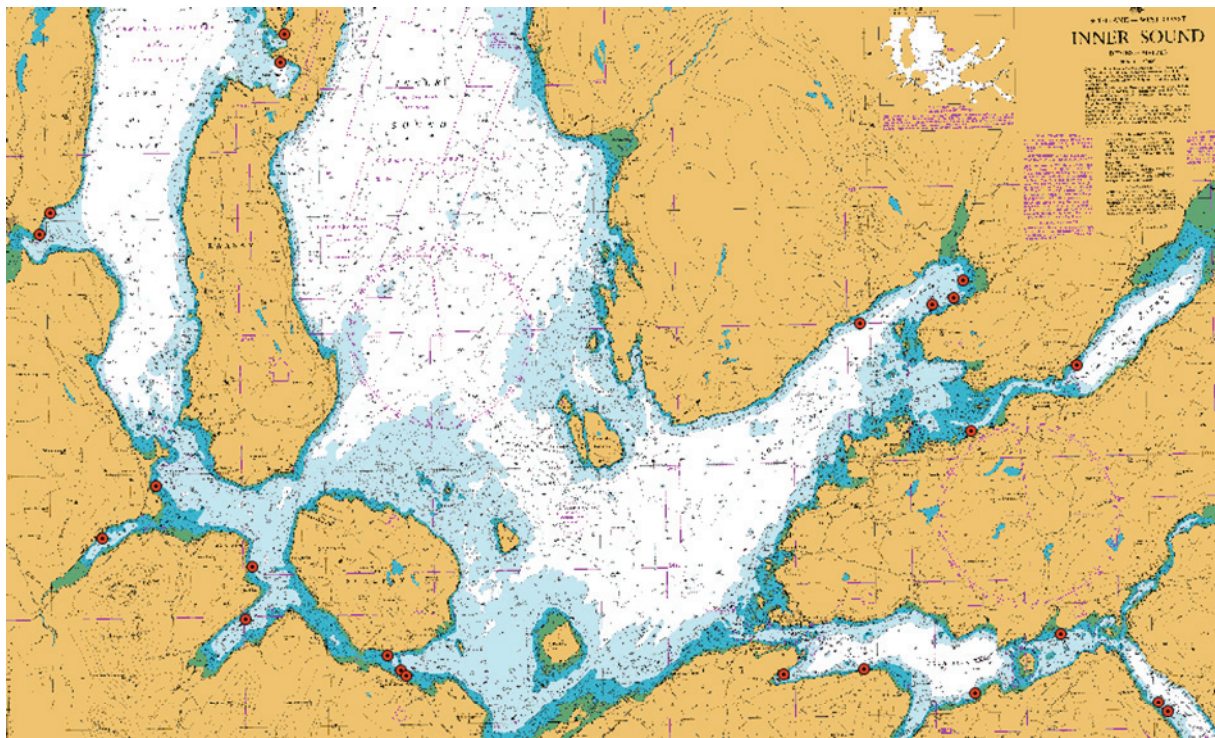


Figure 1: Map showing aquaculture sites (red and black circles) in the western approaches overlaid against chart data (© Crown copyright 1980).

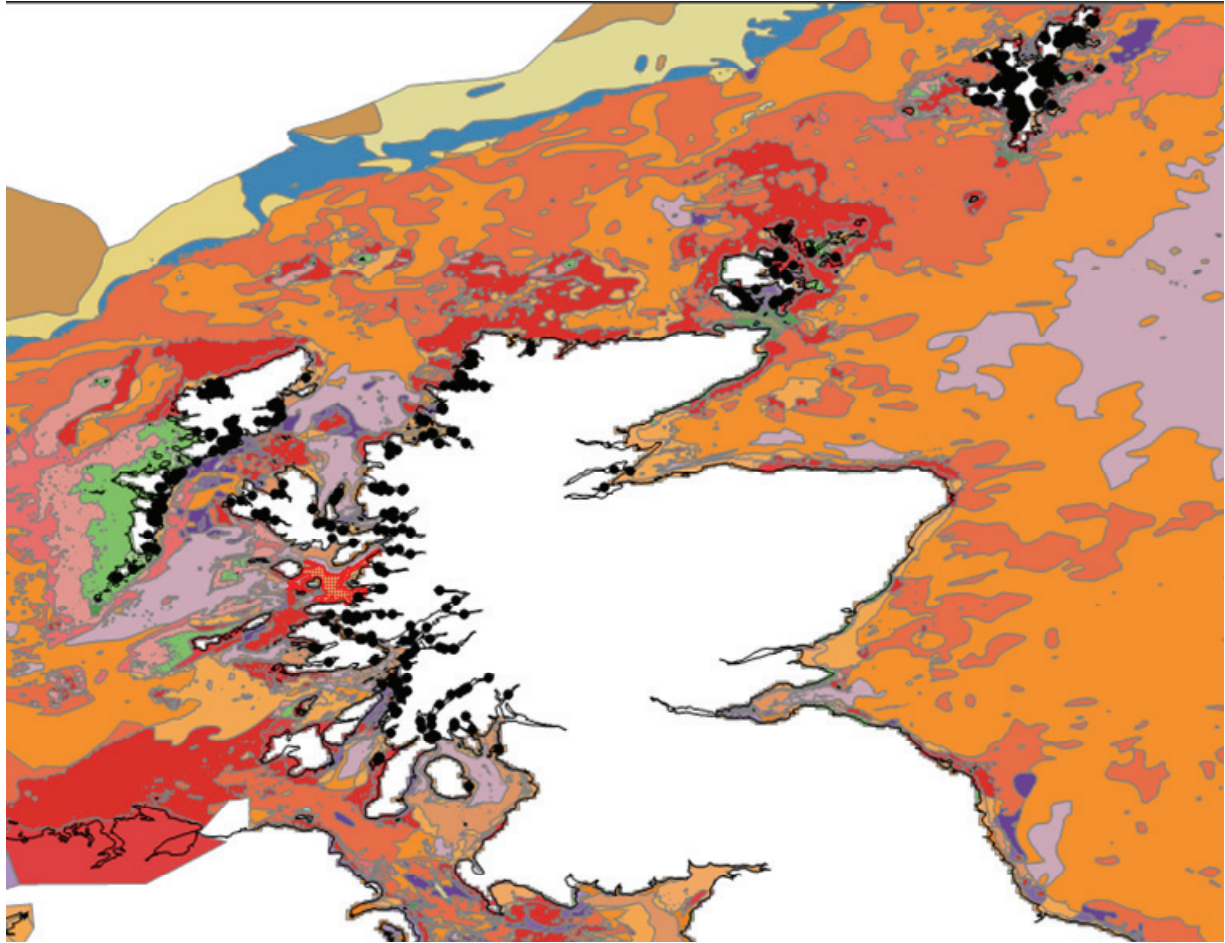


Figure 2: Map showing Scottish aquaculture sites (black dots) and predicted EUNIS (EUNIS, 2010) habitats for Scottish coastal waters using GIS data layers. Different sediment types represented by colours, for example orange is described as deep circalittoral sand, purple as deep circalittoral mud (silt-clay) and brown as circalittoral sandy-mud (sandy silt).

2.1.2 Summary

An extensive GIS database of Scottish aquaculture sites has been developed, including site details, seabed bathymetry and habitat data. Additional acoustic survey data from 2007, 2008 and 2009 obtained by Booth (2010) and the Hebridean Whale and Dolphin Trust (HWDT) have also been reviewed. These data have been used for model parameter definition, validation and site usage and have provided an insight to marine mammal sensitivities discussed in section 3 of this report. Interviews with manufacturers (Airmar, Terecos and Ace Aquatec) have also provided valuable insight into the status and use of their own and other ADD systems within Scottish waters.

2.2 Review of ADD systems in use in Scottish waters

2.G1 Introduction

The acoustic characteristics of the three most commonly used ADDs in Scottish aquaculture have been reviewed. These are the Airmar (dB Plus II), Ace Aquatec Silent Scammer and the Type DSMS-4 – Terecos system. The characteristics of these devices are summarised below.

2.G2 Airmar (dB Plus II)

Acoustically the Airmar (dB Plus II) system is one of the simplest signals. It emits a pulsed sinusoidal tonal burst of around 10 kHz. Each burst is around 1.4 ms long with a 40 ms gap, Figure 3 (middle panel). A sequence of just under 60 pulses lasting around 2.25 seconds is then fired followed by a 2 second quiet period with an approximately 50% duty cycle. A broadband spectral response is seen at the sharp turn 'on' pulse edge at the beginning of each pulse with detectable energy levels from the fundamental at 10.3 kHz to frequencies greater than 50 kHz and down to a lower frequency component around 1.5 kHz shown in Figure 4.

Lepper *et al.* (2004) measured the peak frequency response at 10.3 kHz with an equivalent Root Mean Square (RMS) source level of 192 dB re 1 $\mu\text{Pa}\cdot\text{m} \pm 1$ dB (with re 1 $\mu\text{Pa}\cdot\text{m} \pm 1$ dB RMS being the reference pressure). Manufacturers claim a 9.8 kHz centre frequency (Figure 4). Additional evenly spaced harmonic components of the fundamental frequency are evident at equivalent source levels of greater than 145 dB re 1 $\mu\text{Pa}\cdot\text{m} \pm 1$ dB (RMS) up to 103 kHz.

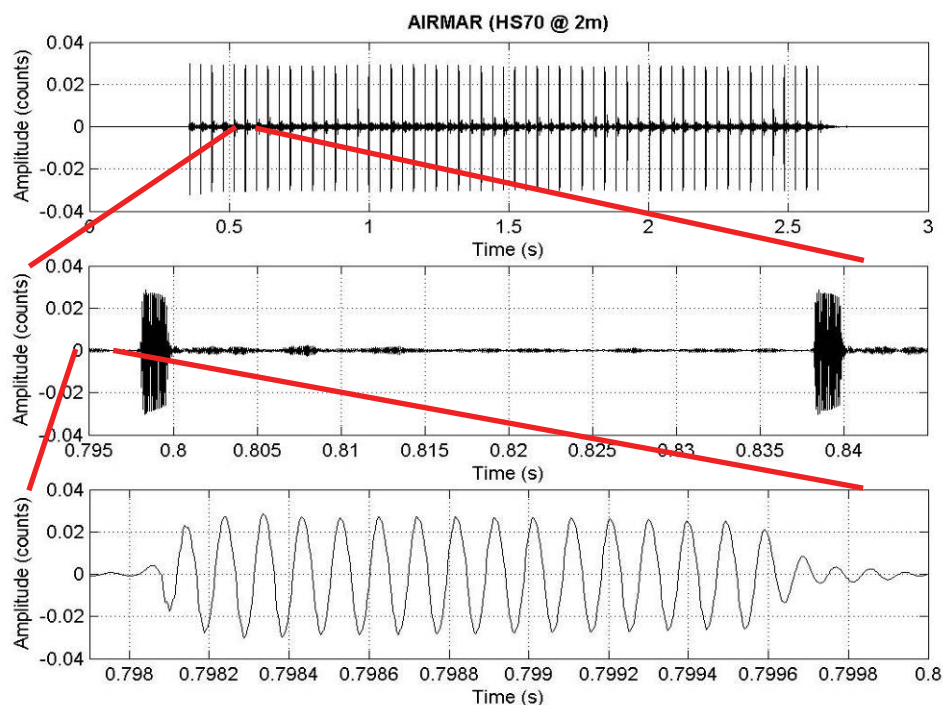


Figure 3: Time domain plot of (dB Plus II) Airmar (upper panel shows a 10.3 kHz single tone burst, lower pane shows a sequence of tone bursts).

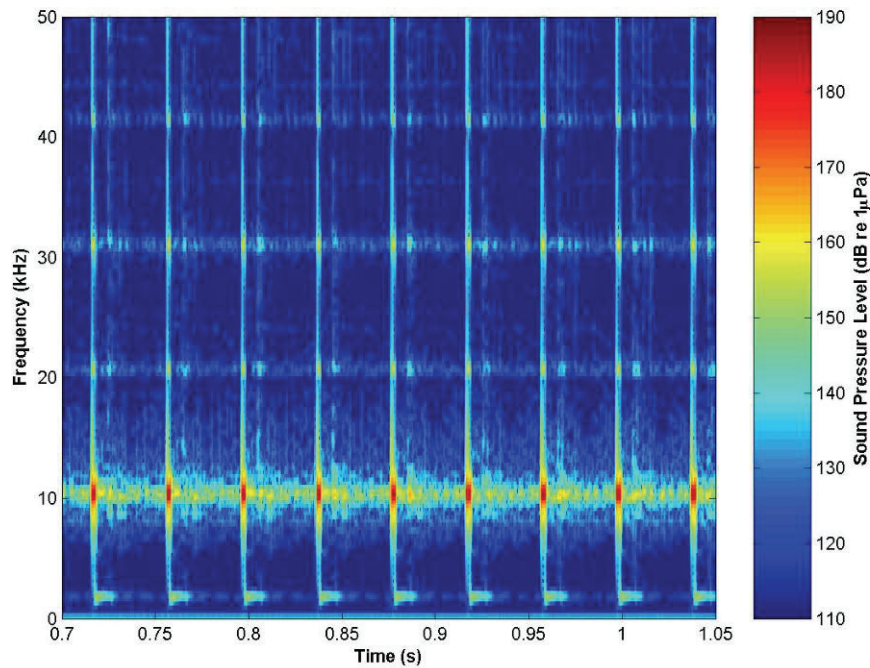


Figure 4: Time versus frequency spectrogram for a sequence for a single Airmar system recorded at a range of 2 m (Lepper et al., 2004).

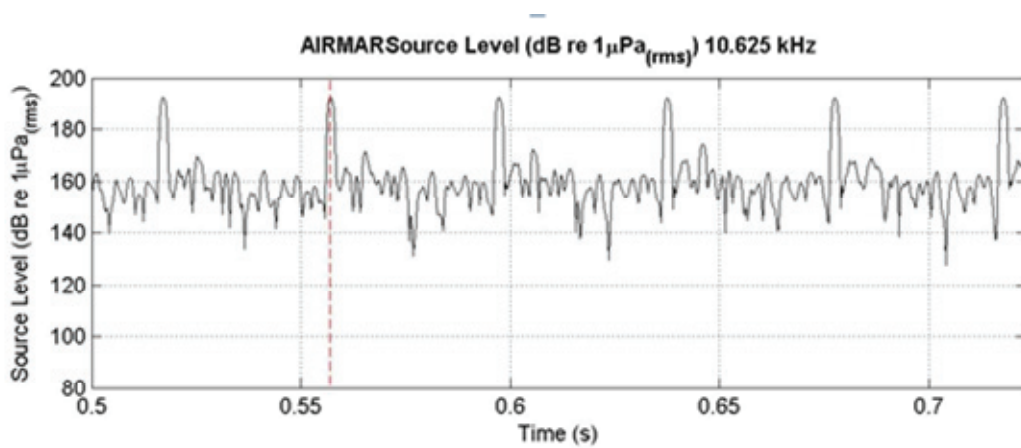


Figure 5: Effective RMS source level versus time at fundamental frequency. Duty cycle of around 3.5% during a burst sequence.

Figure 5 shows the fundamental frequency duty cycle of around 3.5% during a burst sequence.

The operation of more than one transducer simultaneously has also been reported at some sites (pers. comm., Booth, 2012) with a typical deployment involving four transducers (Figure 6), each being fired in turn with a 2 second quiet period. It is also possible to configure systems to cover each and every cage (Figure 7). Manufacturers also claim a soft-start feature with a 70 second ramp-up to full power when first switched on.

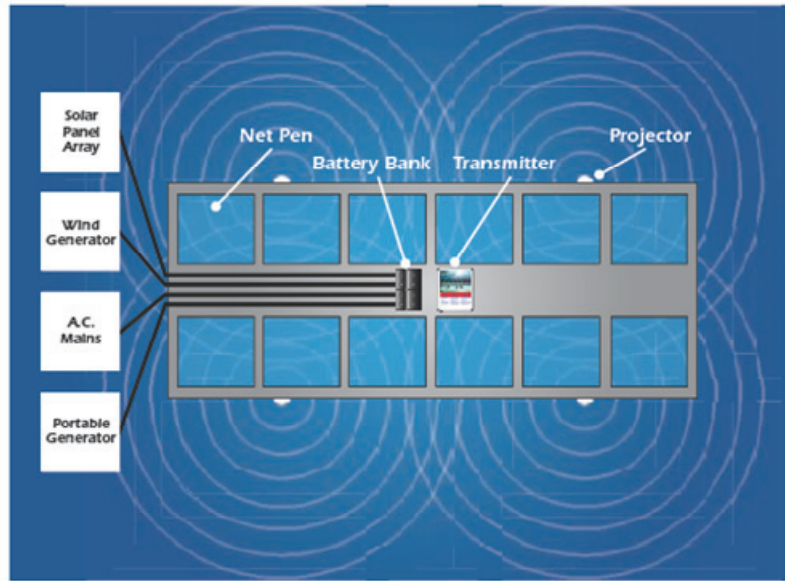


Figure 6: Typical Airmar (dB Plus II) deployment at fish farm cages (Source www.airmar.com).

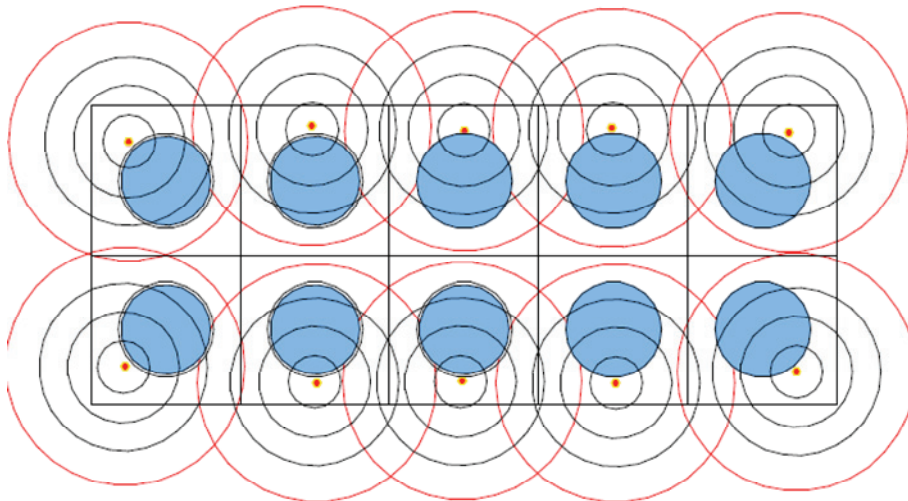


Figure 7: Ten transducer (Airmar dB Plus II) deployment at fish farm cages (Source www.benex.co.uk).



Figure 8: Airmar dB Plus II calibration trials 2003 (Lepper et al., 2004).



Figure 9: Airmar (dB Plus II) system (Source www.airmar.com).

Acoustic output can vary with depth of the source due to surface interactions. It is also likely that output will vary depending on manufacture, site layout, etc. (pers. comm. with Airmar USA). Multiple transducers may be deployed per controller, fired in sequence. Figures 8 and 9 show an Airmar transducer and control system. Several units may be deployed across large aquaculture sites with a consequence of simultaneous firing from multiple transducers. Manufacturers (Airmar USA) recommend transducers are deployed below (1-2 m) the lowest point on the net cages or in mid-water although this varies from site to site. They advise not deploying near the surface. In the UK, transducers are bought under licence from Airmar USA and then cables are custom spliced to suit each farm. Therefore it is likely that similar transducer depths will be used across Scottish sites for the Airmar systems, typically 2 m below maximum net depth.

The Airmar system was calibrated in a free-field in 2003 (Lepper *et al.*, 2004) at a range of 2 m. On this occasion the RMS source level was found to be 192 dB re 1 μ Pa.m (\pm 1dB). This is reasonably consistent with previous studies with values of 194 dB re 1 μ Pa.m (RMS) reported by Haller and Lemon (1994) and Yurk and Trites (2000). This also corresponds with the manufacturers (per. comm. Airmar USA) stated source level of 194 dB re 1 μ Pa.m (RMS) or 198 dB re 1 μ Pa.m (peak-peak) measured in a small calibration tank. Lower source level values have been reported of 152 dB re 1 μ Pa.m (RMS) (Taylor *et al.*, 1997) and 179 dB re 1 μ Pa.m (peak-peak) (Jacobs and Terhune, 2002). These lower source levels may be due to the build-up of fouling on the transducer and/or lower battery voltages (Gordon and Northridge, 2002; Booth, 2010).

2.G3 Terecos (Type DSMS-4)

Based on data from calibration trials by Lepper *et al.* (2004) the Terecos system deploys a complex series of multi-frequency components with a high degree of randomness in the sequence timing. The system operates in four different programmes or combination of programmes. These programmes can be broken down into a number of key features. These include a sequence of 5 segment (16 ms duration) continuous tonal blocks forming an up and down frequency sweep (labelled Seq.1), randomly timed sequence of continuous and time variant multi-component tonal blocks and sequences (Seq.2) of eight segment (8 ms duration) continuous tonal blocks forming an up and down frequency sweep. Each programme either uses a signal type in isolation or combination. Figure 10 shows an

example of a programme 4 sequence containing seq.1 signals, seq. 2 signals, continuous and time variant signals.

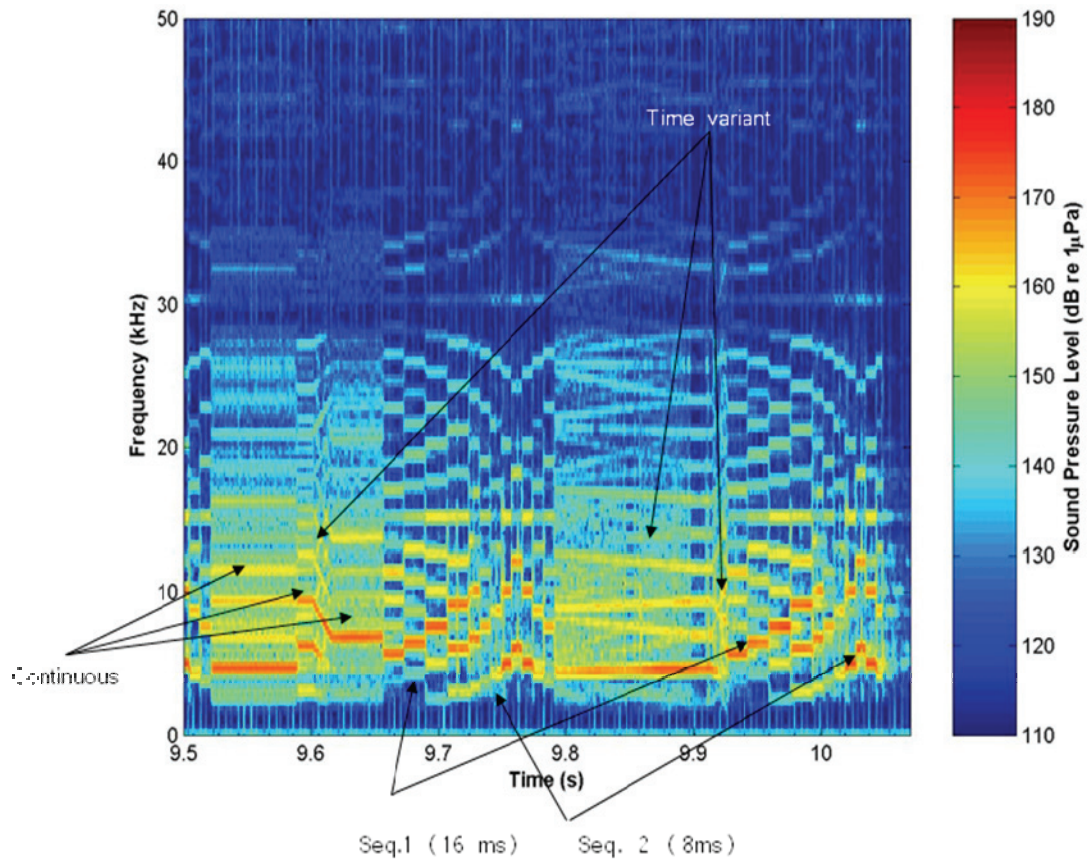


Figure 10: Spectrogram of the Programme 4 example from the Terecos system.

Programme 1: Sequence (Seq.1, Figure 10) of repetitive five segment (16 ms duration) continuous tonal blocks forming an up and down frequency sweep. Seq. 1 has fundamental frequencies ranging from 1.8 kHz - 3.8 kHz with uniformly distributed harmonic components. The maximum levels were often seen in the second and third harmonic components with a maximum observed source level of 177 dB re 1 μ Pa.m (RMS) (\pm 1 dB) at 6.6 kHz with no equivalent source levels of greater than 146 dB re 1 μ Pa.m (RMS) at frequencies above 27 kHz.

Programme 2: Randomly timed sequence of continuous and time variant multi-component tonal blocks.

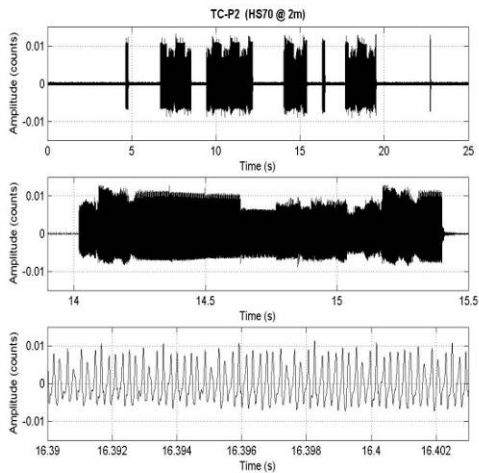


Figure 11: Terecos programme 2 example time domain on various scales.

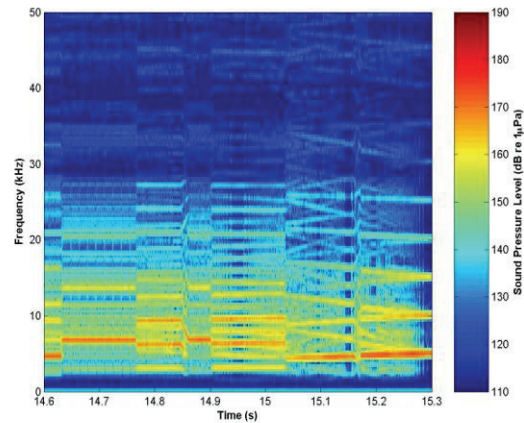


Figure 12: Terecos programme 2 spectrogram.

In Figure 11 multi-component continuous tonals were observed with a peak level frequency of 4.7 kHz and 6.8 kHz with equivalent source level of 179 dB re 1 μ Pa.m (RMS) \pm 1 dB and 178 dB re 1 μ Pa.m (RMS) \pm 1 dB respectively. Both contain complex multiple frequency components with a broad energy distribution away from the peak level tonal component with equivalent peak source levels of less than 145 dB re 1 μ Pa.m for frequencies above 27 kHz (Figure 12). In addition, examples of the complex time variant signals can be seen, these appear similar in total energy distribution and maximum observed source level to the previously described tonals with the addition of complex time varying components. These data spectrally appear similar to data reported by Gordon and Northridge (2002).

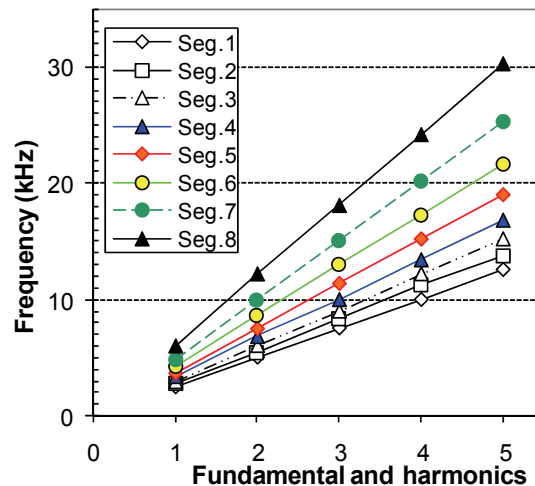


Figure 13: Seq. 2. Fundamental and harmonics.

Programme 3: Sequences (Seq.2) of eight segment (8 ms duration) continuous tonal blocks forming an up and down frequency sweep combined with variable continuous multi-component tonal blocks. Seq.2 has fundamental frequencies ranging from 2.4 kHz – 6.0 kHz again with uniformly distributed harmonics and maximum observed source level of 178 dB re 1 μ Pa.m (\pm 1 dB) at 4.9 kHz (Figure 13).

Programme 4: Randomly timed combined sequence of Seq.1, Seq.2 tonal blocks, continuous multi-component tonal blocks and time variant multi-component tonal blocks (combination programs 1-3).

Source level of fundamental and harmonics from Seq.1 & 2 signal types are shown in Figure 14. The vertical bars represent the frequency distribution of the fundamental and the 1st four harmonics and the circles the peak level frequency. Highly randomised quiet periods were observed in each of the programmes with different combinations of the sequence signal type during the transmission phase. Due to the randomization the effective duty cycle between sequences was not directly quantifiable.

Due to the complex nature of the time signals, key continuous tonal components will be modelled individually including the seq.1 and seq.2 signals and the fundamentals of the continuous signals observed in the program 4 signal. In addition broadband SEL levels not originally reported in the 2003 study could be modelled in equivalent third octave bands (TOB) across the band of interest. The random nature of the duty cycle, however, will make cumulative SEL estimates complicated. Manufacturers report transmission duration of between 15 seconds and 2 min with pulse duration 200 ms to 8 seconds.

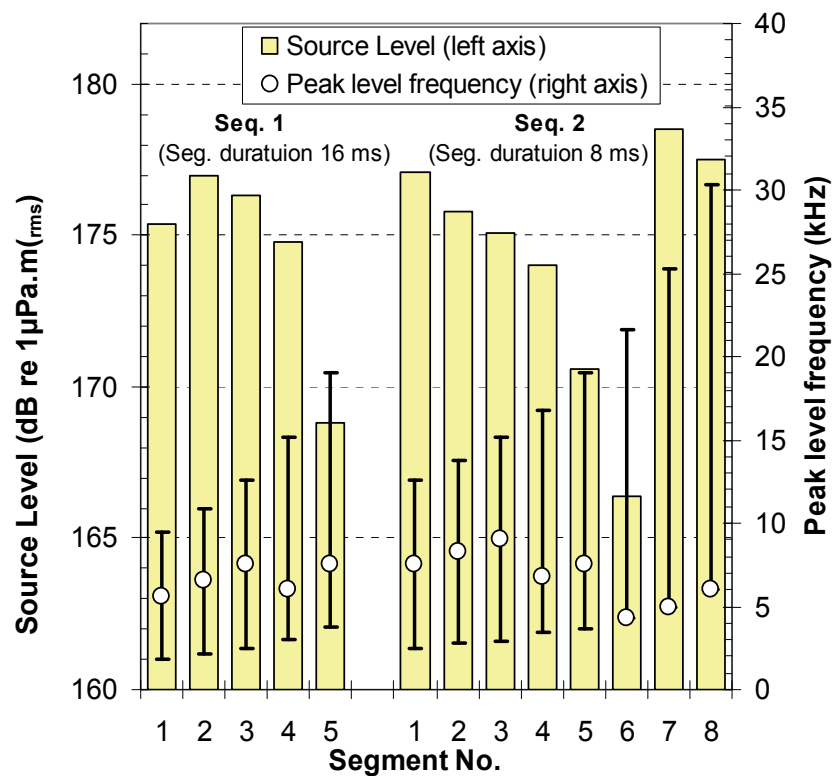


Figure 14: Sequence 1 and sequence 2 peak frequency RMS source level estimates (DSMS-4).

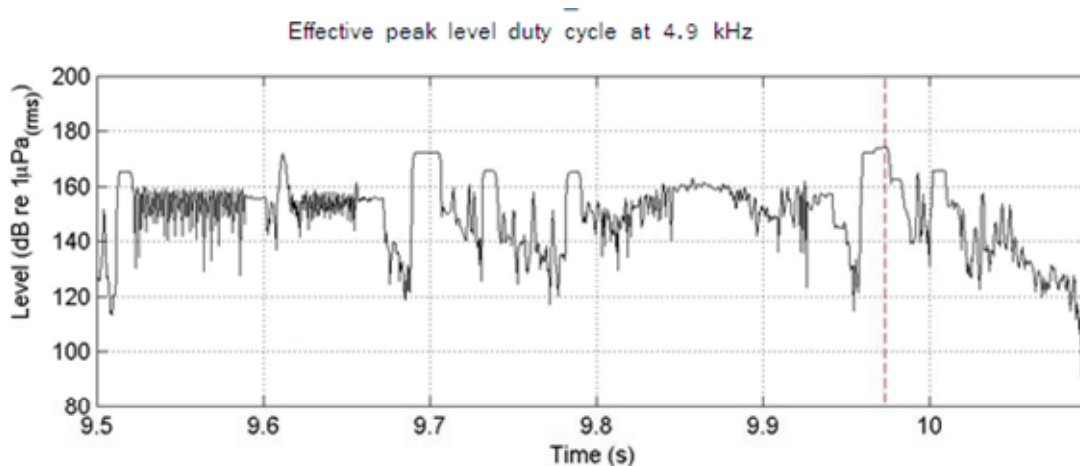


Figure 15: Effective RMS received level versus time at 4.9 kHz for a programme 4 sequence (DSMS-4 range 2 m).

Figure 15 shows the typical RMS levels at 4.9 kHz across programme 4 sequences combining programmes 1-3. Examples of the type-DSMS-4 transducer and controller are shown in figures 16 and 17 respectively.

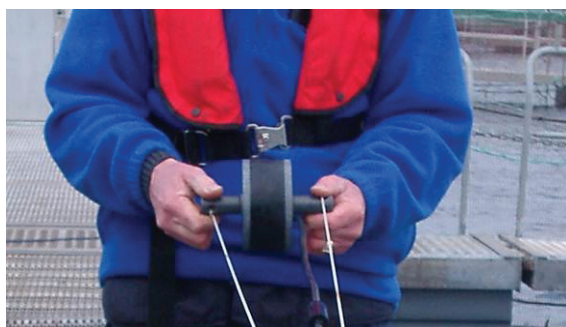


Figure 16: Terecos type DSMS-4 transducer.

Figure 17: Terecos type DSMS-4 controller unit.

2.G4 Ace Aquatec (Silent Scrammer)

The Ace Aquatec Universal Scrammer unit (Figure 18) can be programmed to operate in a timed mode with programmable 5 second bursts between 6 and 72 times per hour. In 'silent mode' the transmission of the Universal Scrammer is acoustically triggered by an independent trigger unit (Figure 19). This may for example translate fish panic from a seal attack into a trigger signal causing the scrammer signal to be emitted, otherwise the system remains silent (<http://www.aceaquatec.com>; pers. comm.).

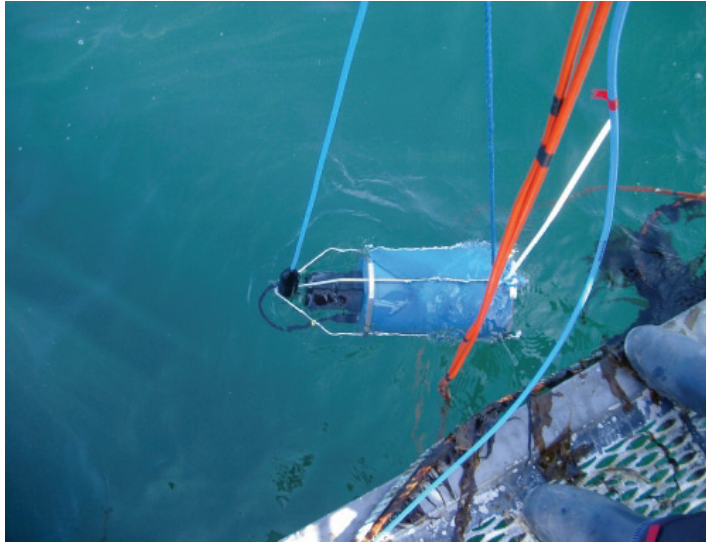


Figure 18: Ace Aquatec Universal Scrammer Unit.

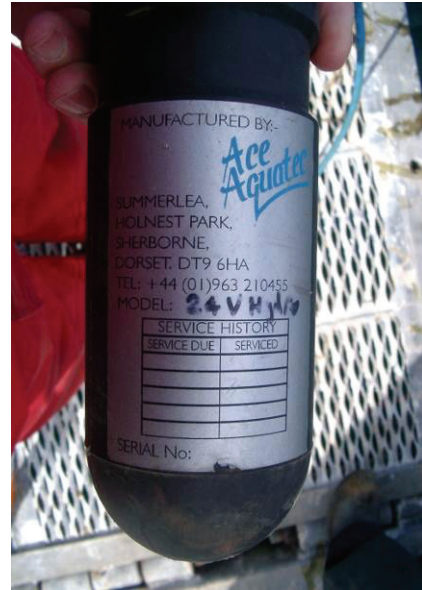


Figure 19: Silent Scrammer trigger unit.

Figure 20 shows a time domain plot for a test sequence showing all possible pulses from the Ace Aquatec Universal Scrammer Unit. The upper panel shows a series of 9 test sequence transmissions. Each test sequence contains 28 possible pulses shown in the middle panel. An expanded view of pulse 19 is shown in the lower panel. In normal operation transmissions are a random selection of the 28 pulses. The randomised sequences are transmitted with a 50% duty cycle for a 5 s period. Each pulse is formed from two or more continuous tonal components producing a closely spaced comb type signal.

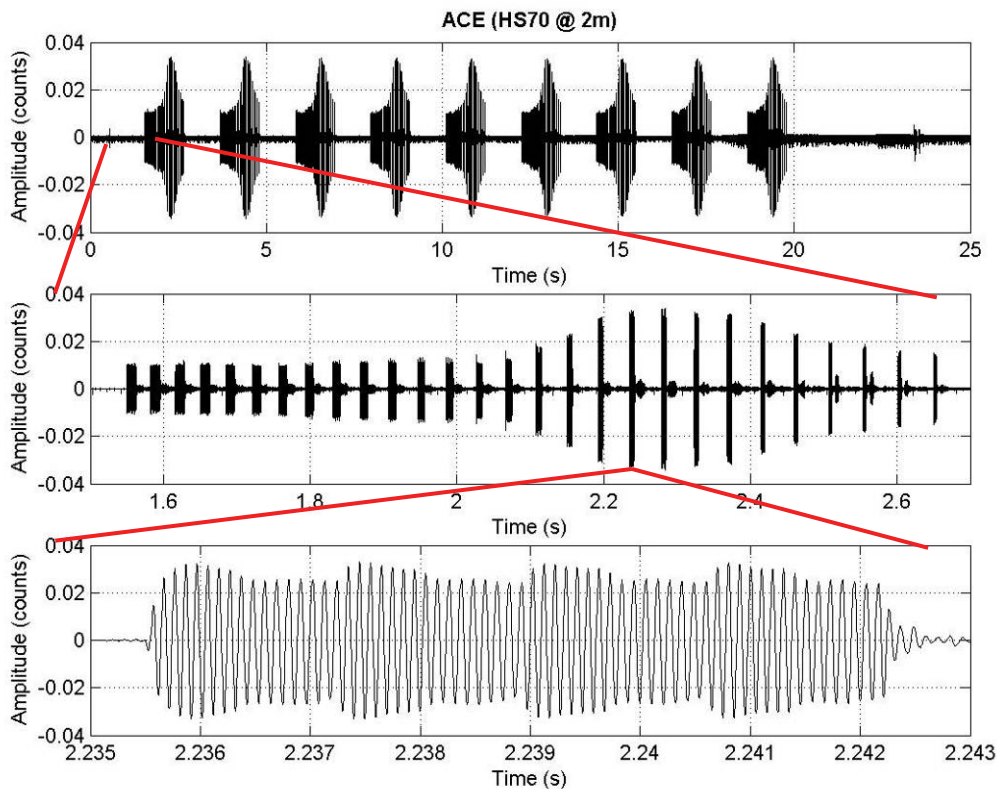


Figure 20: Time domain plots Silent Scrammer (Ace Aquatec) test sequence.

The relative length of the pulses uniformly shortens from around 14 ms to 3.3 ms followed with an up-shift in the frequency of the tonal components and their equivalent distribution to each other. Inter-pulse timing varies from 33.2 ms – 48.5 ms during the sequence related to the pulse length (Figure 21).

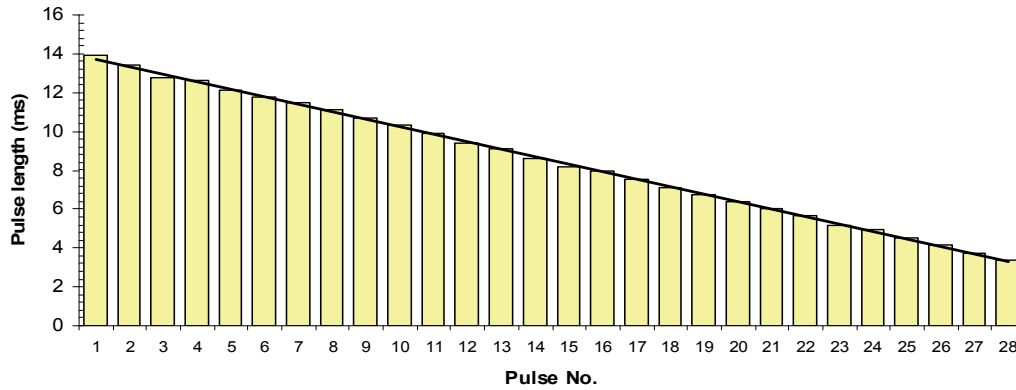


Figure 21: Pulse length variation across all 28 possible pulsed emissions.

Figure 22 shows the frequency–time distribution for the entire sequence. Due to the spread of the tonal components and additional harmonics and inter-modulation products the RMS signal levels > 165 dB re 1 μ Pa.m at 30 kHz and components > 145 dB re 1 μ Pa.m at 70 kHz were observed.

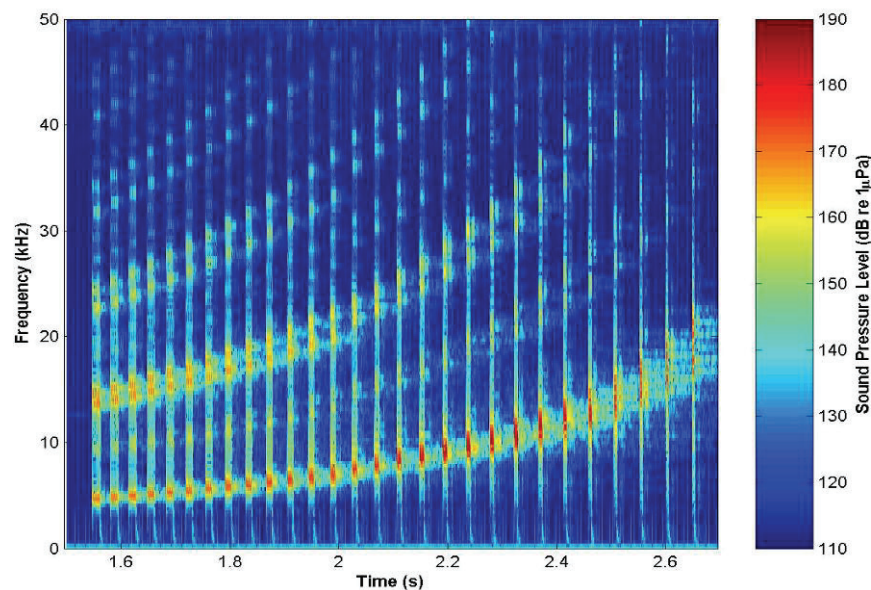


Figure 22: Frequency time distribution of all possible Universal Scrammer transmissions.

Figure 23 represents the maximum observed source level for each pulse with its equivalent peak level frequency. The vertical bars represent the frequency distribution of the peak (circle) and first two (pulses 1-13) first (pulses 14-23) major harmonic and fundamental tonal components. Pulse 19 shows the maximum observed source levels of 193 dB re 1 μ Pa.m \pm 1 dB (RMS) for a ~10 kHz tonal signal.

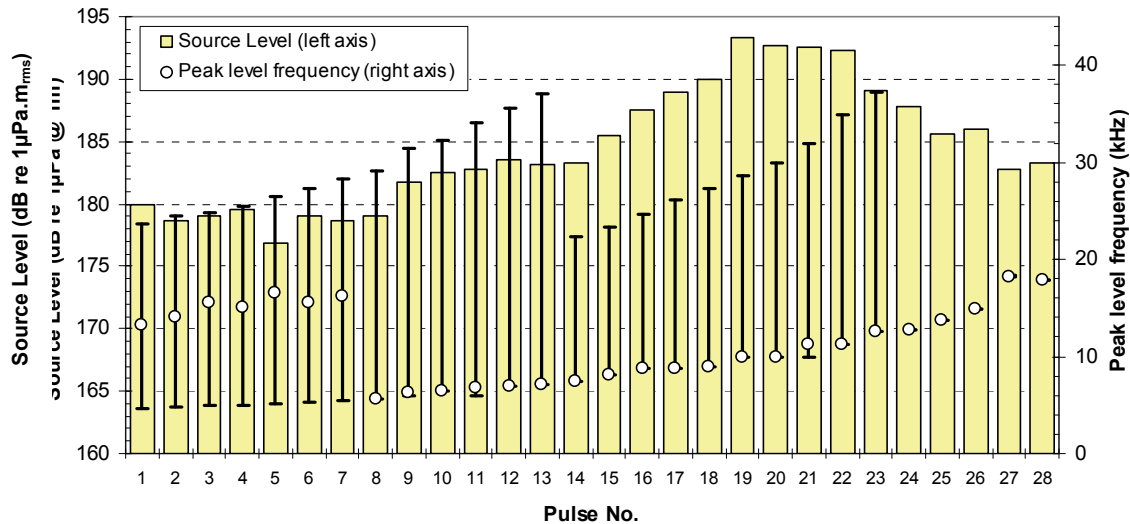


Figure 23: Maximum RMS source level estimates for individual Universal Scrammer signal types (1-28) and frequency of major signal component.

In the case of the first seven pulse types the peak level is at the first harmonic. Individual peak level frequency (frequency at which the highest amplitude was observed) components range from 5.6 kHz to 17.8 kHz. The largest energy levels observed were round 10 kHz. The effective duty cycle for the 28 point test sequence at 10 kHz is shown in Figure 24.

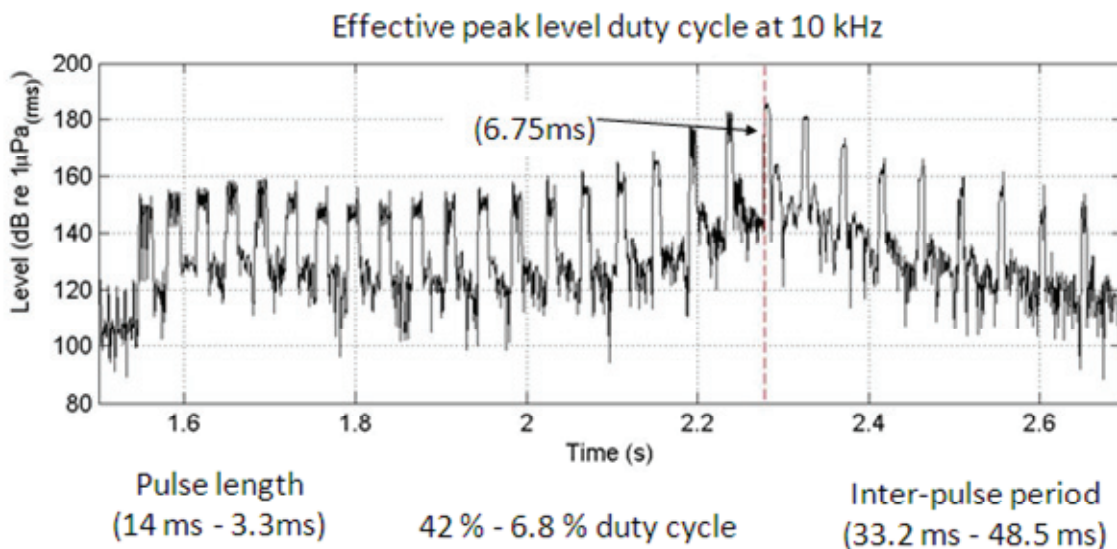


Figure 24: Effective RMS received level versus time at 10 kHz across all 28 signal types.

Overall source levels and broad frequency band are consistent with previous studies with maximum source level estimates of around 193 dB re 1 μPa.m ± 1 dB (RMS) (Lepper *et al.*, 2004) and manufacturer and previous works reviewed by Gordon and Northridge (2002) of 194 dB re 1 μPa.m ± 1 dB (RMS). However, frequency of peak level appears lower in the 2004 study (Lepper *et al.*, 2004) with maximum source level observed around 10 kHz. In a COWRIE report (Nedwell *et al.*, 2010) trials on Ace Aquatec systems report a calculated source levels of 204 dB re 1 μPa.m ± 1 dB (Peak-Peak), 183-184 dB re 1 μPa.m ± 1 dB (RMS) and SEL values from 190-192 dB re 1 μPa².s.m ± 1 dB (SEL). The SEL values are broadly consistent with previously reported RMS values but in this study the RMS values are lower than previous, which may be due to different estimate methodologies.

Output power is also relative to battery level (pers. comm. Ace Aquatec). In the case of the 2004 study maximum power was used typical of normal operation (Lepper *et al.*, 2004). The duty cycle or total cumulative exposure is likely to be highly variable if system is used in a silent mode due to variation in the sensitivity of the triggers (net movement, number of attacks etc.). Again, where applicable, data from active sites using the silent scammer will be reviewed. Modelling will be focused on the fundamental and higher level harmonics component for each signal type.

2.G5 Additional systems

Gordon and Northridge (2002) reported the sale and potential use of several other devices within Scottish waters including the Ferranti-Thomson Mk2 Seal Scrammer ('multi-tone'), Ferranti-Thomson Mk2 Seal Scrammer x4 and the Simrad "Fishguard". Opportunistic recordings of these systems are described by Gordon and Northridge (2002) from various sources although not all ADD types were identified.

Table 1: Other commercially available ADD systems (compiled from Gordon and Northridge, 2002; Ainslie, 2010).

	Freq. (kHz)	Source Level (RMS dB re 1 μ Pa.m)	Transmission duration (s)	Pulse duration (ms)	Duty cycle
Ferranti-Thomson Mk2 Seal Scrammer ('multi-tone')	8-30 kHz	194 dB	20 s double scram 40 s	20 ms	~ 3% 5.5. scrams an hour
Ferranti-Thomson Mk2 Seal Scrammer x4	8-30 kHz	200 dB @ 25.6 kHz	20 s double scram 40 s	20 ms	~ 3% 5.5. scrams an hour
Ferranti-Thomson MK3 "Seal Scrammer"	10-40 kHz	194 dB @ 27 kHz (Taylor <i>et al.</i> , 1997)			
Simrad "Fishguard"	15 kHz	191 dB	6 s	500ms	25-50%
Lofitech	15.6 kHz	193 dB		200ms	
Ocean Engineering Enterprise DRS-8	3 kHz	202 dB (Kastelein <i>et al.</i> , 2007)			

The primary focus of this report will be on the Airmar, Terecos DSMS-4 and Ace Aquatec systems during the modelling phase as these systems are in most common usage in Scottish waters. Historically significant similarities exist between the Ferranti-Thomson and the Ace Aquatec system potentially allowing this to be used as a replacement (pers. comm. Ace Aquatec). Personal communications with manufacturers report that the three systems,

Airmar, Terecos and Ace Aquatec, account for the vast majority of systems in use. A number of Lofitech systems are known to be used by fishermen but not these systems are not used at aquaculture sites (pers. comm. manufacturer). Similarly a number of Ferranti systems may still be in use, however, they are likely to be older and potentially in poorer condition if still operational (pers. comm. manufacturer). No use of newer systems has been reported.

2.G6 Source Characteristics in Third Octave Bands (TOB)

The signal characteristics seen particularly with the Terecos and Ace Aquatec systems are relatively broadband with frequency component source levels of greater than 140 dB re $1\mu\text{Pa}^2\text{s.m}^2$ from a few kHz up to greater than 40 kHz when integrated across a 1 second window. Similarly the Airmar system although generated from a single tonal pulse at around 10 kHz has a lower frequency component around 2 kHz and harmonics of the fundamental frequency of band source level greater than 140 dB re $1\mu\text{Pa}^2\text{s.m}^2$ for frequencies up to around 40 kHz. In the water column these different frequency components will propagate differently and cannot be easily described using a single propagation model run at one frequency. More generally, surface and bottom interaction can result in complex constructive and destructive interference fields that are dependent on both the frequency of the signal and the environments, seabed type, etc. To address this, acoustic output of each system is broken into a series of frequency bands using third octave band analysis. Propagation models are then run for each band centre frequency as representative of the mean transmission loss for all frequency components in that band. Variations of individual components within a band are represented using range averaging, discussed later, as an equivalent of frequency averaging all components within a band.

The equivalent SEL source levels (integrated across a 1 s window) in third octave bands were estimated for each of the systems from the RMS analysis given in sections 2.2.2 - 2.2.4 of this report based on data from Lepper *et al.* (2004). The systems have relatively complex duty cycles with sequences (here termed 'ON period') made up of bursts of signals or pulses and periods without a sequence of signal (here termed 'OFF period'). In the case of the Airmar and Ace Aquatec systems an inter-pulse duty cycle, with periods with no signal, also exists within the ON period, described more fully in section 2.2.2 and 2.2.4. In the case of the Terecos system although generally of lower amplitude, random length sequences of more than several seconds are often generated without inter-pulse gaps. All three systems are capable of generating ON periods sequence of greater than 2 seconds with highly variable OFF period timing due to trigger occurrence, system settings and random timing generators. To capture a representative ON period signal level for each system, the SEL source levels in third octave bands is taken for a given ON period integrated across 1 second. Figure 25 shows the SEL source level in third octave bands (TOB) of the Ace Aquatec system with the dominant frequency band between 4 kHz and 31.5 kHz. This can be compared with equivalent SEL source level in third octave bands for the Airmar system where the dominant frequency components (> 140 dB re $1\mu\text{Pa}^2\text{s.m}^2$) occur in the narrower band centred around 10 kHz but with a lower frequency component at 2 kHz (Figure 26).

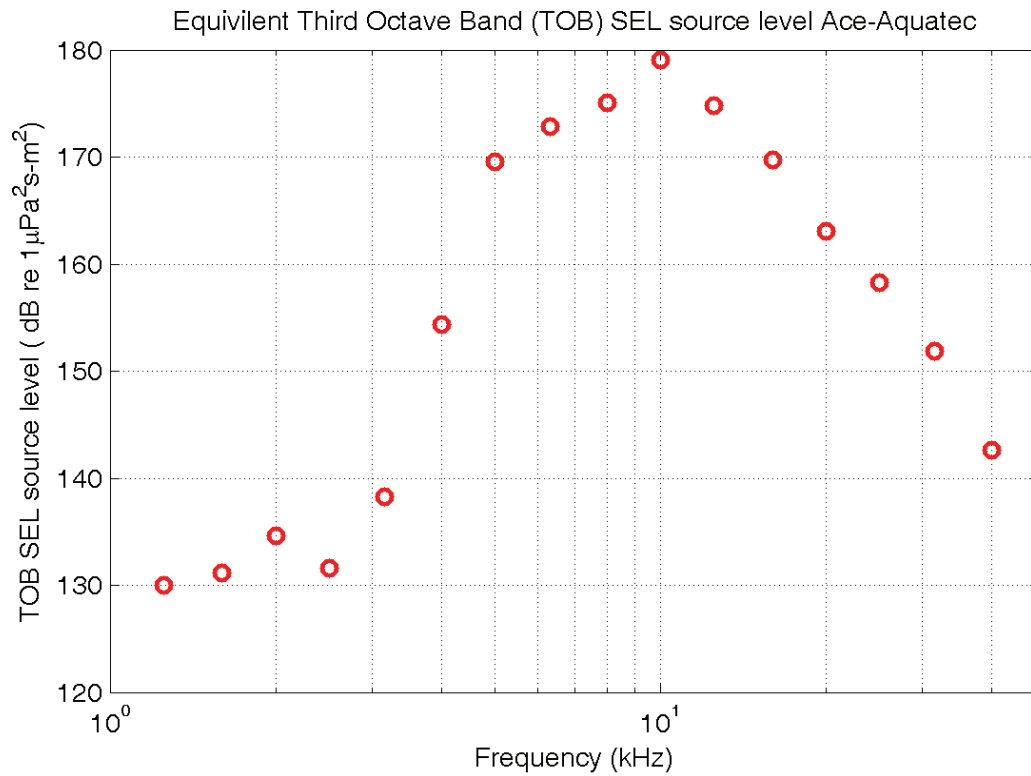


Figure 25: SEL Source Level integrated across 1 s in third octave band for the Ace Aquatec system.

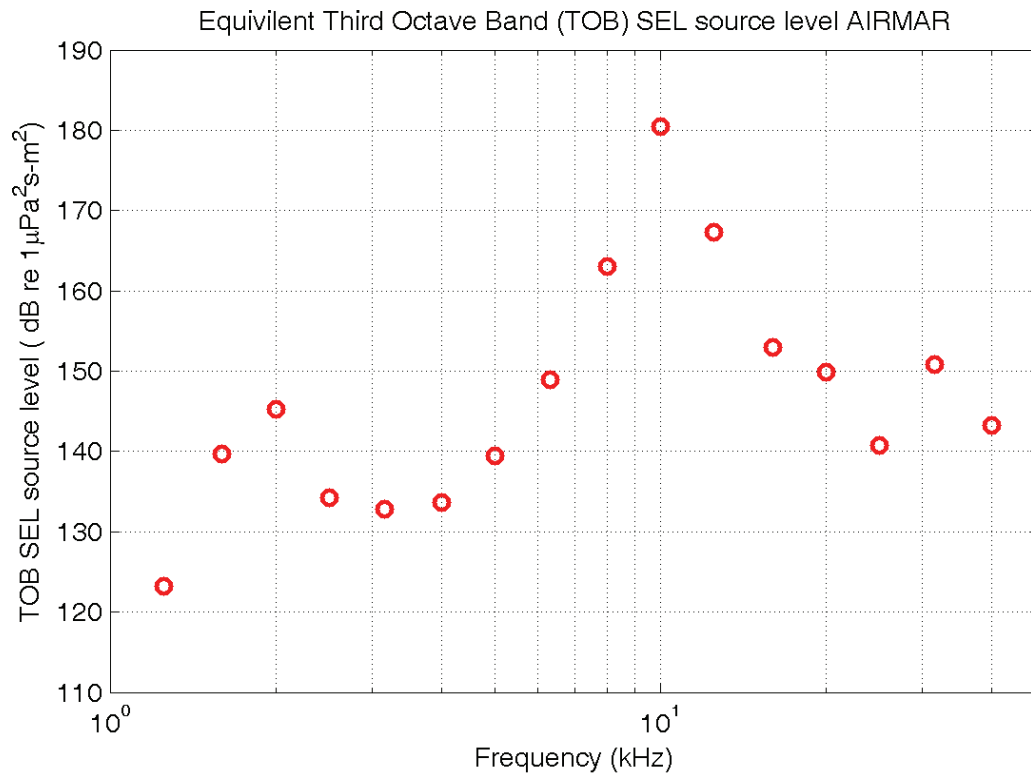


Figure 26: SEL Source Level integrated across 1 s in third octave band for the Airmar system.

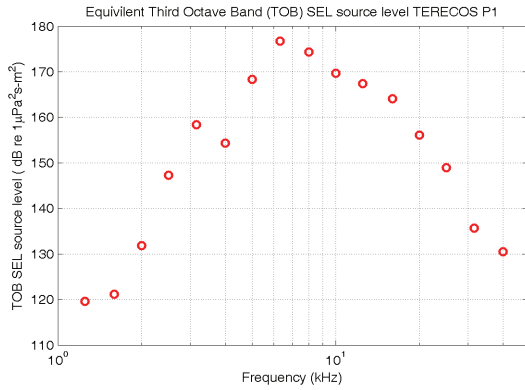


Figure 27: SEL Source Level ‘On period’ integrated across 1 s in third octave bands for the Terecos system Programme P1.

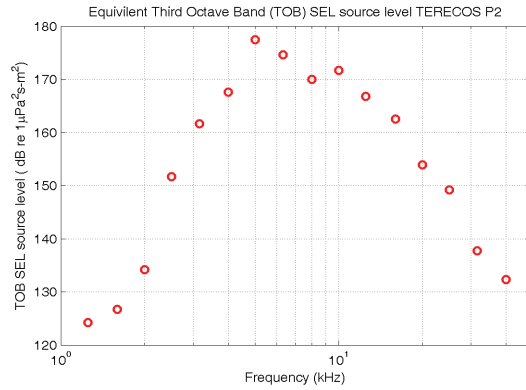


Figure 28: SEL Source Level ‘On period’ integrated across 1 s in third octave bands for the Terecos system Programme P2.

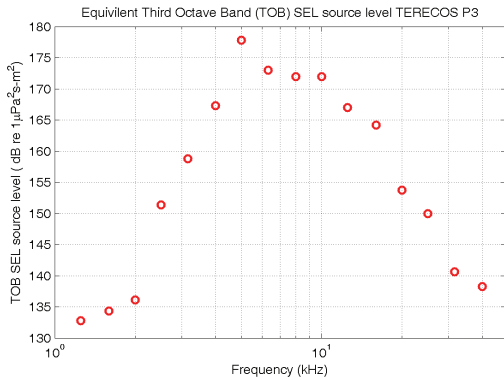


Figure 29: SEL Source Level ‘On period’ integrated across 1 s in third octave bands for the Terecos system Programme P3.

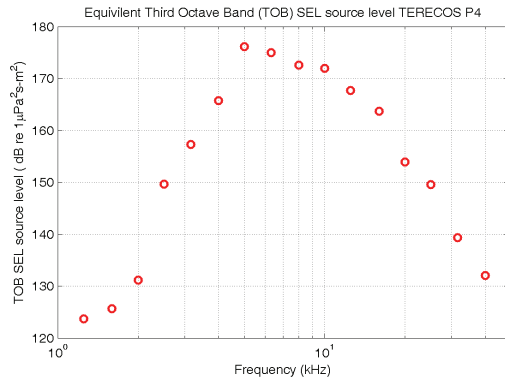


Figure 30: SEL Source Level ‘On period’ integrated across 1 s in third octave bands for the Terecos system Programme P4.

Figures 27-30 show the estimated SEL source levels in TOB for the four programs of the Terecos system. All four programs have equivalent SEL source level of > 140 dB re $1\mu\text{Pa}^2\text{s}\cdot\text{m}^2$ in bands between 2 kHz and 31.5 kHz.

Using these data the centre frequency of each TOB could then be modelled and propagation loss for that band estimated. Using the above analysis transmission loss for each the third octave band centres 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5 & 40 kHz were generated for a variety of conditions to test dependency on depth, sediment type, etc.

2.3 Test case modelling

2.H1 Range dependent modelling

This task was considered critical to the establishment of model sensitivities and parameters of a more ‘generic’ simplified modelling approach. Typically the assessment of potential impacts on a marine species is assessed against predetermined impact criteria (physiological and behavioural) usually in the form of either an instantaneous or cumulative acoustic received level threshold (Southall *et al.*, 2007). The acoustic received level at any given distance from a source is highly dependent on the source characteristics (amplitude, spectral and temporal content) and the environment the sound is travelling through.

In the case of sound propagation in a relatively shallow water environment, typical in marine aquaculture sites, complex interactions between sound in the water column and reflections from the surface and sea bed can take place. These 'multi-paths' can constructively and destructively interfere resulting in complex sound fields. The structure and complexity of these patterns is highly dependent on a range of parameters including, source frequency, source depth, receiver depth, water depth, water column sound velocity profiles, sediment types and surface roughness (mean wave height) and sea bed bathymetry.

Simple geometric models may not adequately model these effects and may therefore incorrectly represent sound fields in these environments (Shapiro *et al.*, 2009). For example in the case of varying bathymetry a site above a sloping sea bed may show significant difference in sound levels versus range going up the slope away from the source compared to going down the slope away from the source. It was therefore felt critical to understand the 'sensitivities' of these environment attributes to better establish more simplified model approach tolerances.

In the case of more complex environments such as those typically seen in Scottish aquaculture sites, more sophisticated modelling approaches can be employed. Various modelling approaches exist that will allow for varying bathymetry (termed range dependent), sediment type and water column acoustic properties. These models, however, are extremely numerically intensive requiring significant computing power and time and therefore are impractical for application to all Scottish aquaculture sites at this time. In order to establish a more generic model, however, these types of models were used to test the various environment properties discussed above on a series of test sites taken from known aquaculture facilities.

Using data on known source characteristics and environmental data, various key parameters were tested including:

- Source amplitude and spectral properties
- Dependence on water depth
- Dependence on sediment type
- Dependence on seabed slope
- Surface roughness

The modelling techniques used include range dependent (varying bathymetry) two-dimensional parabolic equation (PE) methodology (RAMGeo) (Collins, 1988) and a ray tracing code (Bellhop). Both codes are available in Actup suite of software generated by Curtin University (Maggi and Duncan, 2010). The RAMGeo code provides an excellent compromise between computation efficiency and numerical accuracy and is widely established in acoustic propagation modelling. Figure 31 shows an example of a shallow water (~ 16 m water depth) select test site in Veantrow Bay on Shapinsay. This site is of particular interest due to its placement in the mouth of the bay with increasingly shallow water on three sides of the site and slightly deeper water leading to the north. However, more generic attributes applicable to other shallow water sites may also be extracted.

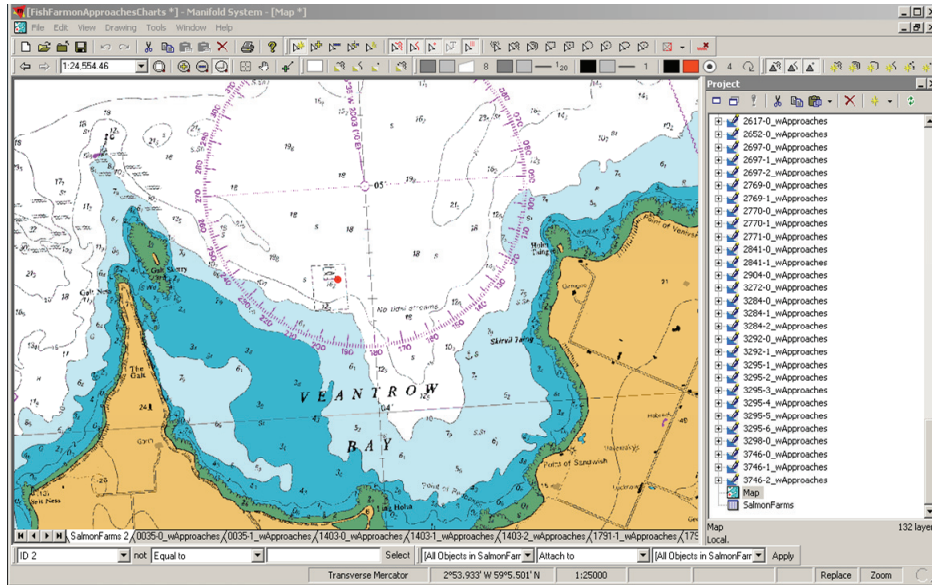


Figure 31: Shallow water aquaculture site of varying bathymetry.

A series of transects on different bearings can then be established. Different ADD properties at the site could then be tested and the received level in this type of environment estimated. Figure 32 shows the seabed profile (bathymetry) surrounding the aquaculture site taken from electronic chart data. Each profile shown as a white dashed line is 2 km long. The corresponding 2 km long seabed profiles are shown in Figure 33. Note, that apart from the three most northerly transects, a ‘beaching’ profile is fairly pronounced with water depths reducing to zero often within 2 km.

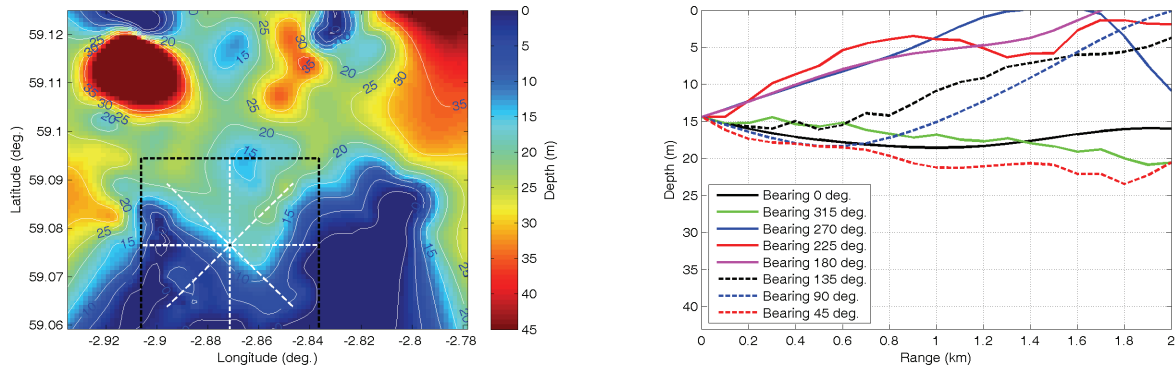


Figure 32: Seabed bathymetry surrounding aquaculture site.

Figure 33: Extracted seabed profiles surrounding the aquaculture site.

Due to the proximity of most aquaculture sites to the shore, within island systems or waterway inlets, the local bathymetry is often highly variable around the site. Figure 34 shows an example of a transmission loss estimate for a northerly bearing for a 10 kHz signal as that seen in the Airmar system using a sandy sediment type at the location shown in Figure 31.

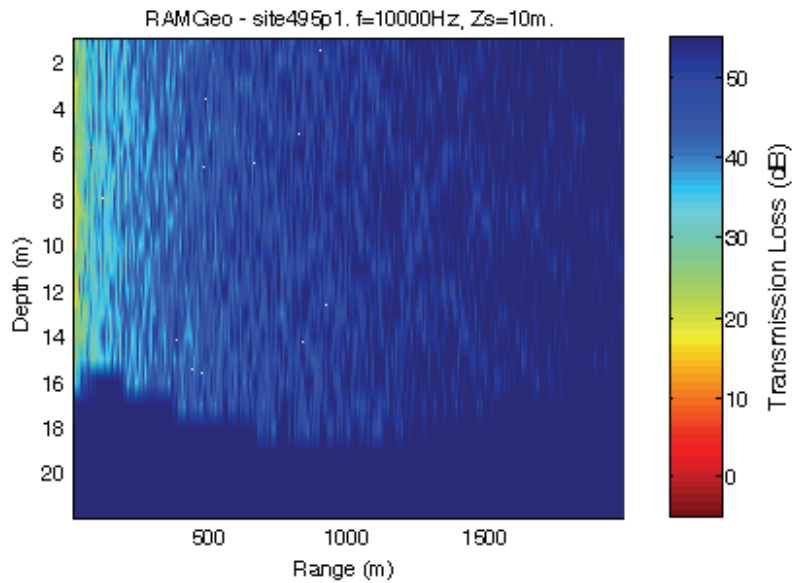


Figure 34: Shows the complex transmission loss profile for a 10 kHz source (Airmar) from a northerly bearing (0°) taken from the shallow water site shown in Figure 31. Source depth 10m.

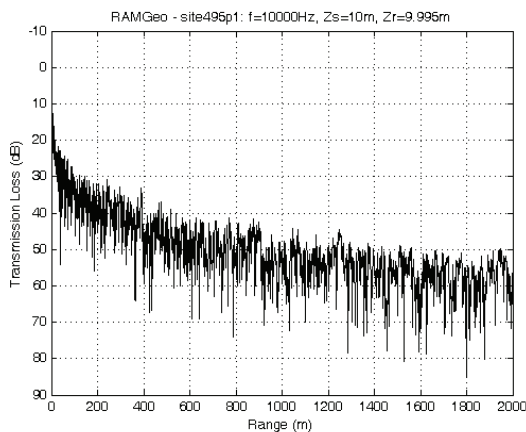


Figure 35: Shows transmission loss at 10 kHz (Airmar system) taken on a northerly bearing from a shallow water site shown in Figure 31. Source and receiver depth 10 m.

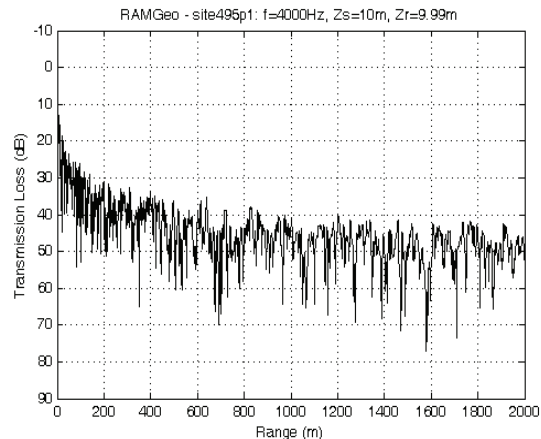


Figure 36: Shows transmission loss at 4 kHz (consistent with the Terecos system) taken on a northerly bearing from a shallow water site shown in Figure 31. Source and receiver depth 10 m.

The transmission loss at specific depths can then be observed. Figure 35 shows the transmission loss at 10 m water depth for a northerly bearing from the above site. Note that losses in the region of 50-60 dB are observed at a range of 2 km. This can be compared with a 4 kHz source shown in Figure 36 (comparable with some of the strongest signals observed in the Terecos system). Note slightly lower losses observed at lower frequencies. These data can then be combined with source level data to provide estimates of received level with range.

The above example illustrates profiles for a real site. However, in development of a more generic approach detailed models have been run for more 'generic' profiles at frequencies of (2 kHz, 2.5 kHz, 3.15 kHz, 4 kHz, 5 kHz, 6.3 kHz, 8 kHz, 10 kHz and 12.5 kHz, 16 kHz, 20 kHz, 25 kHz, 31.5 kHz & 40 kHz) corresponding to the third octave band centre frequencies

for the main spectral content of the three most common devices in use. For a more broadband source such as the *Terecos* system, bands are combined to give a representative broadband response. In addition the dependence on water depth (taken from the range of Scottish aquaculture sites), sediment type (EUNIS data), and seabed slope are tested independently. This analysis forms the basis of the sensitivities for the simplified modelling approach outlined in section 3.3.4.

2.H2 Introduction to Source Image Model (ImageTL)

The acoustic model used to calculate the propagation loss is a source-image model which models the sound field of a source as the sum of the acoustic radiation from the source and a series of images of the source reflected in the medium boundaries: in this case, the water surface and sea bed (Urlick, 1983). The source is modelled as an ideal point source. The arrangement of the source and its images can be seen in Figure 37.

The sound field of the point source with a pressure of unit amplitude in a shallow water channel with a flat seabed and constant sound speed can be modelled as the sum of a series image sources, equation (1). The sound pressure is given as:

$$P = \frac{e^{jkr_1}}{r_1} + R_s \frac{e^{jkr_2}}{r_2} + \sum_{n=1}^{\infty} \left(R_s^{n-1} R_b^n \frac{e^{jkr_{1n}}}{r_{1n}} + R_s^n R_b^n \frac{e^{jkr_{2n}}}{r_{2n}} + R_s^n R_b^n \frac{e^{jkr_{3n}}}{r_{3n}} + R_s^{n+1} R_b^n \frac{e^{jkr_{4n}}}{r_{4n}} \right) \quad (1)$$

where

$$r_1 = \sqrt{R^2 + (h-d)^2}, \quad r_2 = \sqrt{R^2 + (h+d)^2},$$

$$r_{1n} = \sqrt{R^2 + (2nH - h - d)^2}, \quad r_{2n} = \sqrt{R^2 + (2nH + h - d)^2},$$

$$r_{3n} = \sqrt{R^2 + (2nH - h + d)^2}, \quad r_{4n} = \sqrt{R^2 + (2nH + h + d)^2}$$

H : water depth

d : source depth

h : receiver depth

R : horizontal range between source and receiver

$$k = 2\pi f / c,$$

f : frequency,

c : sound speed in water

R_s : surface reflection coefficient

R_b : bottom reflection coefficient

This model has been implemented to predict transmission loss in shallow water channels in a MATLAB program (named "ImageTL" for the purpose of identification in this report). The sea bottom is assumed to be elastic with compressional speed c_b , shear speed c_s and density ρ_b . The reflection from such a bottom is described by Brekhovskikh and Lysanov (2003). The surface reflection coefficient is obtained with the higher value of two surface reflection/ scattering models; a simplified Beckman-Spizzichino model (Coates, 1988) for an incoherent surface scattering and, a Gaussian coherent reflection coefficient (Medwin and

Clay, 1988) using wind speed (Ainslie *et al.*, 1994). Sound attenuation as a function of frequency is included in the model (Francois and Garrison, 1982a, 1982b, Ainslie and McColm 1998).

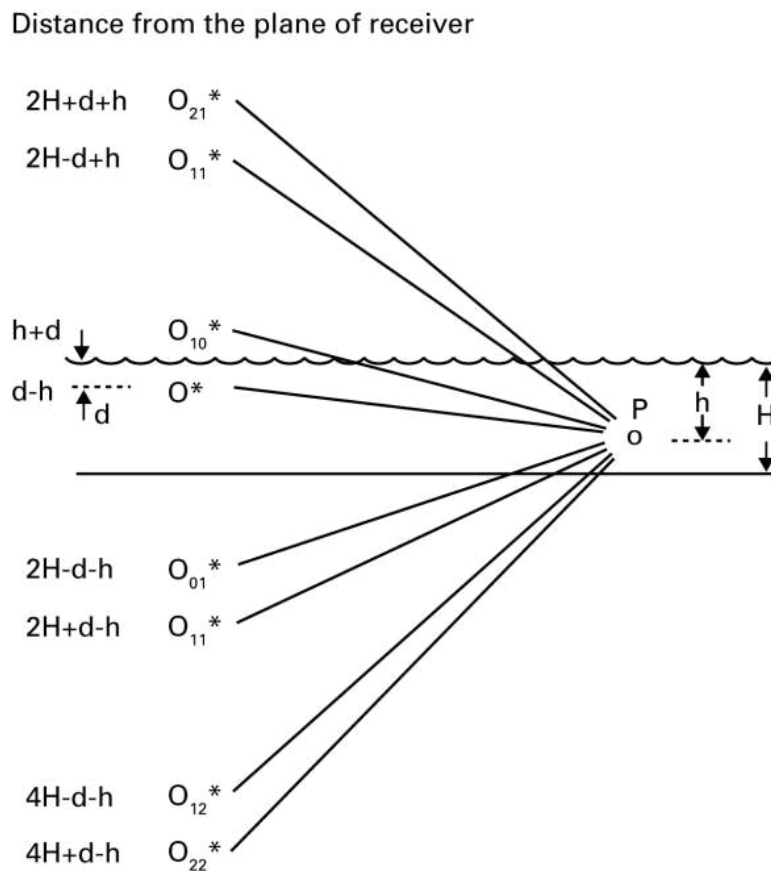


Figure 37: Image sources to a receiver in a shallow water channel.

The models used assume a flat bathymetry which, in the immediate area of the site, is a reasonable assumption; however, dependence on seabed slope is later tested using range dependent code Bellhop (Porter, 2010). Similarly an isovelocity sound speed profile is assumed. The model was run for each of the source-receiver combinations in each of the environments existing during the measurement trials. The input data (along with units) required by the model were:

- Hydrophone range (m)
- Hydrophone depth (m)
- Source depth (m)
- Water depth (m)
- Water density (kg m^{-3})
- Sediment density (kg m^{-3})
- Water sound speed (m s^{-1})
- Sediment sound speed (m s^{-1})
- Salinity (PSU)
- pH
- Wind speed (knots)

The source and hydrophone depths and ranges define the geometry of the model along with the water depth. The salinity and pH are required for the absorption calculation, and the wind

speed for the surface reflection. The water and sediment properties are required to calculate the reflection coefficients. The sediment data were obtained from a paper by Hamilton (1980).

Throughout the modelling used in this study the properties listed in Tables 2 and 3 were used as standard for the water column and sediment respectively.

Table 2: Water column properties used throughout modelling.

Property	Value
Density	1025 kgm ⁻³
Temperature	13.7° C
Salinity	34 PSU
pH	8
Sound velocity	1503 ms ⁻¹
Average depth for absorption calculation	mid-water

Table 3: Sediment properties used throughout modelling (Hamilton, 1980).

	Course Sand	Sandy-Silt	Silt	Silty-clay (mud)
Density	2034 kgm ⁻³	1596 kgm ⁻³	1740 kgm ⁻³	1421 kgm ⁻³
Sound Velocity (compressional)	1836 ms ⁻¹	1579 ms ⁻¹	1615 ms ⁻¹	1520 ms ⁻¹
Absorption (compressional)	2 dBm ⁻¹	4 dBm ⁻¹	4 dBm ⁻¹	4 dBm ⁻¹
Sound Velocity (shear)	180 ms ⁻¹	350 ms ⁻¹	450 ms ⁻¹	100 ms ⁻¹
Absorption (shear)	1.5 dBm ⁻¹	1.5 dBm ⁻¹	1.5 dBm ⁻¹	1.5 dBm ⁻¹

2.H3 Range averaging

The imageTL model calculates the propagation loss (PL) as a function of range, depth and acoustic frequency. To obtain a PL which is appropriate for an entire third-octave band, some form of averaging must be done. This can be done in the frequency range, but this would require the model to be run many times at individual frequencies within the band before the results could be averaged to produce a representative value for the entire band. Instead, a range averaging technique was used on the PL data for each third-octave band centre frequency. This passes an adaptive Gaussian filter through the data to smooth out the rapid fluctuations which occur in the loss data for single frequency analysis (Harrison and Harrison, 1995). The range averaging technique was checked against frequency averaging and the agreement between the two was found to be excellent (Robinson *et al.*, 2011).

Figures 38 and 39 show a general good agreement for a 10 kHz and 2 kHz band centre signal respectively with and without range averaging. At these frequencies the relative high variance would be expected in the complex pressure field for a shallow water environment as seen in the non-ranged averaged data. Rapid fluctuations potentially in the order of 20 dB can occur within a few metres. The use of non-range averaged data (shown in blue) for received level estimates would be highly variable dependent on environmental conditions. Range averaging (red line) effectively smooths these rapid variations allowing the underlying trend in transmission loss to be estimated and therefore provides a reasonable estimate of 'mean' levels for simplified model generation, Figures 38 and 39 show potential loss levels lower than that of the mean loss level at a specific range. For the example of the 10 kHz data shown in Figure 38 losses at a range of 300 m from source may be greater than

5 dB lower than the average and therefore 5 dB higher received levels. However, this effect is highly localized and will vary quickly with time dependent on sea conditions. For longer term exposures it is likely that the average level is generally representative of the longer term average level at that location. However, it should be noted that the range average losses does not represent the instantaneous maximum or minimum levels possible at a specific location.

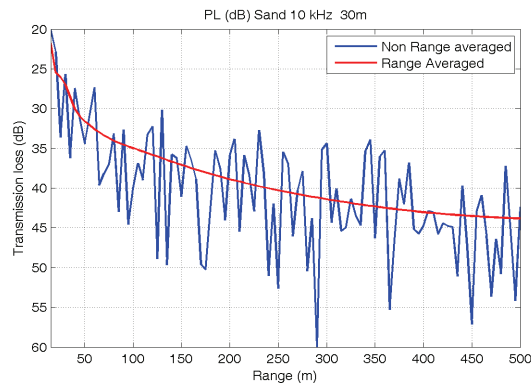


Figure 38: Example of range averaging for a sandy sediment in 30 m water depth at 10 kHz TOB centre frequency.

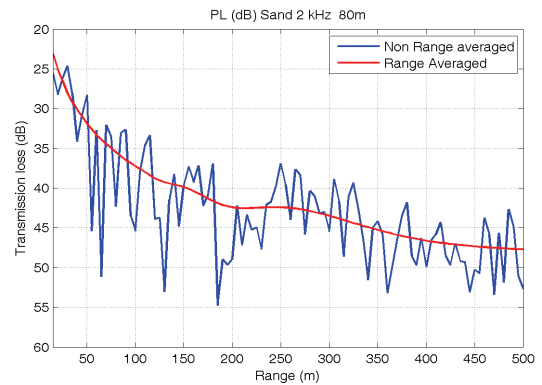


Figure 39: Example of range averaging for a sandy sediment in 30 m water depth at 2 kHz TOB centre frequency.

2.H4 Surface Roughness (wind speed)

Overall acoustic levels in the water column in shallow water are also dependent on energy reflected from the surface. A flat sea surface may act as a near perfect reflector returning energy back into the water column and adding to a complex interference structure through interaction with direct signals and seabed reflections. The degree of surface roughness (waves) will alter the stability of the interference field with reflections being both coherent at a point in the water column and energy contributions from other parts of the sea surface as roughness increases.

The source-image model incorporates a surface reflection coefficient obtained using the higher value of two surface reflection/scattering models; a simplified Beckman-Spizzichino model (Coates, 1988) for an incoherent surface scattering and, a Gaussian coherent reflection coefficient (Medwin and Clay, 1998) incorporating the wind speed (Ainslie *et al.*, 1994).

The ImageTL model was used to test dependence of overall propagation losses on surface roughness and therefore wind speed for a typical 30 m water depth site with sandy sediment for frequencies 2, 5, 10 & 31.5 kHz. Wind speeds were varied from 0 ms^{-1} to 10 ms^{-1} in steps of 0.25 ms^{-1} . By comparison with the Beaufort scale force 2 that has a mean wind speed of around 2.3 ms^{-1} (wave height 0.2 m) described as a light breeze, force 3 has a mean wind speed of around 4.3 ms^{-1} (wave height 0.6 m large wavelets) and force 4 has a mean wind speed of around 6.8 ms^{-1} (wave height 1 m small waves).

Figure 40 shows the range averaged propagation loss at a range of 500 m for the frequency range tested for a 30 m deep sandy site. For frequencies below 10 kHz and wind speed below 3 ms^{-1} propagation loss variations are within 1 dB. However, higher losses are seen at the higher frequencies with increasing wind speed. At 10 kHz around a 4 dB additional loss is seen with an increase up to 10 ms^{-1} . The above analysis shows that increased losses and therefore lower received levels are generally seen with increasing wave height and wind speed, with higher losses at higher frequencies. Aquaculture sites are often deliberately placed in sheltered areas avoiding rougher conditions. The worst cases of lower losses are

therefore more likely in better weather conditions. The use of a 'calm state' with a 1 ms^{-1} wind speed was therefore used throughout additional modelling processes as representative of precautionary typical conditions.

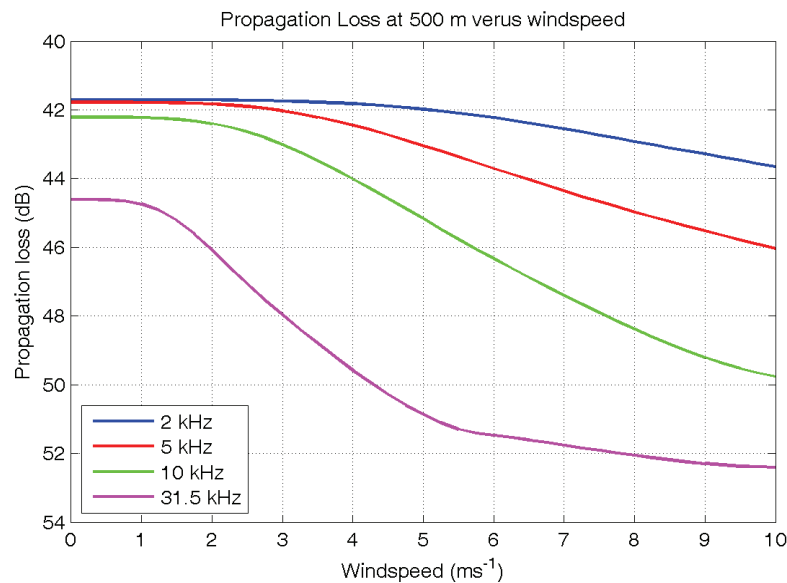


Figure 40: Propagation loss at a range of 500 m for a 30 m deep site with a sandy sediment versus wind speed.

2.H5 Water depth

The water depth surrounding a source may have an effect on propagation loss along with the devices' acoustic characteristics and the different sediment types. To test this dependence source-image propagation loss models were run for a range of depths for each of the third octave band centre frequencies discussed in section 3.3.1. The propagation loss at a depth of 10 m was estimated for each third octave band and for water depths of 20 m, 25 m, 30 m, 35 m, 40 m, 50 m, 60 m, 80 m, 100 m, & 120 m. These depths represent a majority of site deployments for aquaculture sites within Scottish waters with the average between 30-40 m (data drawn from GIS data base and pers. comm. with manufacturers of the Airmar, Ace Aquatec and Terecos systems).

The receiver depth of 10 m was selected to represent potential mean location for a marine mammal. Otani (2001) reported typical diving depths of 10-20 m for harbour porpoise and similar for seals (Bjørge *et al.*, 1995). Both species are capable of diving significantly deeper, however, based on mean site water depth, a profile of 10 m was used to represent typical exposure levels and to allow the same profile to be used from site to site. In each case a single source was modelled at a depth of 15 m. Actual source depths vary from site to site based on size of sites, water depth, depth of nets, etc. Typically transducers are deployed 1-2 m below the lowest point of the net and at depths never less than 5 m from surface (Terecos system), with a typical deployment of 15 m source depth, (pers. comm. manufacturers). Profiles run are for a flat sea bed (modelled as a homogenous half space) assuming an isovelocity sound velocity profile in the water column. Model properties used throughout are given in Table 3. To compensate for the finite bandwidth of the third octave band being represented by the use of the centre frequency each third octave band model was then range-averaged to reduce variance as discussed in section 2.3.3 in line with (Harrison and Harrison, 1995). This technique has shown an excellent agreement with frequency averaging a series of closely spaced band centres within the third octave band to provide a representative band propagation loss.

Typical losses estimated for the 10 kHz centred band for a 10 m deep receiver are shown in Figure 41 assuming a silty (mud) seabed sediment and surface roughness of 1 ms^{-1} versus range for various water depths. Figure 41 shows that losses vary only slightly (2-3 dB) with increasing depth at the 10 m receiver depth for this sediment type. The shallow water profiles showing slightly lower losses (and therefore potentially higher received levels) of 4-5 dB compared to water depths of greater than 30 m with generally slightly higher losses with increasing depth. However, in this case the levels were slightly lower at 25 m compared to 20 m waters depth at these frequencies. Very little variation was observed in propagation losses for water depths greater than 30 m with losses lying with 4-5 dB of each other at a range of 500 m. The modelling showed losses of around 50 dB at 500 m for water depth of greater than 30 m.

By comparison, Figure 42 shows the lower frequency 2.5 kHz band model for a silty (mud) seabed. In this case a more complex structure can be seen particularly for the shallower water sites with, in some cases, decreasing losses with range. In general, losses vary between 45 – 55 dB at a range of 500 m with very little variation for the water depths below about 40m. At the higher frequencies, for example 31.5 kHz shown in Figure 43, losses are generally less dependent on water depth, but as before, have slightly increased losses (lower received levels) as the water gets deeper. General losses are 50 – 55 dB at a range of 500 m. Analysis of all frequency bands for each sediment type is given in Annex 1.

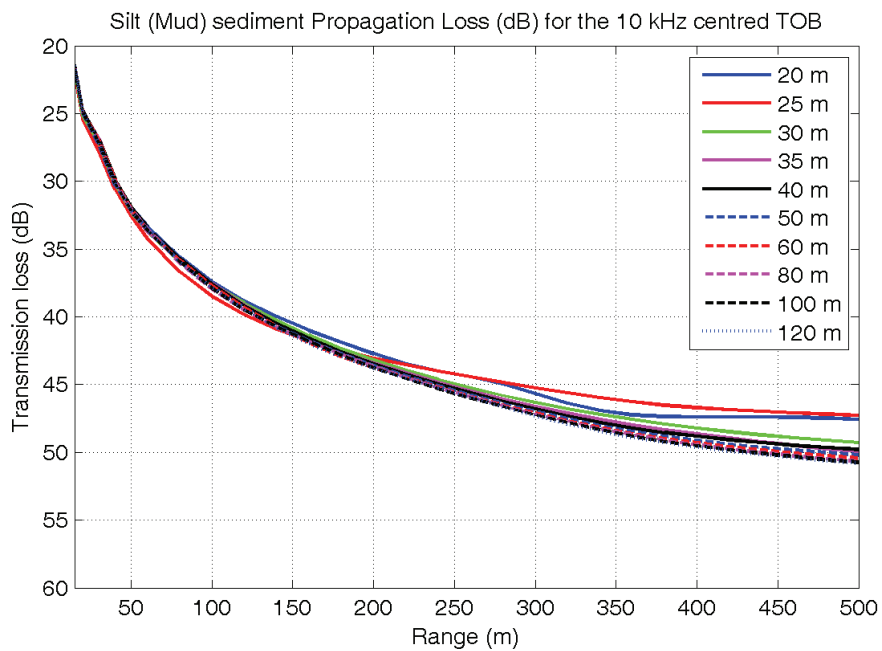


Figure 41: Range averaged propagation loss versus water depth for a silty (mud) sediment for a 10 kHz centre frequency.

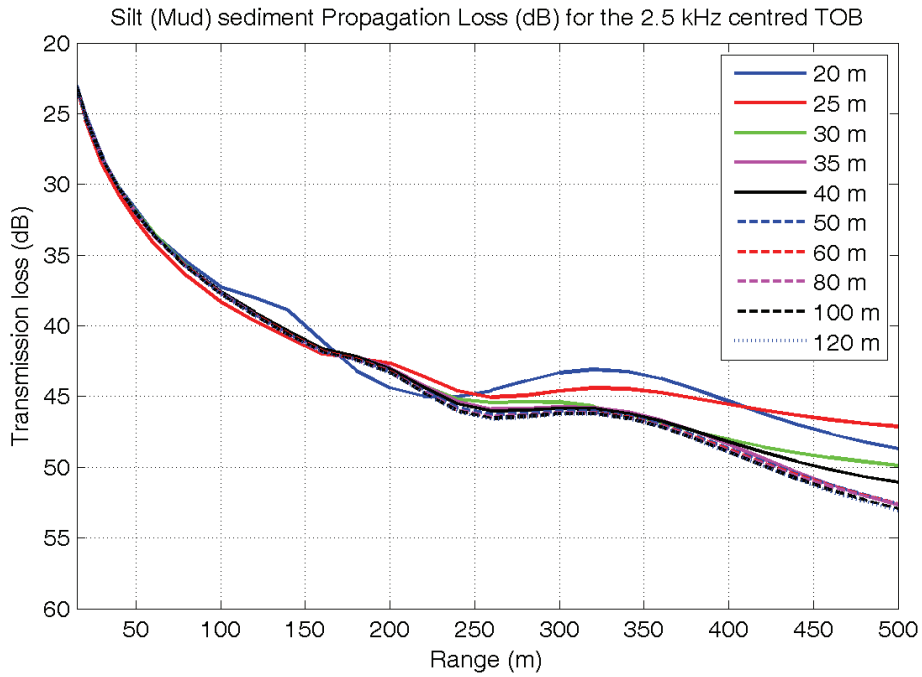


Figure 42: Range averaged propagation loss versus water depth for a silty (mud) sediment for a 2.5 kHz centre frequency.

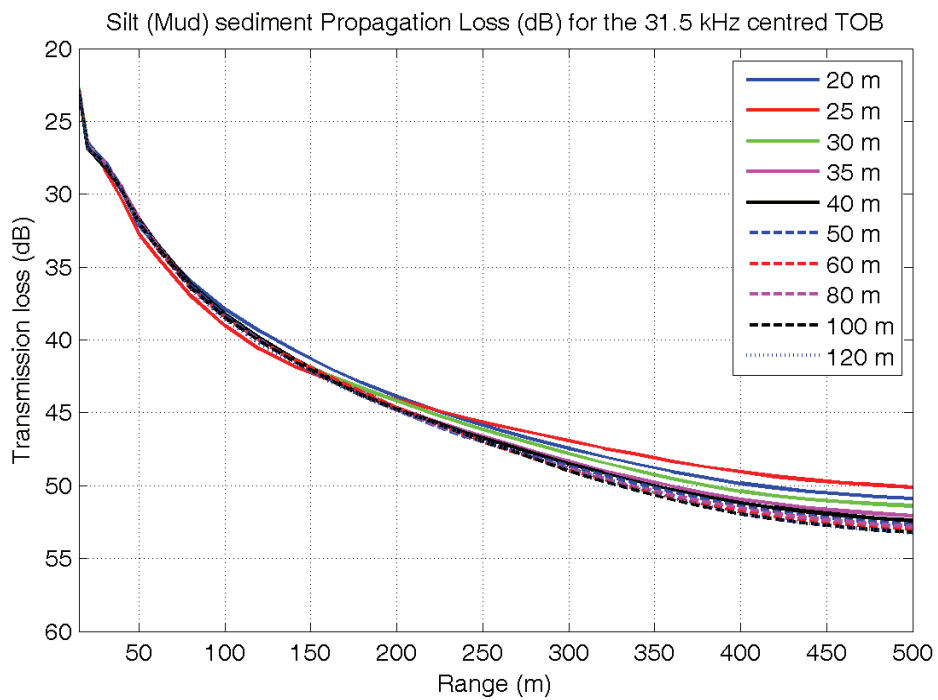


Figure 43: Range averaged propagation loss versus water depth for a silty (mud) sediment for a 31.5 kHz centre frequency.

Analysis shows that for increasing frequency, less dependence on water depth was observed with gradually increasing losses in deeper water. The most pronounced losses were recorded in the region of 45-55 dB for silty (mud) sediment at a range of 500m. Analysis of the effect of sediment type is discussed in the following Section 2.3.6. Strong variation in loss with range was observed particularly in shallower water (< 40 m) and at lower frequencies. This fluctuation potentially resulted in higher received levels in these bands with increasing range.

2.H6 Sediment type

Losses within the water column in shallow water are dependent on complex multiple interactions of signal through the water and reflections from the surface and the sea bed. In the case of the sea bed the degree of reflection (ratio of intensity of reflected energy versus incident energy, termed reflection coefficient) is related to the acoustic impedance of the sea bed in relation to the equivalent impedance of the water column (Urick, 1983). The acoustic impedance in turn is related to the density (kgm^{-3}) and the sound velocity (ms^{-1}) of the material / fluid etc. Propagation loss models such as RAM and the Source–Image codes use these properties to estimate the effect of the seabed reflection coefficient and incorporate these into estimation of likely losses and therefore received levels in particular.

As outlined in Section 2.3.2 the image-source model was used to test different sediment types for each third octave band and for each of the water depths listed above. Sediment types include sand, sandy-silt, silt and a silty-clay (mud). As before a 15m source depth was used and all other model parameter kept identical. The four general categories described taken from Hamilton (1980) describe the spread of sediment types likely to be encountered in Scottish waters taken from the EUNIS data: ranging from Sand – Silt – Clay with a corresponding reduction in mean particle size. This also represents the diversity of sediment acoustic properties likely to be encountered (Table 3) and therefore propagation properties at aquaculture sites. Data sets like EUNIS may be used to determine various sediment categories, these will then be grouped into the above generalised categories. A table for conversion of EUNIS data description has been provided with the database to allow translation of description and sediment type selection.

Figures 44 and 45 below show propagation loss for each sediment type for a typical 30 m deep water depth for frequencies 5 kHz (frequency of the peak energy of a type Terecos system), 10 kHz (frequency of the peak energy of the Airmar system) and the lower frequency examples at 2 and 3.15 kHz (Figures 46 and 47 respectively). Figure 44 shows losses are generally similar for the sandy-silt, silt and silty-clay sediment types with overall losses of around 47 dB at 500 m with slightly higher losses for silty-clay (mud) at shorter ranges. The biggest difference can be seen with a sandy sea bed with losses around 5 dB lower (therefore higher received levels) due to the higher acoustic impedance associated with a sandy seabed. These trends are similar for the 10 kHz TOB with slightly increasing losses with increasing frequency. The largest variations can be seen at lower frequencies, Figure 46 shows much higher variation in the losses in a silty-clay (mud) sediment at this frequency even with range averaging due to interference structure which is strongly frequency dependant with around 10 dB variation in losses at 500 m for an increase in frequency from 2 kHz to 3.15 kHz, shown in Figure 47.

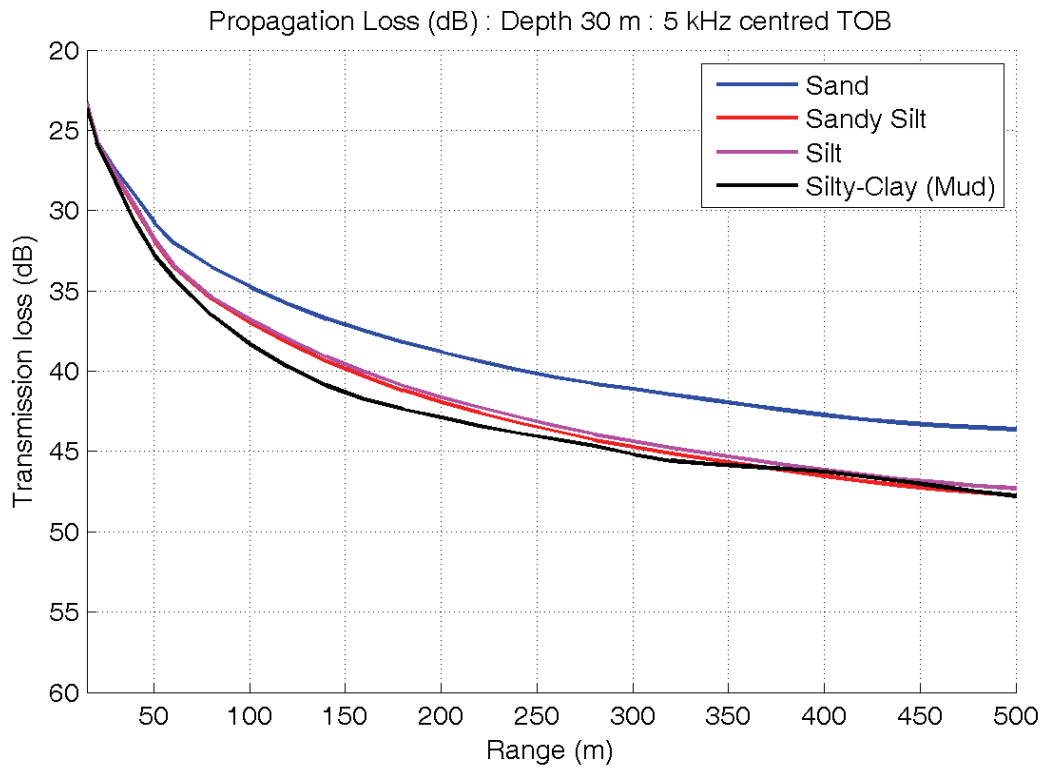


Figure 44: 5 kHz TOB propagation loss for different sediment types in 30 m water depth.

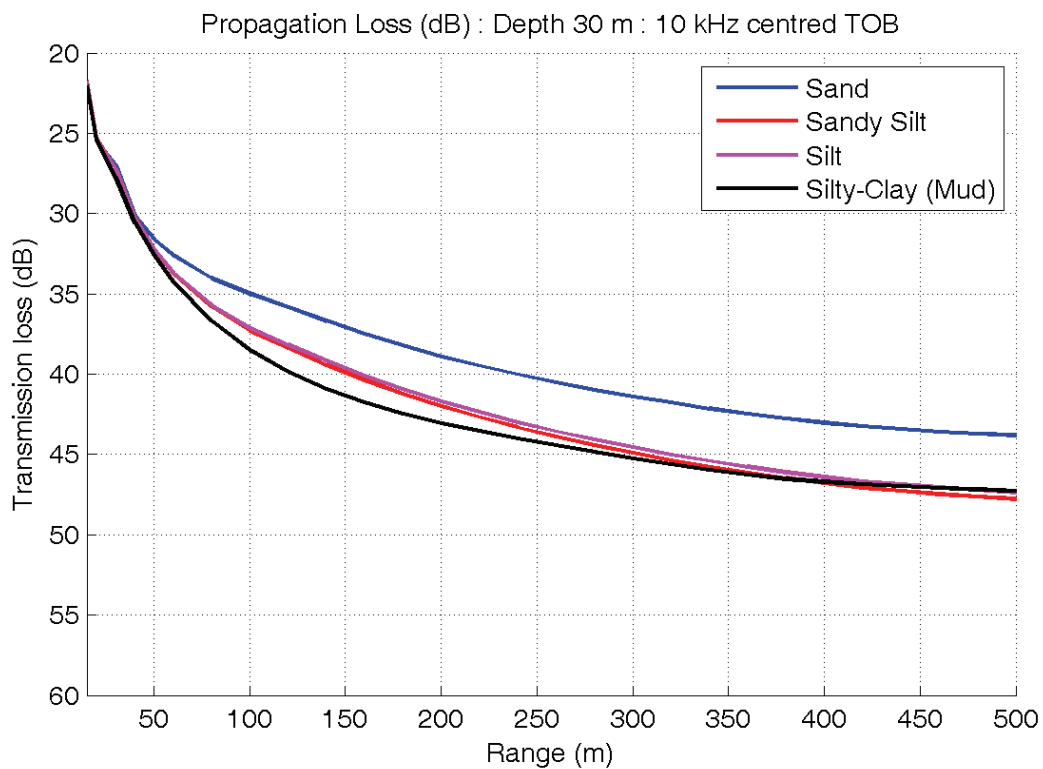


Figure 45: 10 kHz TOB propagation loss for different sediment types in 30 m water depth.

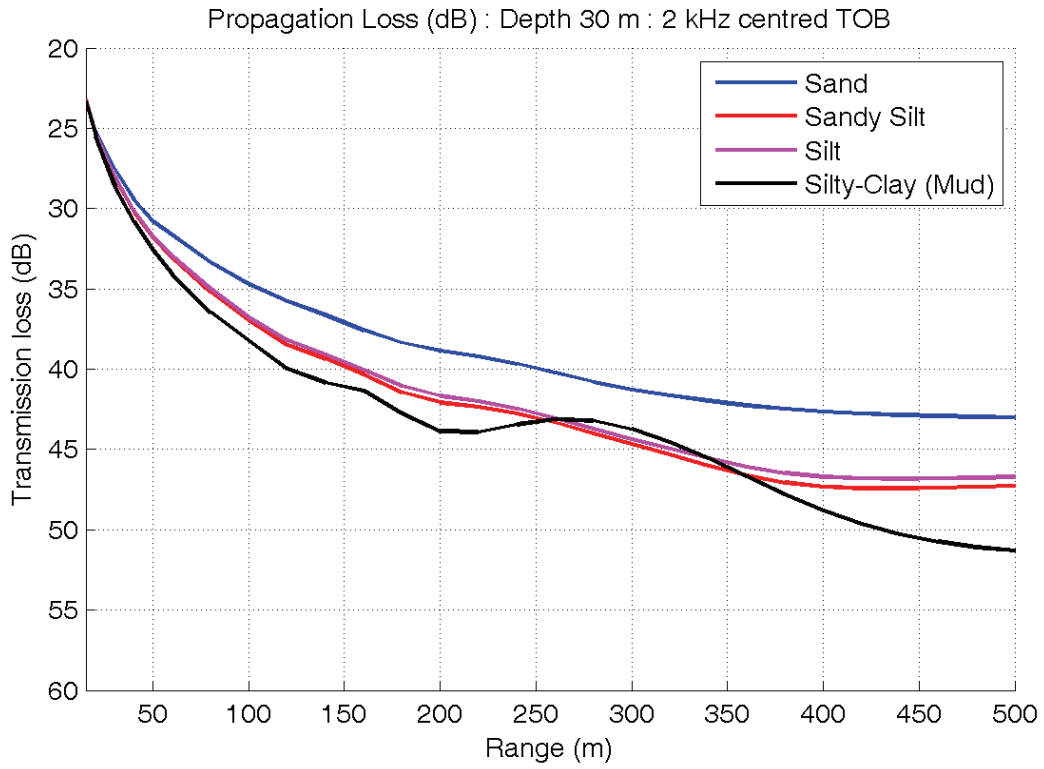


Figure 46: 2 kHz TOB propagation loss for different sediment types in 30 m water depth.

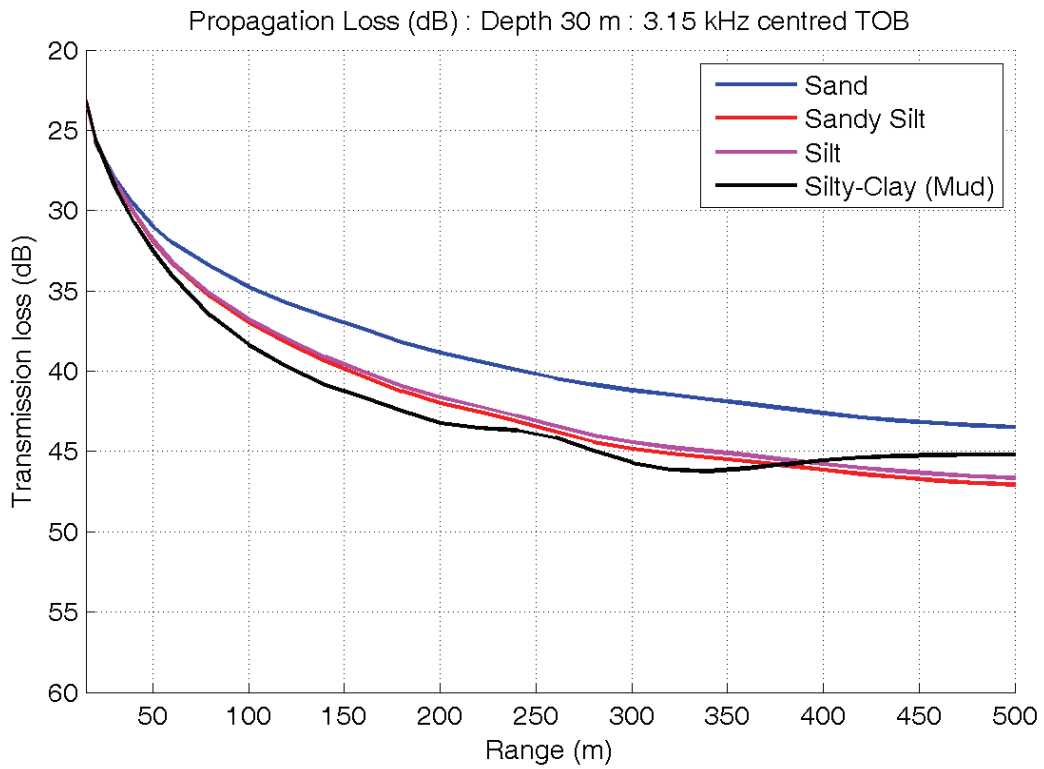


Figure 47: 3.15 kHz TOB propagation loss for different sediment types in 30 m water depth.

2.H7 Seabed slope

Due to the strong interaction with the sea bed in relatively shallow water the slope of the sea bed may affect overall transmission loss properties. The propagation loss versus seabed slope was measured using the range dependent code (Bellhop) for both up and down slopes. The site depth was chosen as 100m to allow upslope propagation for as far as possible at steeper seabed angles. For this example a sandy, higher impedance sediment was modelled using properties used in previous examples. The data were left un-range averaged to fully understand seabed interaction. Figure 48 shows the propagation loss at 10m depth for a 10 kHz signal for a flat and gradually increasing down-slope from under the site. The results show that losses are generally similar as the seabed slope increases compared to the flat seabed profile. However, the response gradually begins to show less variance due to less direct (coherent) seabed interactions with steeper angles. Strong structures (nulls and peaks) also become more dominant as the sea bed becomes steeper. This is most likely due to source - surface interactions also present at shallower seabed angles combined with fewer coherent seabed interactions at the steeper angles. Much of the reflected seabed energy will go forward at ever increasing grazing angles and not interact closer to the source as it would have for a flat sea bed. Figure 49 shows the range averaged equivalent data the forward reflected energy resulting in higher transmission loss (lower received levels) with increasing slope compared to the flat sea bed case.

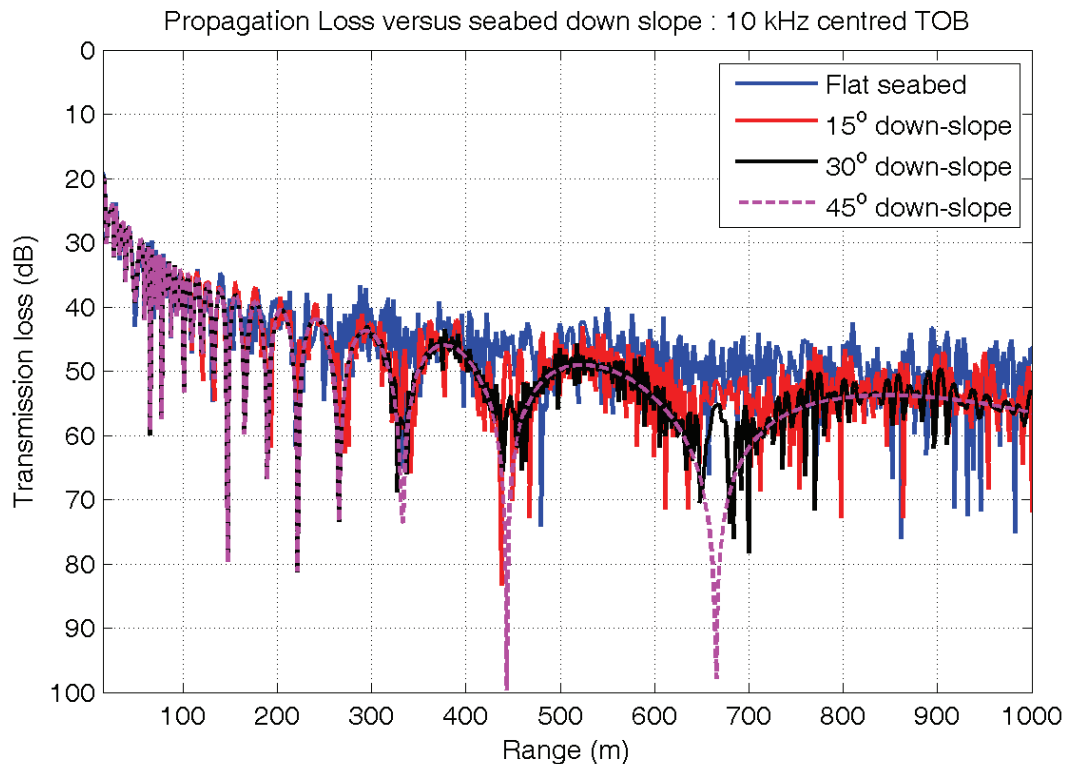


Figure 48: 10 kHz propagation loss versus seabed down slope for a 10 m deep receiver using a sandy sediment.

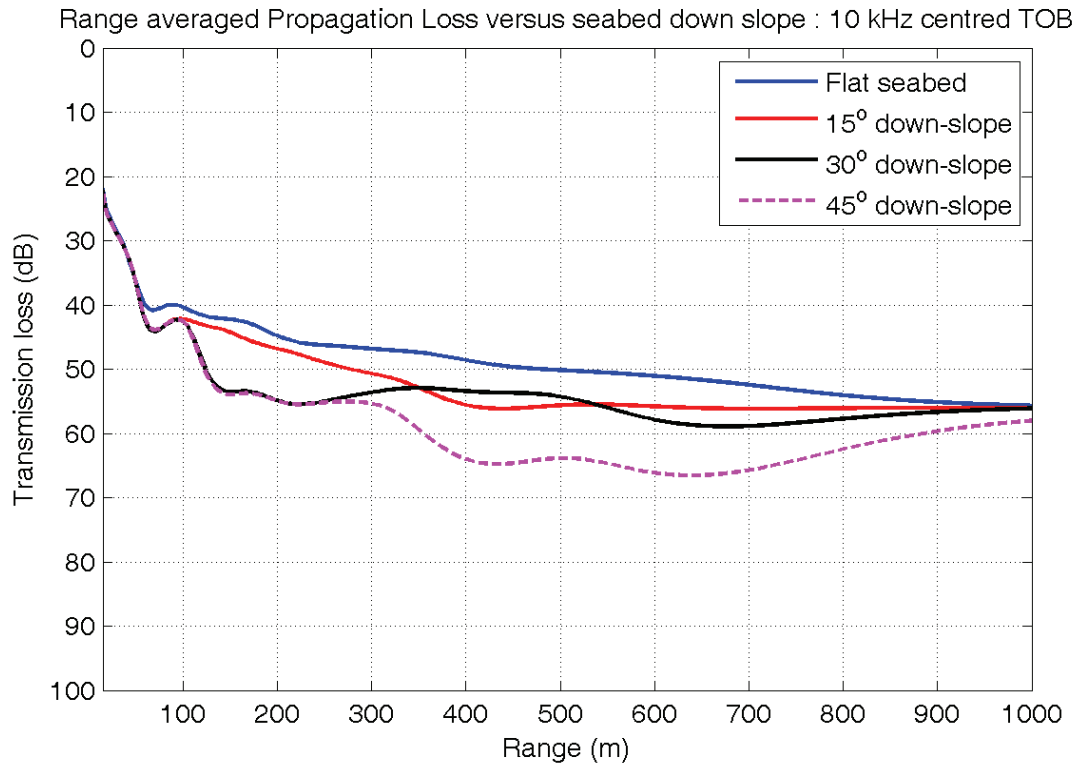


Figure 49: 10 kHz range averaged propagation loss versus seabed down slope for a 10 m deep receiver using a sandy sediment.

In addition Figure 50 shows range-averaged data inclusive for an up-slope sea bed of 15° and 30° overlaid on the flat and down slope data for an identical environment. In this case losses are almost identical independent of seabed slope for ranges less than 50 m close to source due to the strong seabed interaction. In the up slope case energy from seabed reflections is more readily scattered into the field closer to the source resulting in slightly higher levels compared to the flat seabed scenario. Both the 15° and 30° up-slopes show a potentially maximum increased level of around 3 dB compared to the flat sea bed in the models tested. Figure 51 shows a more typical shallower water case for up and down slope angles 5°, 10°, 15° as with deeper water losses are generally higher for a down-slope scenario. As with the deep water case for an up slope decreased losses of 2-3 dB can be seen particularly at shorter ranges.

The above data suggest that slightly elevated received level (lower transmission loss) may in general terms be possible with an upslope from source site compared to a flat sea bed of same depth, however, generally lower levels are observed on a down slope site at this depth. For purposes of development of a 'generic' model the use of a flatbed equivalent for a down slope is more precautionary as it will tend to overestimate received level with range. However, consideration should be made for up slope cases where levels may be higher due to the seabed slope, discussed further in Section 2.5.1.

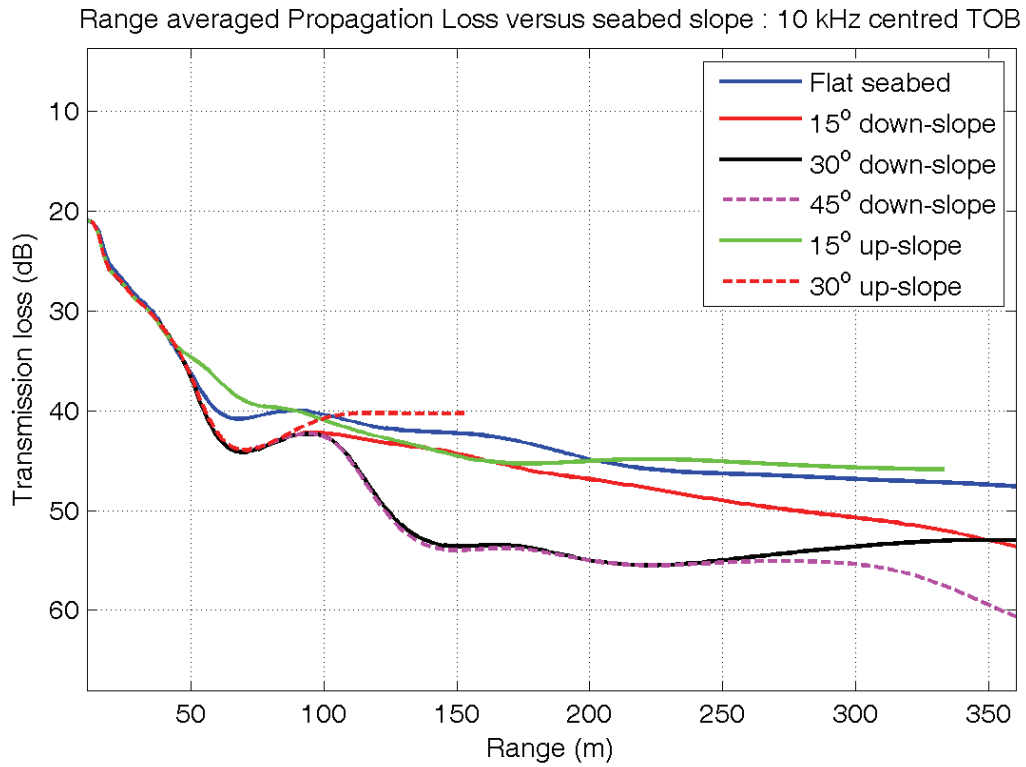


Figure 50: 10 kHz propagation loss versus seabed slope for a 10 m deep receiver using a sandy sediment in 80 m water depth.

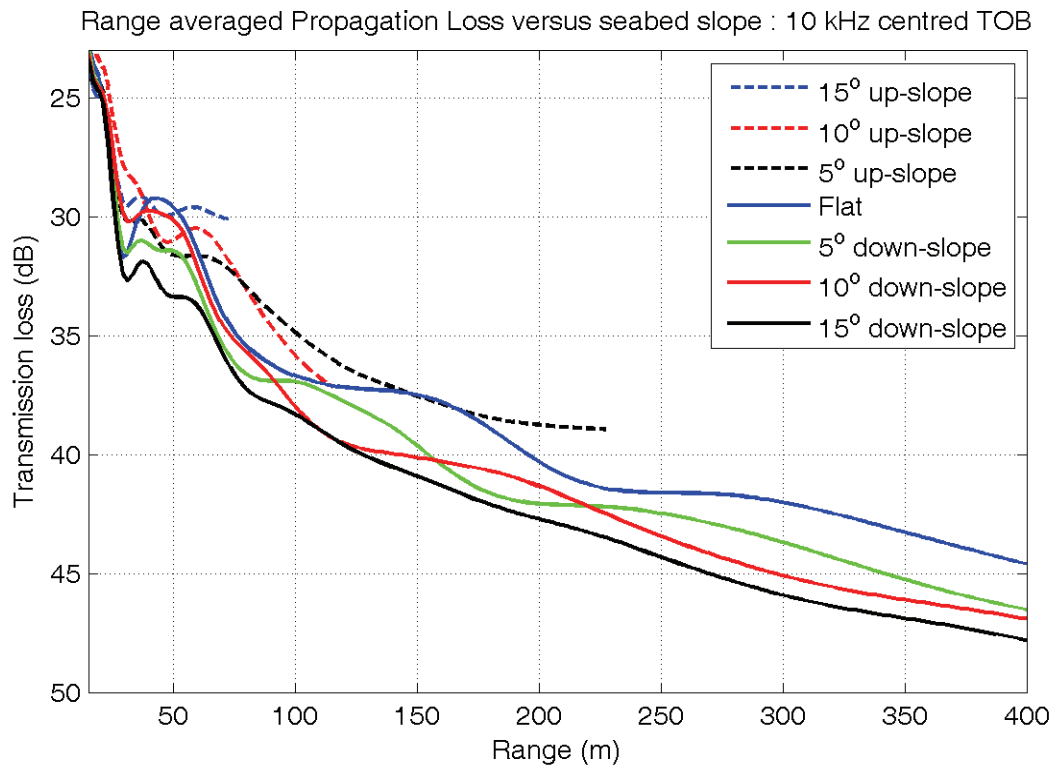


Figure 51: 10 kHz propagation loss versus seabed slope for a 10 m deep receiver using a sandy sediment in 30 m water depth.

2.4 Model validation against measured data

2.1.1 Model comparisons

The source–image model has also been benchmarked against other well established acoustic propagation models, including PE-based codes (RAM, RAMGeo), (Tappert, 1977; Collins, 1988), Normal Modes (Kraken) and Raytracing (Bellhop) (Porter, 2010) within a MATLAB Act-up suite of software (Maggi and Duncan, 2010) with good agreement (Robinson *et al.*, 2011).

Bellhop is a beam-tracing program that can include range dependent bathymetry. Beam tracing is similar in principle to ray tracing but traces the paths of finite width beams rather than infinitesimal width rays. This reduces problems caused by ray theory artefacts such as caustics and shadow zones. Bellhop can use beams with a Gaussian intensity profile, or geometric beams which produce the same result as a standard ray trace. Bellhop is inherently a high frequency code, however, its useful frequency range extends lower than standard ray trace programs.

RAM (Range-dependent Acoustic Modelling) is a parabolic equation (PE) code that uses a split-step Padé algorithm to achieve high efficiency and the ability to model propagation at large angles from the horizontal (the usual limitation of PE codes). There is a trade-off between the angular range and the speed of computation that is governed by the number of terms the user specifies for the Padé approximation – the more terms, the wider the angle, but the slower the code runs. RAM is capable of modelling low frequency propagation in fully range dependent environments (i.e. range dependent bathymetry and sound speed).

Two modified versions of Mike Collins' RAM have been integrated into the AcTUP framework:

- RAMGeo is a CMST version based on Mike Collins' RAMGeo version 1.5. It has been modified to output complex transmission loss data as well as the standard magnitude only files.
- RAMSGeo is a CMST version based on Mike Collins' RAMS version 0.5 and the RAMGeo version discussed in the previous section. Mike Collins' elastic substrate version of RAM has been modified so that it uses the same (bathymetry datum) substrate profile specification model as RAMGeo.

These two models are used for comparisons with ImageTL since they cover different frequency ranges.

Range average is applied to all models to smooth out rapid variation of amplitude with range. The effect of range averaging is equivalent to frequency averaging (Harrison and Harrison, 1995). This is very useful for a noise signal with very wide bandwidth where details of the frequency response are not required.

The results from the comparison prove the ImageTL model is capable to predict the transmission loss reliably in shallow water. However the uncertainties in the environmental conditions will introduce errors when used as input in the predicted transmission loss.

2.1.2 Comparison with measured data

Specific test cases where measured data have been obtained from literature and the consortium's previous studies have been compared to models to confirm model accuracy.

This is seen as two fold; firstly the validation of detailed modelling studies and the validity of simplified modelling approach taken in this project.

Data from numerous recordings of active ADD devices were reported by Booth (2010). Booth was able to map several areas with numerous surveys where active ADDs were present. On a relatively shallow (15-20 m) active site just off the west coast of Kerrera, Firth of Lorn an Airmar system was recorded at different ranges on transects surrounding the site. The closest point of approach was 366 m with a reported RMS received level of 140.6 dB re 1 μ Pa. Using the ImageTL applied to the reported RMS source level of 193 dB re 1 μ Pa.m the two closest data points taken on similar bearings recorded by Booth showed good the agreement with the source image model within 2 dB variance.

Figure 52 shows sampled longer range data from Booth (2010) recorded in Loch Nevis in a deep water site with water depths at the middle of the loch as deep as 80 m. The equivalent range and non-ranged averaged data are given in Figure 53. The general trend with range is again reasonably good. Levels in this case are generally lower that what would be expected for the manufacturers published data and calibration trials (Lepper *et al.*, 2004). The data shown would give an equivalent RMS source level of 175 dB re 1 μ Pa.m to best fit. These data are, however, reasonably consistent with lower maximum source levels observed by Jacobs and Terhune (2002) of 178-179 dB re 1 μ Pa.m. Gordon and Northridge (2002) suggest the building up of fouling on transducers or surrounding net structures, poor battery conditions, and damaged cables as possible explanations for lower observed levels within field data.

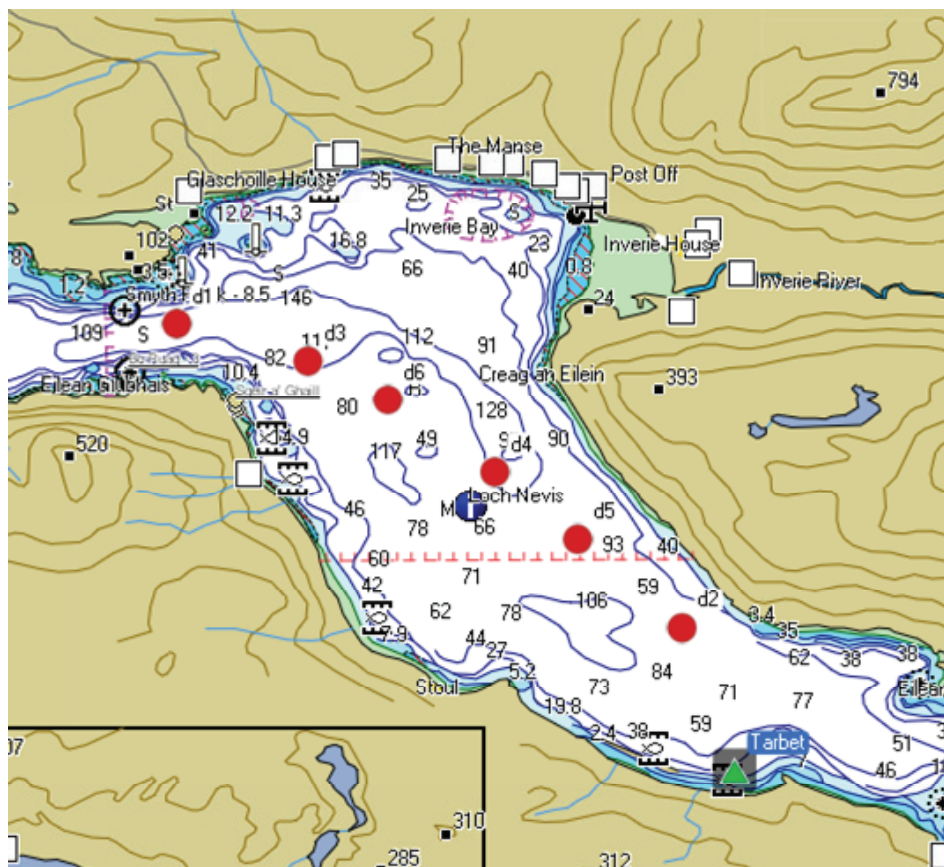


Figure 52: Sampled measurement points in Loch Nevis (red circles) and Tarbet aquaculture site (green triangle).

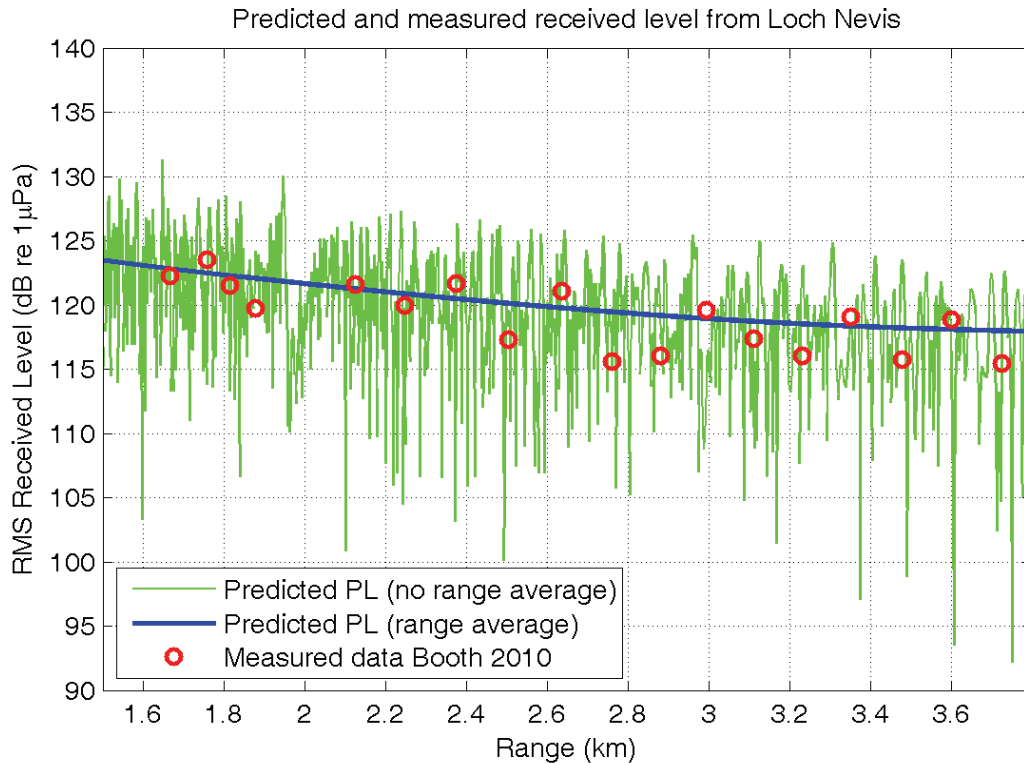


Figure 53: Predicted (using source image model) and measured received level for at a deep water site on Loch Nevis. Received level based on an equivalent RMS source level 175 dB re 1 μ Pa.m.

2.5 Critical analysis of different models

2.5.1 Discussion

The intent of analysis presented in Sections 2.3 and 2.4 is to better understand general dependences on source type and environment conditions (water depth, seabed type, etc.) of acoustic propagation modelling and the development of a 'simplified model' for application across Scottish aquaculture sites. Across the whole of Scotland these sites vary due to local seabed bathymetry and differing sediment type. Relatively sophisticated range dependent models can be used as outlined in Section 2.3 to fully map potential received levels surrounding a site. This process is, however, computationally intensive and therefore impractical for application to all sites individually. To address this, various models have been used to test the dependence on propagation losses due to variables such as water depth at site, sediment type, and seabed slope. The models used have included computationally intensive range dependent codes such as (RAMGeo and Bellhop). In addition range independent models such as a source image model have been used to test dependence on sediment type and water depth. All codes have been benchmarked against each other (Robinson *et al.*, 2011) and standard solutions.

Analyses of the types of ADD devices being used in Scottish waters suggest primary frequency components in ranges from 2-40 kHz. The signals themselves are highly variable with complex duty cycles and broadband and tonal energy components. The frequency band 2-40 kHz was therefore divided in third octave bands. The equivalent SEL source level for each third octave band was estimated for the three most commonly used systems based on

data drawn from literature. The propagation losses in each of these bands were then estimated for each scenario, for example water depth, sediment type, etc.

Propagation losses are often frequency dependent due to the complex interference structures occurring at different frequencies, with higher frequencies often being more highly attenuated. Due to this, different parts of the acoustic spectrum will propagate differently and therefore a single one frequency model may be unrepresentative for the potentially broadband source typically seen in ADD devices. The use of individually propagated third octave bands, however, allows estimation of these effects band by band. These data can then be recombined with the third octave band source level estimates to reconstitute the equivalent broadband received level response more accurately.

Scottish aquaculture sites are generally in relatively shallow water 20-80 m (pers. comm. manufacturers) and due to the frequency band of interest, individual frequency bands often show highly variant losses with range due to complex interactions with seabed and surface reflections, for example that seen in Figures 38-39 for a 10 kHz signal. For a pure tonal signal in ideal conditions movement of a few metres in range could result in large variations in received level, making estimation of range, for example a specific impact threshold level, very difficult to estimate and equally variable. In reality these complex structures are likely to be highly variant over time and frequency. The net result in reality for a broadband signal is that an average response in both frequency and time is likely seen as a mean of the responses shown in Figures 38-39. In the case of third octave bands these also have a finite bandwidth and all frequencies within a band are therefore not likely to propagate similarly. The use of range averaging provides an estimation of the 'mean' losses for that band, individual losses may be higher or lower but underlying trend is representative of overall energy content for application to an impact criterion.

In terms of development of an average response for a 'simplified model', the overall trends in source characteristics and propagation loss have been assessed. Using a source-image model incorporating surface roughness, water column characteristics, seabed type and water depth, the dependence of signal propagation loss in each third octave band in range 2- 40 kHz has been measured. The effect of water depth is reviewed for depths between 20 and 120m in Section 3.3.5. This was carried out for each third octave band and for four different typical sediment types. Using range averaged data in general lower losses and therefore potentially higher levels were observed for water depths less than 40m with gradually increasing losses at greater depths and increasing frequency. In the case of lower frequencies and shallower site depths, however, occasional complex structures were observed with the potential for increasing levels with range due to complex surface bottom interactions.

The effects of four general sediment types, sand, sandy-silt, silt and silty-clay were assessed for each frequency band and water depth. In general lower losses (4-5 dB) were observed with a sandy sediment due to higher acoustic impedance. Losses for sandy-silt, silt and silty-clay (mud) were generally similar with highest losses seen in the mud substrate. Again, however, at lower frequencies complex structures were observed with potential for increasing received levels with increasing range, particularly for a muddy sediment type (Figures 46-47). In both cases variation in water depth and changes in sediment type may not be adequately described by a simple geometric single frequency spreading law model. The combination of strong frequency dependence and environmental conditions dependence potentially leads to significant variation in estimated received levels and therefore ranges to zones of influence.

Due to these complex dependences it is felt that no single simple rule could be used to best estimate potential received levels and ranges to impact thresholds. It is therefore proposed that look-up tables may be used to take complex averaged curve data from the pre-

computed propagation loss models for bands of water depth, and sediment types for each third octave band in range 2-40 kHz. Data from these tables would then be combined with third octave band source level data for each ADD type to estimate combined broadband (all frequency components) received levels. These levels will then be dependent on source type, water depth, sediment type, etc. The combined received levels with range can then be compared to impact criteria (a threshold level at which an impact occurs for a given species) and ranges from source predicted for that impact.

A third influence tested is due to seabed slope, Section 2.3.7. This was carried out using the range dependant (varying bathymetry) propagation code Bellhop from the ActUP suite of software. Both a shallow water (30 m, typical) and deep water (80 m) case were tested. In both the deep and shallow water cases a seabed down-slope (getting deeper from the site) resulted in generally lower losses compared with up slope case where the potential for lower losses (higher received levels) was possible at specific frequencies and ranges compared to a flat seabed scenario due to strong constructive interference structures. These variances were, however, dependent on frequency range and depth with maximum observed increases above flat sea bed case of around 2-3 dB relatively independent of angle. In terms of a model to predict range to an impact level threshold, the potential lower propagation losses for an up-slope environment could result in underestimation of ranges of influence. Again there is no simple 'rule' for this so a precautionary approach is proposed that the effective source level is adjusted by the maximum observed increase (2-3 dB) above the flat-seabed case. This results in a vertical shift in the transmission loss profile, however the features of the curve are maintained, including higher changes in losses at shorter ranges.

This will in most cases result in a more precautionary over estimation in received level and therefore zones of influence. In the case of down slopes use of the flat seabed profile is again felt more precautionary as the losses associated with the down slope are generally higher or equal to that of a flat sea bed in cases measured.

It should be noted that for typical broadband (all frequency) SEL source levels, losses of greater than 40 dB are seen within the first 500 m in most situations. For a 180 dB re $1\mu\text{Pa}^2\text{s.m}^2$ broadband SEL source level the received levels are likely to be below 140 dB re $1\mu\text{Pa}^2\text{s}$ at a range of 500 m. This is by example approximately 48 dB below the SEL physiological injury criteria for a high frequency cetacean as proposed by Southall et al. (2007), assuming no cumulative exposure. Lucke *et al.* (2009) report a Temporary Threshold Shift (TTS) for harbour porpoise at an SEL level of around 164.3 dB re $1\mu\text{Pa}^2\text{s}$, which again is above the likely SEL received at 500 m range (assuming no cumulative exposure). This suggests that for instantaneous injury criteria, zones of influence are likely to occur within 500 m of the source. Because of this, environmental conditions in the immediate area of the source are most critical to the accurate prediction of zones of influence for instantaneous injury criteria. The combination of transmission loss models and source level estimates will be used to develop a general sensitivity model outlined in Section 3 of this report.

2.1.2 Example of broadband received level estimate

Individual transmission losses for each third octave band in a particular environment (water depth, sediment type and seabed slope) can be combined with the individual third octave band source levels to estimate the combined broadband received level with range. These estimates will then form the basis of the prediction of range to impact threshold. The following example shows the individual SEL source level estimates in third octave bands for the Airmar system (Figure 54). This is then combined with propagation losses for each frequency band for in this example a sediment silty-clay sea bed in 30 m water depth. The resultant third octave band received levels are then combined to give the broadband received level versus range given in Figure 55.

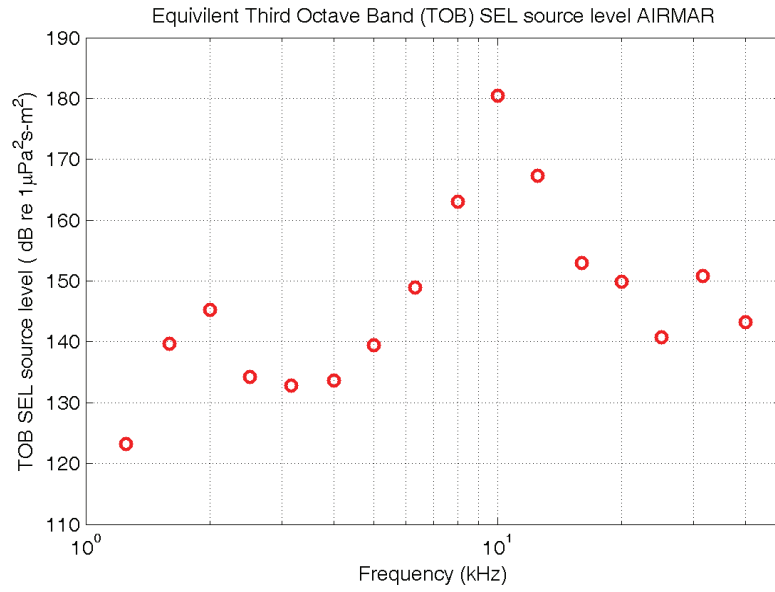


Figure 54: SEL source levels in third octave bands for the Airmar system.

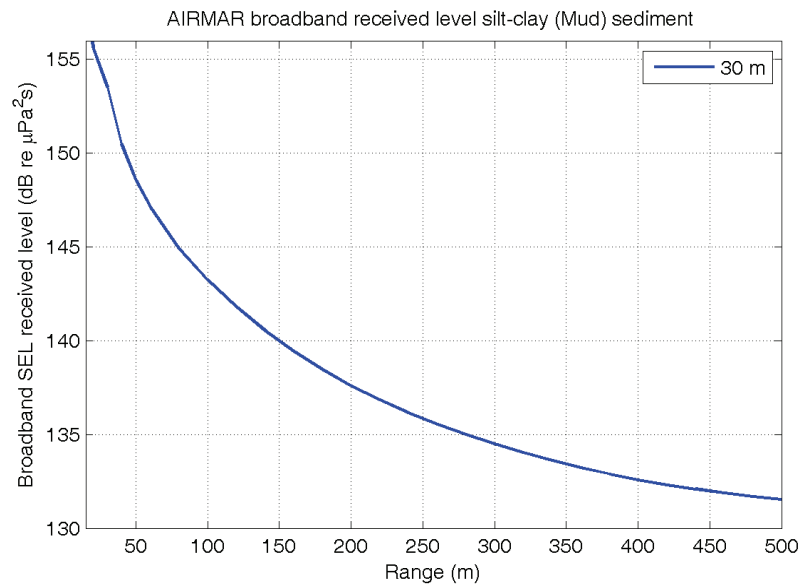


Figure 55: Broadband SEL received levels for a 30 m deep site with a silt-clay sediment using an Airmar system.

These data can then be directly compared with impact threshold levels and ranges of influence predicted.

3. EFFECTS OF SOUND ON CETACEANS AND SEALS

3.1 Effects of underwater sound

3.1.1 Introduction

Underwater sound can have a range of impacts on marine mammals extending from disturbance (leading to behavioural change and habitat exclusion), through to hearing damage and physical injury. In addition, long term exposure to noise can result in stress and noise can also have secondary effects, by influencing the distribution of prey for example. In general, physical effects, such as raised hearing threshold shifts, correlate well with the total quantity of sound energy received by a receptor and therefore, length of exposure as well as sound levels are important metrics. Here we briefly review effects of noise on marine mammals from the perspective of ADDs use

3.1.2 Non Auditory Physical Effects

At short range, powerful sources generate high peak pressure levels that can have physical effects on body tissues, leading to injury or even death. Some of these effects may be considered to be barometric and shear effects due to the shock waves, rather than acoustic effects per se. There has been considerable research into the levels of incident peak pressure and impulse (integral of the peak pressure over time) that cause lethal injury in species of fish, submerged terrestrial mammals and in human divers. The work of Yelverton *et al.* (1973, 1975, 1976) highlighted that for a given peak pressure the severity of the injury and likelihood of a lethal outcome is related to the duration of the impulse. In Yelverton's model, smaller fish are generally more susceptible to damage than larger ones. Richardson *et al.* (1995) adapted Yelverton's findings for fish mortality in order to apply them to larger marine mammals. Peak pressures generated by ADDs and AHDs are not high enough to directly cause this type of lethal injury and these effects are not considered further in this report.

3.1.3 Auditory Injury and Threshold Change

The auditory system has evolved to be sensitive to sound, and as a consequence is most vulnerable to being damaged by it. Exposure to high level of sound can cause a temporary loss in hearing sensitivity, known as a Temporary Threshold Shift (TTS) while greater exposures lead to a permanent loss of hearing sensitivity known as a Permanent Threshold Shift (PTS).

Threshold shift can be caused both by instantaneous exposure to a very high sound pressure, and by longer term exposure at lower levels. It may be that this represents two different mechanisms for damage. The first resulting from the ear being driven beyond its mechanical limits the second resulting from severe fatigue. For this reason dual criteria are often applied when assessing risk of threshold shift. One based on the highest sound pressure level experienced, however, short the exposure and the second based on the total acoustic energy the subject is exposed to over an extended period of time.

No studies have directly investigated the effect of ADD signals on the auditory systems of marine mammals, although Gordon and Northridge (2002) did attempt some extrapolations based on the limited understanding of TTS in marine mammals at the time of that report. Southall *et al.* (2007) reviewed the scientific literature on sound induced TTS in marine mammals after exposure to intense sound and proposed criteria for injury; a series of thresholds above which exposures would be likely to result in PTS. They identified four classes of marine mammals: seals, low frequency, mid frequency and high frequency cetaceans. Harbour porpoises were listed as 'high-frequency cetaceans' (based on their functional hearing capabilities - though no data on TTS for this species were considered in

this assessment. JNCC (Joint Nature Conservation Committee, 2010) have recommended the application of the marine mammal impact criteria as proposed by Southall *et al.* (2007) for assessing risk of injury to marine mammals in UK offshore seas and in English and Welsh coastal waters.

3.1.4 Behaviour

Underwater sound will often cause behavioural responses or disturbance at levels well below those at which hearing impairment occurs. In fact, animals may, and in some cases have been shown to, respond to a sound that is just detectable. Behavioural responses are inherently highly variable. Measures of the perceived “loudness” of a sound, (for example the number of decibels above sensation levels for the species of interest) has been shown to be a rather poor predictor of an animal’s response to sounds, especially sounds that are not novel and new to the animal. Usually, an individual’s response will strongly depend on the perceived significance (if any) of a sound. This will vary with a host of factors in addition to species identity, including, age, gender, motivation and context. Crucially, responses will vary as a result of prior exposure and learning. Animals may either become habituated to signals to which it has been repeatedly exposed but which lacked apparent consequence, or become sensitised to signals which were associated with significant positive or negative reinforcement. For example, animals may learn to avoid sounds associated with predators and be attracted towards those associated with food or mating opportunities. It should be remembered that what is important in this context is how an individual animal perceives a sound. For example, an anthropogenic sound that shares some characteristics with a predator call might well be perceived as being very significant, especially if the receiving animal is in a location where it is exposed and vulnerable. It is hardly surprising, in the light of these factors, that there are often conflicting reports of the type and extent of behavioural responses to sound by both marine and terrestrial species, and reliable criteria for predicting behavioural responses, based on simple acoustic metrics, such as decibels above sensation level, have not emerged. Further, it is clear from the discussion above, that there should be no expectation of any such simple relationships existing.

Clearly, however, an animal can only respond directly to a sound that it can perceive, so consideration of frequency dependent sensitivity (i.e. audiograms, see section 3.1.7) and frequency dependent levels of background noise do have some relevance in determination of the ranges at which sound can be detected. In some cases behavioural responses to sound can be broadly correlated with a sound level above sensation level at a particular frequency which can be determined by comparing a sound’s spectrum with the audiogram of a species. This approach is most likely to be useful for sounds that are novel and that do not have any perceived significance for the subject. The measure that is obtained in this manner is indicative of the perceived level of the sound for that animal. In a human this would be termed “loudness” and is measured in phons.

3.1.5 Behavioural Responses to ADDs

A number of studies have investigated behavioural responses of marine mammals to ADDs, many of these are summarised and reviewed in an earlier report for SNH, Gordon and Northridge (2002); and in Gordon *et al.* (2007). Here we will briefly review the most pertinent of these as well as some more recent work presenting new data on the effects of ADDs on porpoises in Scottish waters (Booth, 2010; Northridge *et al.*, 2010). Kastelien *et al.* (2007, 2010) present recent results from trials with captive animals but it is difficult to relate observations of behavioural responses in captivity to the real world.

Most studies on the effects of ADDs have collected data from harbour porpoises, and the largest concerted effort was a series of experimental exposures reported by (Olesiuk *et al.*, 2002). This research team established an observation station overlooking an area of

protected waters close to a fish farm site in a region of high porpoise density on Canada's west coast. A team of visual observers recorded porpoise sightings in the observation area over an 18 week period during which an Airmar ADD was alternately active or inactive for blocks of three weeks at a time. Comparison between active and inactive periods revealed striking differences. During active periods, porpoises were completely excluded within 400m of the ADD and densities between 2,500 and 3,500 m were less than 1/10th of those observed in the same areas during non-active periods. The maximum range observed was 3.5 km and there is no reason to expect that responses did not occur at greater distances than this. In a complimentary study, Johnston (2002) tracked individual porpoises from a cliff top in the Bay of Fundy using a theodolite. Johnston showed that animals swam away from ADDs when they were activated and no individuals were ever seen closer than 645 m (at which SPL received levels were estimated to be 128 dB re 1 μ Pa) when the ADD was active. Research in Scotland using passive acoustic porpoise logging devices (PODs) to measure porpoise presence and relative abundance around operating fish farms has generally supported this (Northridge *et al.*, 2010). For example, at a monitoring site 4km from a fish farm, porpoise detection rates were nine times higher when ADDs were inactive at the farm site than when they were active. Northridge *et al.* (2010) observations are particularly pertinent here in that they are from the west coast of Scotland, the core area for fish farming in Scotland. This is also an area where ADDs are almost continuously active at many sites. Booth (2010), for example, mapped extensive ADD noise fields around several sites in the region. Thus, these results show a lack of habituation and an indication that habitat exclusion from ADDs is a long term phenomenon.

Canadian research also indicates long term effects of ADDs on the distribution of resident killer whales off British Columbia. These are one of the best studies of population of whales in the world and there were long term sightings and photo-id datasets for the area. Morton and Symonds (2002) reported that when ADDs were introduced at some fish farm sites the number of days on which killer whales were seen fell by a factor of three and remained at this reduced level for the next six years while ADDs were in use. Once the ADDs were removed from the fish farm encounter rates returned to pre-exposure levels. Encounter rates at a control site, 25km from the ADD site, remained constant over this period.

One interesting caveat should be stressed. All of the research on the effects of aquaculture ADDs on cetaceans has investigated the effects of only one make of ADD, the Airmar. In Scotland, two other types, those from Terecos and Ace Aquatec, account for about half the fish farm sites at which ADDs are deployed. Given their contrasting acoustic characteristics (section 2.2) it is quite possible that cetaceans will respond in a different way to these devices. Indeed, some preliminary investigations of the effects off Terecos ADDs on harbour porpoise in a Scottish sea loch suggest that this may be the case (pers. obs.)

There are no published studies that show a consistent effect of ADDs on the distribution of pinnipeds, nor, ironically, any that show they are effective at altering seal predation impacts at fish farm sites.

3.1.6 *Perceptual Effects: Auditory Masking*

Auditory masking occurs when one source of sound (or noise) reduces the audibility of another, the signal. For masking to occur the frequency of the noise and signal must be close to each other; they must be within in the same "critical" frequency band. The widths of critical bands vary between the auditory systems of different species but are typically ~1/3 octave. Signal and noise must also occur very close in time. Many animals, including marine mammals, can also utilise their directional hearing capability to provide relief from masking. Thus a noise is a more effective masker if it arrives from the same direction as the signal. Auditory masking can reduce the ability of an animal to communicate with sound and to detect other significant acoustic cues such as those from predators or prey, by passive

listening (Hafner *et al.*, 1979; Barros and Myrberg, 1987; Gannon *et al.*, 2005; Mohl, 1981). For sonar-equipped animals, masking will also reduce the performance of their active acoustic echolocation system if the noise is in the same frequency band as their echolocation signals (Au, 2004).

3.1.7 Audiograms

Audiograms are plots of the lowest received sound level at a particular frequency that can be detected. Knowledge of audiograms has some relevance to assessing the effects of underwater sound.

If the sound is composed only of frequencies which do not lie within the reception bandwidth of the animal, direct behavioural impacts will be unlikely. For example, a sound at an ultrasonic frequency of 50 kHz will not be heard by a human (Kinsler *et al.*, 2000). Physical damage, including damage to hearing, however, can be caused by intense acoustic energy outside an animal's auditory range.

When assessing the effects of noise on humans it is common to weight sound by applying a frequency weighting filter which can be related to, but not the same as, the frequency response of the human ear. Different weighting curves are applied to sounds of different intensity with "flatter" weighting curves being used for more intense sounds. Thus the dB A-weighting curve is used for relatively quiet sounds (20-50 dB re 20 μ Pa). This is based on the 40-phon Fletcher-Munson human hearing curves which quite closely tracks the human audiogram. By contrast, the weighting applied to higher received levels (85-140 dB re 20 μ Pa), the C weighting is based on the 100 phon curve and is much "flatter" than the audiogram (Burns, 1973).

3.1.1.1 Techniques for Measuring Audiograms from Marine Mammals

Audiograms are a convenient way of representing hearing sensitivity as a function of frequency. They are plots of the sound pressure levels of pure tones required for the subject to just perceive them (hearing thresholds).

Measuring audiograms from marine mammals requires a technique which does not rely on direct cognitive compliance because the animal cannot be asked whether the sound is perceptible. Two approaches are commonly used. The first relies on behavioural response and requires the animal to be trained to perform a task (e.g. press a paddle) in response to an aural stimulus. This is still considered the gold standard method but can only be used with captive animals after extensive training. The second technique involves measurement of the evoked auditory potential which is the electrical impulse in the auditory nerves and brain stem that result when a sound is being processed in the brain. In this approach, electrodes are attached to the animal to measure the electrical response to the sound directly.

3.1.1.2 Marine Mammal Audiogram data

Figure 56 shows the audiograms for species of cetaceans. Figure 57 shows the audiograms for some example species of pinniped.

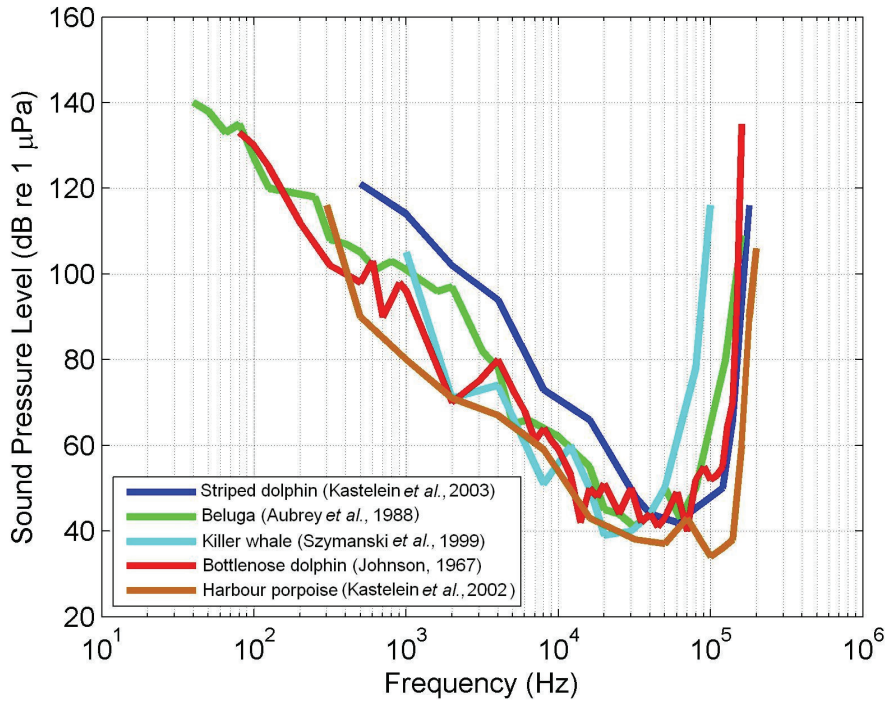


Figure 56: Hearing threshold data for a range of cetaceans.

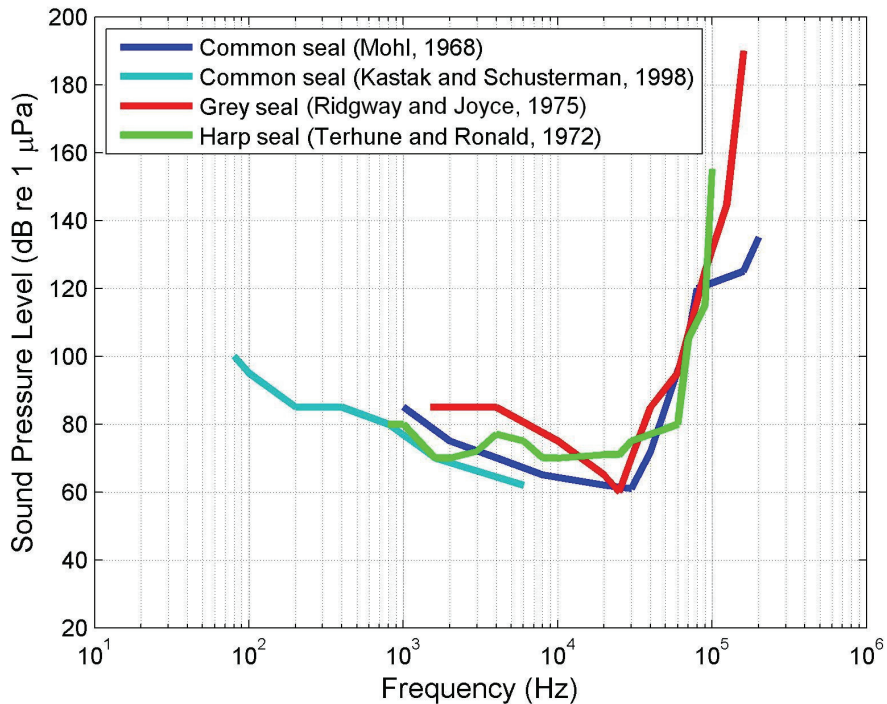


Figure 57: Hearing threshold data of a range of pinniped species.

These audiograms show the hearing responses for some example marine mammals. There are limited data of this type. Audiograms for many species are based on a measurement of a single individual animal and there are very few data for animals that cannot be kept in captivity. (In this respect it is interesting to note that there are no audiograms based on behavioural response for the grey seal a species heavily exposed to ADD signals in Scotland.) As with human subjects, hearing sensitivity can change substantially from

individual to individual and will depend on factors such as age, disease and previous exposure. This can result in very different audiograms being measured from different subjects of the same species and points to the importance of representing a species audiogram with a statistical sample rather than a single measurement.

Behavioural audiograms are usually derived by measuring responses to pure tones. In a recent study, (Kastelein *et al.*, 2010) measured the hearing threshold of a captive porpoise and common seal for a range of ADDs. They found that observed sensitivity to ADDs was very much in line with that which could be predicted based on knowledge of sensitivity to pure tones provided by audiograms.

An animal's ability to detect a faint signal can be affected by masking from background noise (see 3.1.6 section). Recent work (Kastelein *et al.*, 2009) has shown that the low frequency sensitivity measures used in earlier audiograms for seals was determined by low frequency noise masking in noisy facilities, rather than the animals' actual sensitivity. He showed that seals are more sensitive to low frequency sound than had previously been assumed. This finding is likely to lead to a reassessment of the low frequency sensitivity in a number of pinniped and cetacean species. However, as the dominant frequency in most ADDs is somewhat above those at which these effects were an issue, it is unlikely that this will have much influence on the impacts being considered here.

3.1.8 *Measuring and Predicting Damage and Behaviour: Some Comments*

In the case of acoustic deterrent devices, concerns focus on both the potential for damage to animals present at close range to the source and behavioural effects and disturbance which can occur at much greater ranges and potentially affect many individuals. These two classes of effect vary substantially in both the ease with which we can measure their occurrence and the reliability with which they can be predicted on the basis of received sound levels.

Measuring hearing damage in marine mammals is technically difficult, is expensive and raises ethical concerns. It is only in the last decade that extensive trials have been conducted with a few species of captive marine mammals to measure TTS. On the other hand, the effects are largely mechanical and physiological and as such our expectation is that high level of consistency and repeatability will be exhibited. In addition, similarities in form and function between mammalian ears provides a basis for the application of understanding and the cautious extrapolation of results from the relatively well researched area of human and terrestrial mammal audiology to the poorly understood marine mammal field. Thus, there is every reason to believe that once thresholds for effects such as PTS have been established for a particular species and type of sound they will be generally applicable for that sound type within that species.

By contrast, behavioural responses and behaviour are relatively easy and inexpensive to measure for any particular combination of species and sound type. However, as outlined above, responses are expected to be inherently variable and unpredictable, and this has certainly been born out in practice. Thus, after an extensive review, Southall *et al.* (2007) found no reliable relationship between received level and type or severity of behavioural response. For this reason, they recommended that "the only currently feasible way to assess whether a specific sound could cause disturbance is to compare the circumstances of the situation with empirical studies that have carefully controlled variables".

These fundamental differences in the nature of criteria for damage and for behavioural change should be reflected in contrasting strategies for assessing risks for each type of impact.

Assessment of injury risk is more amenable to modelling. Because injury effects are reasonably predictable it may be effective to put effort into understanding received levels through characterising sources and propagation conditions to allow predictions of sound fields around particular sound source. (It is important to note, however, that SEL results from cumulative exposure and this will be largely determined by animals' behaviour. Namely, their movement within a sound field and in particular whether and how rapidly they move away from a loud sound source.) For behavioural effects, characterisation of sources and propagation will do little to provide improve understanding. A more empirical strategy will be better in this case, directly measuring behaviour and changes in distribution at different ranges and exposure levels in the particular habitats of interest.

4. DAMAGE RELATED CRITERIA AND THRESHOLDS FOR ACCEPTABLE EXPOSURE

4.1 Introduction

Improved understanding of the effects of noise on marine mammals and growing public concern about the issue has resulted in underwater noise impacts being included in legislation and being increasingly considered by regulators. This in turn had led to the need for agreed criteria for what constitutes unacceptable exposure. Different jurisdictions and societies have differing legislation and regulations relating to noise exposure and disturbance, which, in part, reflect differences in public opinion, ethical consensus and politics. We should not therefore expect criteria developed in one jurisdiction to be directly applicable in another.

The JNCC is working on guidance notes on the protection of European Protected Species from injury and disturbance (JNCC, 2010). This guidance will apply to all cetaceans in UK offshore waters (beyond 12 miles) and in English and Welsh inshore waters. The Scottish Government is working on similar guidance for Scottish inshore waters, which may also include advice on seals.

4.1.1 US Marine Mammal Noise Exposure Criteria for Injury

The most substantial effort to derive criteria for unacceptable sound exposure for marine mammals based on the best available scientific information has been a US initiative. The US Marine Mammal Criteria Group of the NMFS (National Marine Fisheries Service, part of NOAA) was an expert committee of North American scientists that met at a number of workshops held over several years. During these, they critically reviewed available literature and science based information, and developed a reasoned scheme for applying this information to develop a range of noise exposure criteria. The results of this process, including the criteria and detailed explanations of how they were derived and how they should be applied, were published in a peer reviewed special issue of Aquatic Mammals (Southall *et al.*, 2007).

We consider this to be a very substantial and useful piece of work. Particular strengths include the large number of expert scientists involved in the process, the extensive period over which they met and worked on the project, and the eventual publication of a peer reviewed paper as a consensus report. It is particularly helpful that the report describes in detail the logic by which criteria were arrived at and how they should be applied. This makes it possible to introduce and use new scientific information as it becomes available and to adapt criteria appropriately so that they can be applied in different regulatory regimes. Thus, it is the framework and process that should have long term application rather than the particular thresholds calculated using the best evidence available when the report was authored in 2007. The criteria and the approach behind them are gaining wide acceptance and are being applied outside the US. JNCC (2010) have recommended that these criteria should be used in assessing impacts on marine mammals in UK waters beyond 12 nautical miles and in English and Welsh coastal waters.

The total amount of acoustic energy received by an individual animal is measured over a period of 24 hours (Southall *et al.*, 2007). Southall *et al.* (2007) go on to consider the onset of PTS to constitute injury. In mammals, sound induced PTS represents irreversible damage to the cochlear hair cells and a permanent impairment in hearing function. By contrast TTS is more equivalent to fatigue from which recovery is possible. As PTS has not been measured in marine mammals, the injury criteria were extrapolated from data for TTS-onset and from the rate of TTS growth with increasing exposure levels above the threshold for

TTS-onset. It was assumed, based on available data from terrestrial mammals, that a sound exposure capable of inducing 40 dB of TTS would cause PTS-onset.

The authors recognised that auditory systems can be damaged both by an instantaneous exposure to a very intense sound and by cumulative exposure over a period of time. They thus proposed two criteria to cover both types of effect.

For the first, the relevant acoustic metric was the highest (zero-peak) level, with no frequency weighting, experienced by the animal. PTS, the damage criteria, is assumed to occur at 6 dB above the levels of instantaneous (zero-peak) level that induce TTS onset.

For the second, the relevant metric was a measure of the amount of acoustic energy entering the auditory system and for this they chose sound exposure level (SEL) after application of the appropriate frequency weighted filter (known as M-weighting, see section 4.1.2 for explanation). Sound exposure level is a measure of received energy and a function of both the level and amount of exposure (which will generally be determined by the duration of exposure). Over an extended exposure time an animal may move extensively within a sound field, thus its behaviour (in particular its movements) will substantially affect the level of exposure. In this case, PTS onset (injury) is assumed to occur at an SEL which is 20dB above that which induces TTS if the sound is continuous and 15dB above TTS for pulsed sounds.

The Marine Mammal Noise Exposure Criteria is applied differently for three sound types representing the range of sound sources to which marine mammal might be exposed. These are: i) single pulses; ii) multiple pulses; and iii) non-pulses. Southall *et al.* (2007) comment that acoustic harassment/ deterrent devices have characteristics of both pulsed and non-pulsed sound. The extent to which ADDs have pulsate characteristics will also vary between models and with range from the source. In this report we consider them to be pulsed sound sources at relatively short ranges < 500 m.

As has already been mentioned, a particular strength of the Southall *et al.* (2007) process is that it provides a framework within which new knowledge can be used as it becomes available. Indeed, this was always intended. Since publication of these criteria new data have been published which, for the first time, provided information on thresholds for TTS in harbour porpoises (Lucke *et al.*, 2009). This is particularly relevant to this current report because harbour porpoises are the most common cetacean in Scottish inshore waters where ADDs are utilised. Lucke *et al.* (2009) found that porpoises were more vulnerable to TTS than other previously measured small cetaceans. They reported a threshold for TTS onset of 165 dB re 1 μ Pa²s. Some recent supporting data from a related species *Neophocaena phocaenoides asiaeorientalis* the Yangtze finless porpoise have also shown similarly relatively low TTS- onset thresholds (Popov *et al.*, 2011). As these are the only available data on TTS onset for phocénids, we believe that data from Lucke *et al.* (2009) should be considered the appropriate values to use for harbour porpoise and we calculate thresholds based on them in Section 4.1.3.

4.1.2 Auditory Sensitivity and Frequency Weighting Applied to Marine Mammal Noise Exposure Criteria

Southall *et al.* (2007) proposed the use of a range of marine mammal specific frequency weighting filters (M-weighting) be applied when assessing the damage risk from underwater noise. It is clear from research with humans and terrestrial mammals that it is not appropriate or precautionary to simply use an audiogram as a filter. To derive appropriate filters marine mammal species were classified into one of four groups (three for cetaceans and one for pinnipeds). To reflect the fact that these filters are being applied to effects of sound at high received levels and to provide a degree of precaution, the M-weighting filters

are quite "flat" as is the case with human C-weighting for high-amplitude sounds (Section 3.1.7). In fact these filters largely reflect the functional hearing ranges of the proposed groups so that for signals containing multiple frequency components, energy contributions from frequency components outside the hearing band of the species will be removed from the overall exposure estimate. The appropriate M-weighting filter is applied to sound being considered in much the same way as A or C weighting are used in airborne acoustics when considering effects on a human receptor. Sound Exposure Levels (and accumulated SEL) are then calculated using the output from the filter (Theobald *et al.*, 2009). This process is applied only when assessing criteria based on SEL, other assessments may use un-weighted values.

The filter functions which were based on current understanding of appropriate marine hearing data for the five marine mammal hearing groups are summarised in Table 4 and plotted in Figure 58.

Table 4: Functional marine mammal hearing groups taken from Southall et al. (2007).

Function hearing group/Frequency-weighting network	Estimated auditory bandwidth	Genera represented
Low-frequency cetaceans – M_{lf}	7 Hz to 22 kHz	<i>Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera</i> (13 species/subspecies)
Mid-frequency cetaceans – M_{mf}	150 Hz to 160 kHz	<i>Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon</i> (57 species/subspecies)
High-frequency cetaceans – M_{hf}	200 Hz to 180 kHz	<i>Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus</i> (20 species/subspecies)
Pinnipeds in water – M_{pw}	75 Hz to 75 kHz	<i>Arcocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocartos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydruga, and Odobenus</i> (41 species/subspecies)
Pinnipeds in air – M_{pa}	75 Hz to 30 kHz	Same species as pinnipeds in water

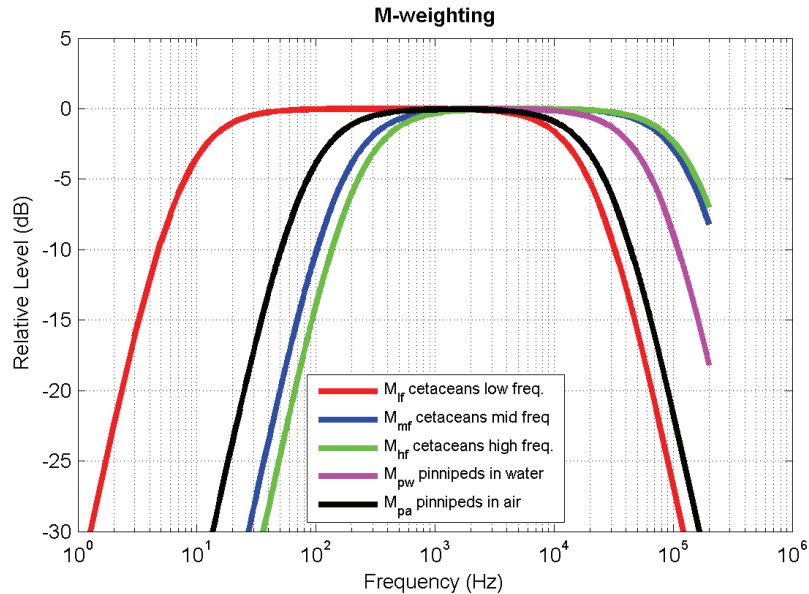


Figure 58: The M-weighting filters taken from Southall *et al.* (2007).

4.1.3 Injury Sound Exposure Criteria

The injury criteria we work to in this report uses values from Southall *et al.* (2007) for high and mid frequency cetaceans and for pinniped species groups. However, for porpoises we have calculated alternative thresholds by applying the new values for TTS from Lucke *et al.* (2009) using the Southall *et al.* (2007) procedure:

Lucke *et al.* (2009) reported TTS in a harbour porpoise after it had received a sound exposure of 199.7 dB re 1 μ Pa (peak to peak), = 194 dB re 1 μ Pa (zero to peak) or a sound exposure level of 164.3 dB re 1 μ Pa²·s. Under the procedure proposed by Southall *et al.* (2007) predictions of PTS are generated by adding 6 dB to sound pressure level TTS exposure values, 15 dB to SEL TTS levels for pulsed sound exposures and adding 20 dB for SEL TTS levels for continuous sound exposures. Thus, predicted thresholds for porpoises are 200 dB re 1 μ Pa (zero to peak), 179 dB re 1 μ Pa²·s SEL and 184 dB re 1 μ Pa²·s SEL respectively.

Thresholds for injury used in this report are:

For high and mid frequency cetaceans (e.g. dolphins, killer whales etc):

- Sound Pressure Level injury criteria : 230 dB re 1 μ Pa (peak) (flat)
- Sound Exposure Level injury criteria (for multiple pulses): 198 dB re 1 μ Pa²·s (M-weighted)
- Sound Exposure Level injury criteria (for continuous sound): 215 dB re 1 μ Pa²·s (M-weighted)

For harbour porpoise:

- Sound Pressure Level injury criteria: 200 dB re 1 μ Pa (zero-peak) (flat)
- Sound Exposure Level injury criteria: (for multiple pulses): 179 dB re 1 μ Pa²·s (M-weighted)

- *Sound Exposure Level injury criteria (for continuous sound): 184 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ (M-weighted)*

Pinnipeds in water:

- *Sound Pressure Level injury criteria: 218 dB re 1 μPa (peak) (flat)*
- *Sound Exposure Level injury criteria: (for continuous sound) 203 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ (M-weighted)*
- *Sound Exposure Level injury criteria: (for multiple pulses) 186 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ (M-weighted)*

4.1.4 Behavioural Noise Exposure Criteria

As already stated, in spite of an exhaustive review, Southall *et al.* (2007) were unable to find any acoustic criteria which were reliable predictors of behavioural response to underwater sound. Instead they recommended that "*the only currently feasible way to assess whether a specific sound could cause disturbance is to compare the circumstances of the situation with empirical studies that have carefully controlled variables*".

A certain amount of work has already been done to measure behavioural responses and movements in response to ADDs (see section 3.1.5). These have been shown to result in partial or complete habitat exclusion over considerable ranges for at least two species of cetacean in response to one of the ADD types widely used at Scottish fish farm sites.

These data already provide an evidence base which could be used to generate likely scenarios which regulators could consider to allow them to start to make a reasoned assessment of whether this likely degree of disturbance of EU protected species is unacceptable and whether it could pose a risk to the wellbeing of local populations. Even if such an exercise was not conclusive, it would help to clarify the key data gaps and determine the focus any further research.

If future studies of cetacean responses and displacement were carried out in conjunction with better measurements of received levels and sound fields then acoustic metrics, such as received sound levels, might be shown to be useful predictors of response. In which case, modelling of sound fields, particularly at longer ranges (several kilometres), using the tools developed in this project, would be useful in predicting expected impacts at different farm sites. Within this project, however, there is no scope for such an exercise and models of sound fields at fish farm sites do not help us to predict behavioural effects.

5. ASSESSING DAMAGE RISK FROM ADDS AT SCOTTISH FISH FARM SITES: COMBINING SOUND FIELD PREDICTIONS AND DAMAGE RISK CRITERIA

5.1 Introduction

The first step in developing a damage risk model for Scottish aquaculture sites is to provide a prediction of received level in relation to range from sound source. In the case of criteria based simply on instantaneous sound level thresholds the predicted sound level can be compared to impact threshold directly and an assessment of the maximum distance at which that level is exceeded can be made. The situation is far more complicated for criteria involving a sound exposure threshold (which are also the criteria with the strongest scientific support and those more appropriate for extended sound sources such as ADDs). This is because SEL is a measure of cumulative exposure over time. Exposure level depends on range from the source and over an extended exposure this will be determined by animal movement which has not been measured.

Investigation of underwater sound propagation losses in relation to known ADD system characteristics and environments (e.g. sediment type and depth) were investigated within Section 2.3. In this study the dependency on sound propagation was determined for four common sediment types (sand, silt-sand, silt and silt-clay) and for a range of water depths (20-120m) typical for Scottish aquaculture sites. A review of known acoustic characteristics for ADD systems showed that many of these devices have relatively broadband emissions with complex frequency – time varying components. Comparisons between the three most commonly used systems showed variation in predicted propagation losses with source type (frequency versus amplitude), water depth and sediment type (Section 2.3). In addition, analysis of the effects of seabed slope was conducted for both a shallow (30m) and a deep water (80m) site (Section 2.3). In both cases propagation losses varied due to both the angle and slope direction.

5.2 Propagation loss modelling

The marine mammal impact criteria proposed by Southall *et al.* (2007) for assessing risk of injury which we reviewed in Section 2.1 and propose to apply here specific dual criteria. One based on zero-peak sound pressure level and the second on a frequency weighted cumulative Sound Exposure Level (SEL) (see Section 2.1). Both of these metrics are broadband (containing more than a single frequency component). Acoustic propagation losses in water are generally frequency dependent, with different losses at different frequencies. Broadband (all combined frequencies) losses are therefore not reliably predicted by a single frequency model. Time domain modelling to fully represent all frequency components simultaneously is possible (Jensen *et al.*, 2000) but computationally extremely intensive, and therefore not a feasible method for the development of a generalised model output within the current project.

To adequately describe likely broadband losses for these systems the spectral content of each system was divided into third octave bands (ANSI, 1993) in the range 0.025 - 100 kHz. Analysis showed that dominant frequency components (SEL Source level per third octave band integrated across 1 second of greater than 140 dB re 1 $\mu\text{Pa}^2\text{s.m}^2$) were in the range 2-40 kHz. The devices all have highly variable duty-cycles both between pulses and between sequences of pulses, with sequences of potential duration in excess of 2 s in all three systems. Typical SEL Source levels in each third octave band were estimated from data in the literature over a one second long integration period within a sequence in which devices were acoustically active. In the case of the Terecos system, data for four different program types were reviewed. To establish generalised source characteristics the average level across all four programs in each third octave band was used in this model.

The propagation losses were estimated across a flat seabed for each third octave band with centre frequencies (2, 2.5, 3.25, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5 and 40 kHz) for each sediment type and for a range of depths (20-120m) using a source image model (Kinsler *et al.*, 2000). This model provides dependence on water depth, water column, sediment properties, surface roughness and source frequency and is computational significantly more efficient than other commonly used propagation models such as ray tracing codes like Bellhop (Porter, 2010) or parabolic equation methods (PE) in codes such as RAMGeo (Collins, 1988). The latter two methodologies, however, offer the advantages of modelling range dependent (varying bathymetries) environments and were used in seabed slope analysis discussed in Section 2.3.7.

Figure 59 shows the range averaged (Harrison and Harrison, 1995) propagation loss data for a range of depths for a silt-clay sediment type for 2 kHz centre frequency. Note that range averaging has the effect of reducing short range variance in transmission loss prediction without which relatively large variations in loss can occur within a few meters for these relatively high (kHz) signals in shallow water environments. Figure 60 shows an example both with and without range averaging for a sand sediment in a 30 m deep site for a 5 kHz signal. This structure is also highly dependent on the source frequency with losses varying tens' of dB within a few metres and variation in source frequency of a few tens' of Hz. However the division of the source spectral content into third octave bands means that a combined transmission loss profile at a band centre frequency can be calculated. This band has a finite frequency bandwidth and therefore variations in the structure of frequency components across this band are likely. Analysis by Robinson *et al.* (2011) indicated that the use of range averaging (Section 2.3.3) could be representative of the mean losses across that band and was used throughout latter modelling efforts. Analysis also showed good agreement in shallow water between the source-image model and other modelling techniques such as those mentioned above.

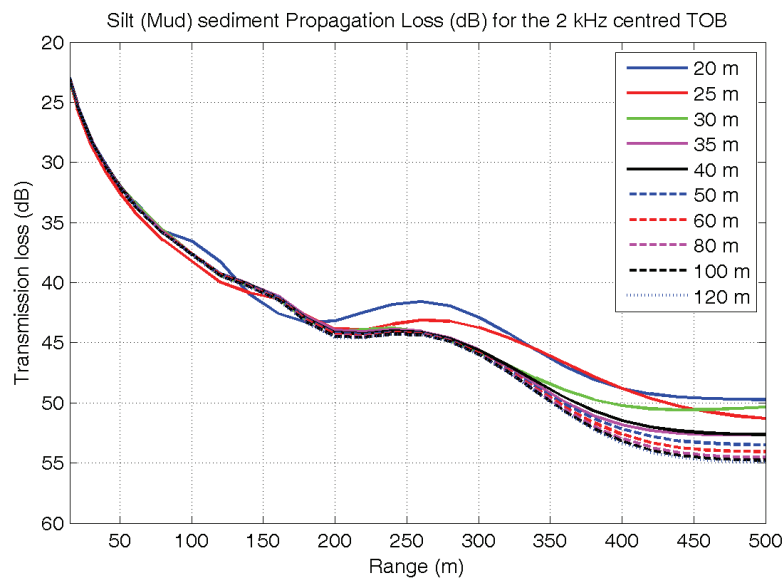


Figure 59: Transmission loss profile in a silt sediment for a 2 kHz centre frequency versus depth (all data range averaged as per Harrison and Harrison, 1995).

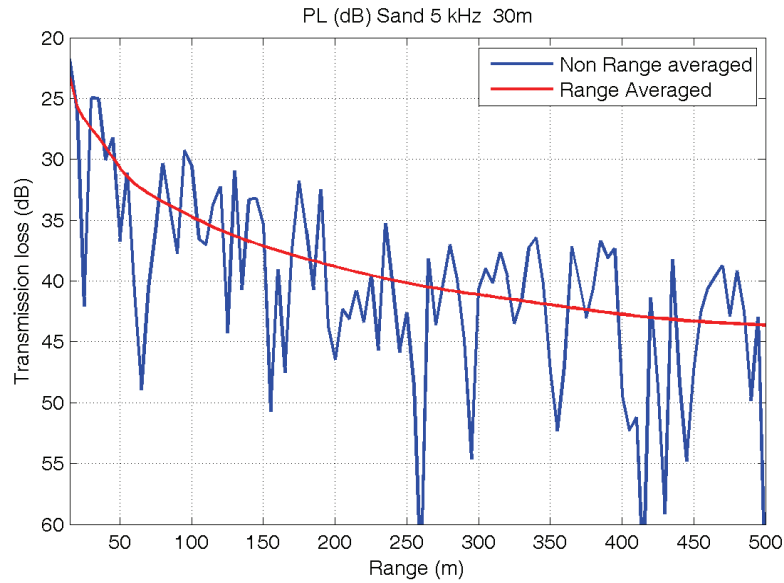


Figure 60: Transmission loss data for a 5 kHz signal with and without range averaging (Harrison and Harrison, 1995).

Using the methodologies described above over 560 transmission loss profiles for third octave band centre frequencies from 2-40 kHz for site depths from 20-120m and four sediment types were calculated for a flat sea bed using an image-source model incorporating sea surface and seabed interaction, sediment and water column characteristics and surface roughness. These data then formed the basis of the received level model developed in Section 3.3.3. All models were run for a source depth of 15m and receiver depth of 10m (Bjørge *et al.*, 1995; Otani, 2001). Water and sediment properties are given below.

5.3 Received level model organization

Data from propagation loss modelling using source-image technique were established in an Excel database. Propagation Loss (PL) data are a profile of propagations loss versus water depth for each element in a 2D matrix of third octave band (TOB) centre frequency versus site depth for each sediment type. This structure is then repeated four times for each sediment type as shown in Figure 61.

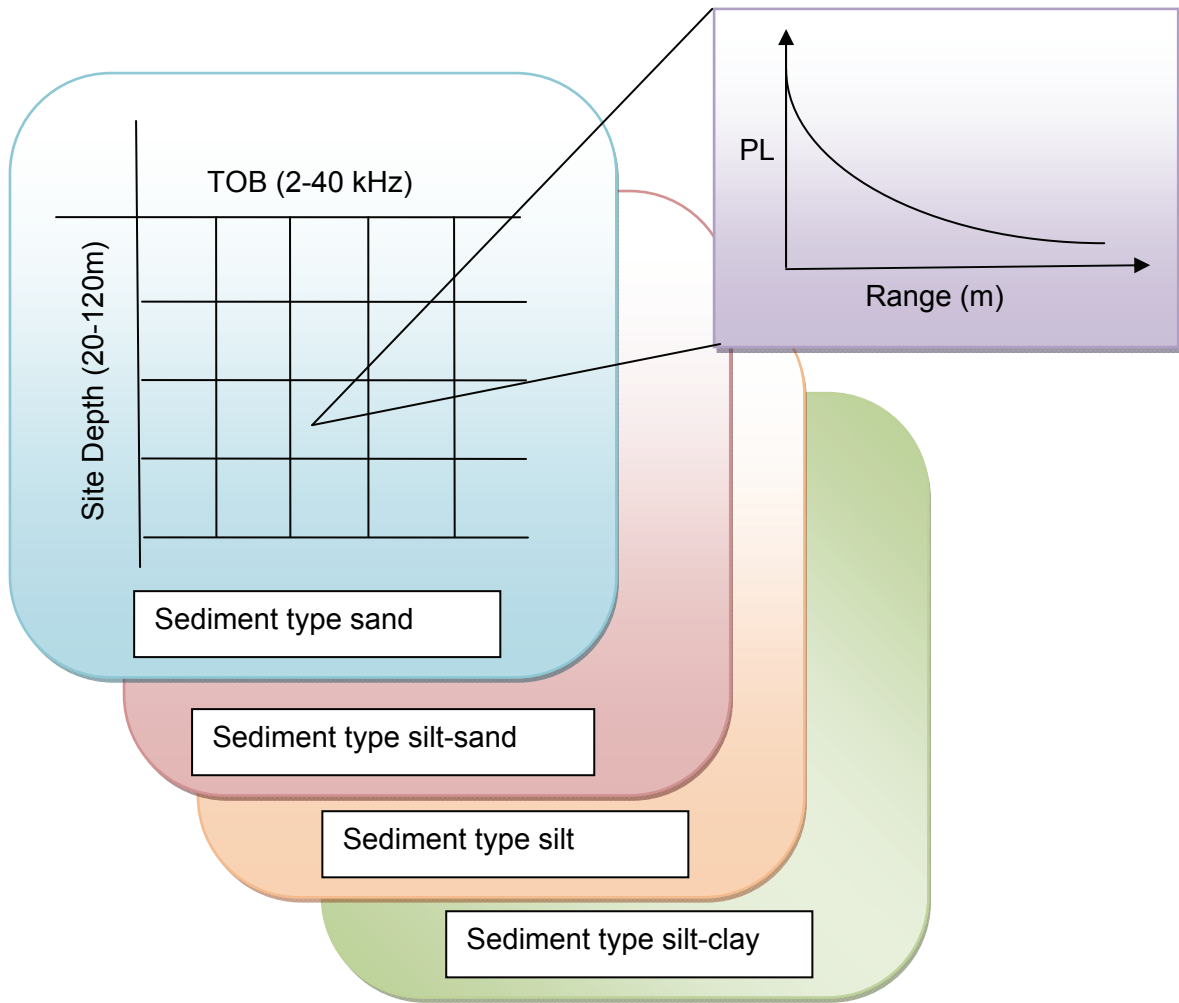


Figure 61: Propagation loss data organization within sensitivity model database (source data generated using source-image model)

Data for each third octave band propagation losses is then combined with SEL source level data for each of the three devices types (Airmar, Ace-Aquatec and Terecos). These data give the effective received level versus range where Received Level (RL) equals the Source Level (SL) - Propagation Loss (PL) for each device type, in each third octave band, and for each site depth and sediment type.

However, it should be noted that the range average is a form of mean level and does not represent the potential maximum or minimum levels possible.

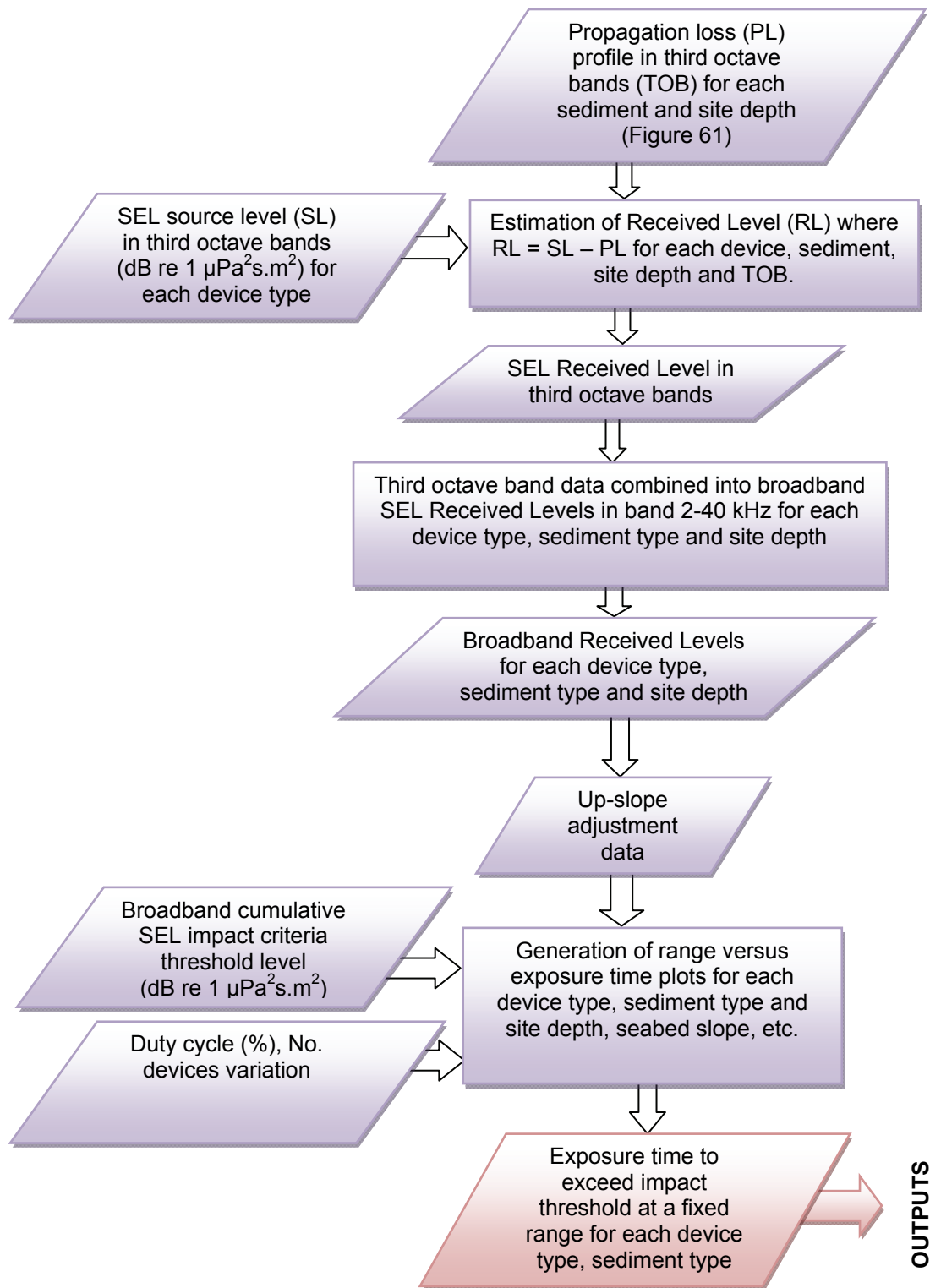


Figure 62: Cumulative SEL exposure model flow chart

These third octave band received level profiles were then summed using the equation below to produce the broadband SEL received level profiles in the band 2-40 kHz for each device type, sediment type and site depth modelled.

$$\text{Broadband SEL} = 10 \times \log_{10}(P_{2\text{kHz}}^2 + P_{2.5\text{kHz}}^2 + \dots + P_{40\text{kHz}}^2) \quad (2)$$

Where P_{kHz} is the pressure in third octave bands between 2 and 40 kHz.

Figure 62 shows an overall flow chart of data generation used within the Excel database and interactive sensitivity model. It is possible to pre-compute received levels for each device type and site parameters in the database reducing the overall complexity of the database structure. However, the separation of the propagation loss data and source characteristics as shown in Figure 62 offers the advantage that the propagation loss data are device independent and could then be applied directly to other types of source as they are measured in future. Figure 62 also shows adjustment for different seabed slopes discussed in detail in Section 2.3.7.

The SEL criteria proposed by Southall *et al.* (2007) is a measure of the total amount of acoustic energy received by an individual animal over a nominal period of 24 hours. The propagation loss model provides a calculation for the received level at a given range but the total SEL dose will depend on how long an animal spends at various ranges from the sound source over a 24 hour period. To understand this we need to apply knowledge, or a reliable model, of animal movement. We don't have this and animal behaviour remains the most significant unknown in the process. However, field observations suggest that two extremes may be exhibited by porpoises and seals respectively. Photo-id studies have shown that seals will remain close to fish farm sites with active ADDs for periods of hours at a time and the same individual may be seen at the site on subsequent days (Northridge *et al.*, 2010; pers. obs.).

5.4 Predicting range to pre-determined SEL Contour

Within the Excel database an estimate is made of the minimum range below a user-defined broadband SEL (for a one second exposure) for each device type, site depth and sediment type. The example shown in Figure 63 is for a hypothetical 140 dB re $1 \mu\text{Pa}^2\text{s}$ broadband impact threshold for a 30 m site depth giving in this case an effective range to the 140 dB sound contour was 180 m.

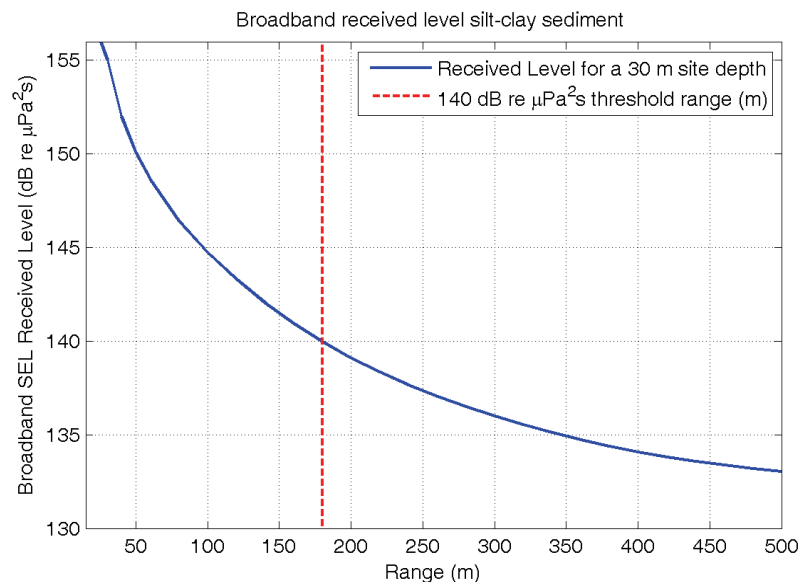


Figure 63: Example of a range of influence estimation for a broadband signal for a 30 m deep site and a 140 dB re $1 \mu\text{Pa}^2\text{s}$ hypothetical impact threshold.

5.1.1 Seabed slope propagation loss adjustment

A range-dependent (varying bathymetry) modelling code known as Bellhop (Porter, 2010) was used to analyse the effect of seabed slope on propagation loss in (Section 2.3.7). This analysis showed that in the case of down slope (sea bed getting deeper) propagation losses were generally higher than those for flat sea bed, and correspondingly, down sloping sea beds have lower potential received level compared to a flat sea bed (Figure 64). However, for an up-slope (where the sea bed gets shallower) potential levels of sound received were possibly up to 2-3 dB higher in some frequency bands. In the latter case lower losses of propagation would result in higher received levels and therefore greater range of influence. The use of a flat sea bed only model in this case would potentially underestimate the range of influence. To address this, an adjustment factor has been included, specifically for the upslope case. Analysis shown in Figure 64 shows that upslope scenario is relatively complex resulting in complex received level profiles with strong range and frequency dependence compared to equivalent flat seabed scenario. It is theoretically possible to model a range of up and down seabed slopes for all cases of site depth, and sediment types and third octave band centre frequencies. Using the current model resolution, this would require additional 560 model runs per slope angle. Due to the higher computational complexity of range-dependant models such as Bellhop (Porter, 2010) compared to the range-independent source image model this approach was beyond the scope of the current study. However, use of the adjustment factor based on analysis from Section 2.3.7 is proposed to compensate for lower losses seen in the upslope case.

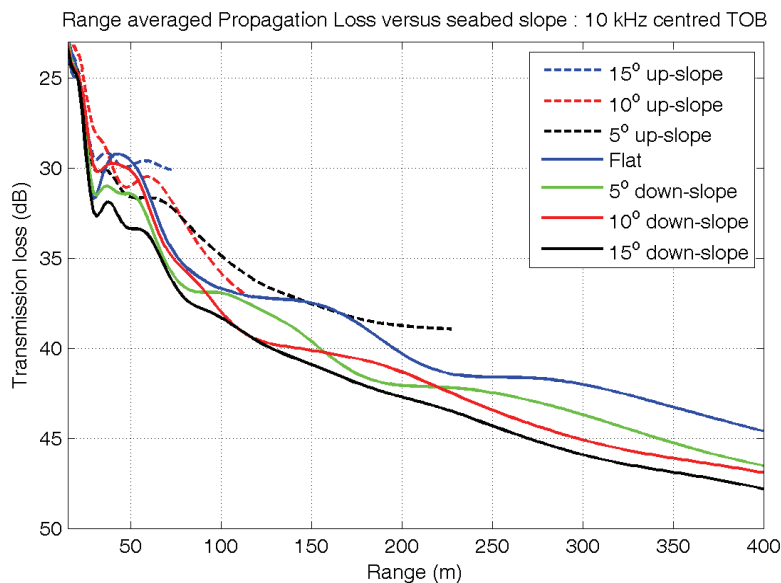


Figure 64: Effect of seabed slope versus received level at 10 kHz for a 30 m deep site with a sandy sediment.

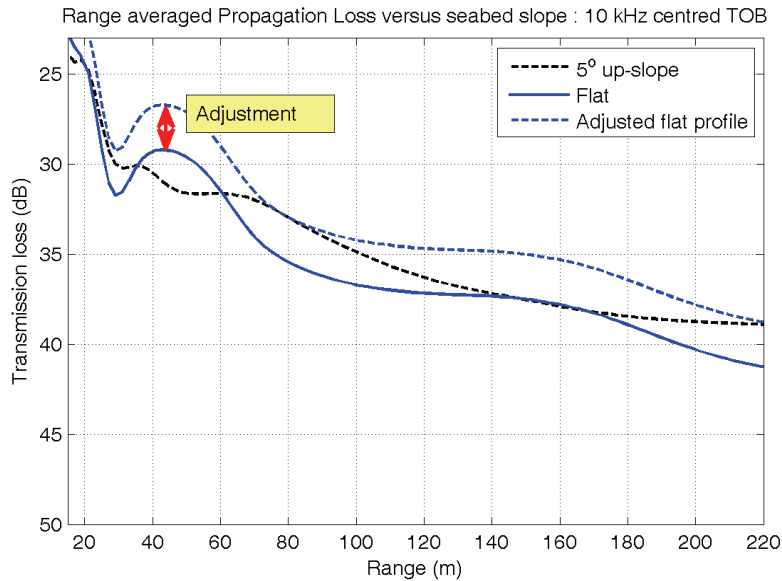


Figure 65: Adjusted flat seabed received level to compensate for upslope loss differences at 10 kHz for a 30 m deep site with sandy sediment.

Using analysis from Section 2.3.7 the maximum observed difference in losses for an upslope and flat sea bed cases is used to adjust the flat seabed curve. Figure 65 shows the equivalent upslope adjustment (around 2.1 dB) of the flat seabed received level profile for a 10 kHz signal in this case. Note that this approach will tend to overestimate potential received levels and therefore range of influence at some ranges and frequencies for the upslope case, however, a precautionary approach was felt more appropriate.

In the case of a down slope, Figure 64 shows that losses are higher compared to a flat seabed case. Again the use of the flat sea bed case as a substitute for a down slope was therefore felt more precautionary in estimating of the ranges of influence.

5.1.2 Frequency Weighting

In the case of the SEL exposure criteria, Southall *et al.* (2007) proposed that broadband SEL data should then be frequency weighted (filtered) for each functional hearing group (m weighting). Figure 58 and Table 4 shows the functional bandwidths of filters applied to each group. In all but the case of the low frequency cetacean the functional hearing range of the group is greater than the bandwidth of the dominant frequency components of the ADD systems modelled, therefore no adjustment was made to the overall received levels. In the case of the low frequency cetaceans a functional hearing range of 7 Hz to 22 kHz is proposed by Southall *et al.* (2007) within the band of dominant frequency components of reported ADD systems. Figure 66 shows an example of the equivalent third octave band SEL source levels for the Ace Aquatic system with and without M-weighting.

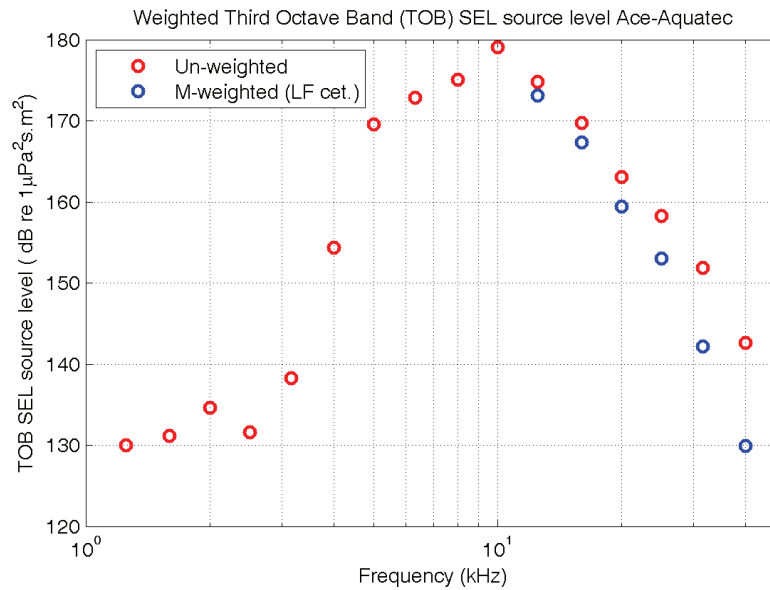


Figure 66: M-weighted (Southall *et al.*, 2007) for a low frequency cetacean equivalent SEL source levels in third octave bands for an Ace Aquatec system.

In this case some of the higher frequency components of the ADD systems are reduced, therefore lowering overall received level perceived broadband SEL value. In an example of the Ace Aquatic device the SEL threshold level of 160 dB would be reported at 30m M-weighted for a low frequency cetacean or at 40m for all other groups also m-weighted. To allow assessment of weighted received level impact ranges each weighting filter must be applied independently and results modelled for each hearing group. For current devices and criteria, however, the mid and high frequency cetaceans and pinnipeds have been grouped together with additional outputs for the low hearing range of the low frequency cetaceans to reduce output complexity.

5.5 Models of Influence Zones and Safe Exposure Times for ADDs at Typical Scottish Fish farms

5.5.1 Zero to Peak Instantaneous Exposure Criteria

Southall *et al.* (2007) proposed impact thresholds for zero-peak SPL of 230 dB re 1 μ Pa (un-weighted) for the low, medium and high frequency cetaceans and 218 dB re 1 μ Pa (un-weighted) for pinnipeds in water. Our calculation for a threshold for harbour porpoise were based on data from Lucke *et al.* (2009) and is 200 dB re 1 μ Pa.

Most reported data for ADD device system source levels are in terms of instantaneous RMS (root mean square) levels. Very little data exist on the equivalent un-weighted zero-peak levels for most devices in use. These levels are also likely to be highly variable due to strong constructive and destructive interference effects in shallow water. However, based on reported RMS levels for known ADD systems (Section 2.2) these levels are unlikely to be exceeded even at source (1m range) for any of the ADDs used at Scottish aquaculture sites.

5.5.2 Sound Exposure Level *v* Range

The prediction of received levels has been developed to form an interactive model based on look-up tables for known source characteristics combined with propagation loss profiles for typical Scottish aquaculture sites as discussed in Sections 3.1 and 3.2. The three most common ADD systems (which account for almost all systems currently in used at Scottish fish farms, Northridge *et al.*, 2010) have been modelled for a representative range of site

water depths and sediment types. Figure 67 shows a screen capture of output data for mid / high frequency cetaceans and pinnipeds in water and for a user defined SEL threshold level in this example of 160 dB re 1 $\mu\text{Pa}^2\text{s}$ for 1 second instantaneous exposure. It should be stressed that these do not represent ranges for damage risk, an energy based criteria based on a 1 second exposure would not be appropriate for a fish farm scenario and we are not aware of any scientifically based damage risk criteria which use this metric (see below).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q			
1																				
2	SEL Threshold				160				dB				Mid / High Frequency Cetaceans and Pinnipeds in water				1 Second Exposure			
3																				
4	FLAT / DOWNSLOPE SEABED																			
5	Site	SAND			Site	SANDY SILT			Site	SILT			Site	SILTY CLAY						
6	Depth (m)	AIRMAR	ACE	TERECOS	Depth (m)	AIRMAR	ACE	TERECOS	Depth (m)	AIRMAR	ACE	TERECOS	Depth (m)	AIRMAR	ACE	TERECOS				
7	20	15	40	30	20	15	40	30	20	15	40	30	20	15	40	30				
8	25	15	40	30	25	15	40	20	25	15	40	20	25	15	40	20				
9	30	15	40	30	30	15	40	30	30	15	40	30	30	15	40	30				
10	35	15	40	30	35	15	40	30	35	15	40	30	35	15	40	20				
11	40	15	40	30	40	15	40	30	40	15	40	30	40	15	40	30				
12	50	15	40	30	50	15	40	30	50	15	40	30	50	15	40	30				
13	60	15	40	30	60	15	40	30	60	15	40	30	60	15	40	30				
14	80	15	40	30	80	15	40	30	80	15	40	30	80	15	40	30				
15	100	15	40	30	100	15	40	30	100	15	40	30	100	15	40	20				
16	120	15	40	30	120	15	40	30	120	15	40	30	120	15	40	30				
17	Threshold range (m)				Threshold range (m)				Threshold range (m)				Threshold range (m)							
18																				
19	UPSLOPE																			
20	Site	SAND			Site	SANDY SILT			Site	SILT			Site	SILTY CLAY						
21	Depth (m)	AIRMAR	ACE	TERECOS	Depth (m)	AIRMAR	ACE	TERECOS	Depth (m)	AIRMAR	ACE	TERECOS	Depth (m)	AIRMAR	ACE	TERECOS				
22	20	20	50	40	20	20	50	40	20	20	50	40	20	20	50	40				
23	25	20	50	40	25	20	50	30	25	20	50	30	25	20	50	30				
24	30	20	50	40	30	20	50	40	30	20	50	40	30	20	50	40				
25	35	20	50	40	35	20	50	40	35	20	50	40	35	20	50	40				
26	40	20	50	40	40	20	50	40	40	20	50	40	40	20	50	40				
27	50	20	50	40	50	20	50	40	50	20	50	40	50	20	50	30				
28	60	20	50	40	60	20	50	40	60	20	50	40	60	20	50	40				
29	80	20	50	40	80	20	50	40	80	20	50	40	80	20	50	40				
30	100	20	50	40	100	20	50	40	100	20	50	40	100	20	50	40				
31	120	20	50	40	120	20	50	40	120	20	50	40	120	20	50	40				
32	Threshold range (m)				Threshold range (m)				Threshold range (m)				Threshold range (m)							
33																				

Figure 67: Example screen capture of interactive sensitivity model output for minimum range to avoid TTS threshold exposure from 1 second exposure.

At each site the effects of seabed slope should also be considered and this may lead to non-symmetrical oval shaped contours of predicted received levels. Figure 68 shows a received level threshold prediction for a site with sea bed slope and asymmetrical noise field. The distances O-A, O-B, O-C & O-D can be extracted from the model and the total area ensonified above the threshold calculated.

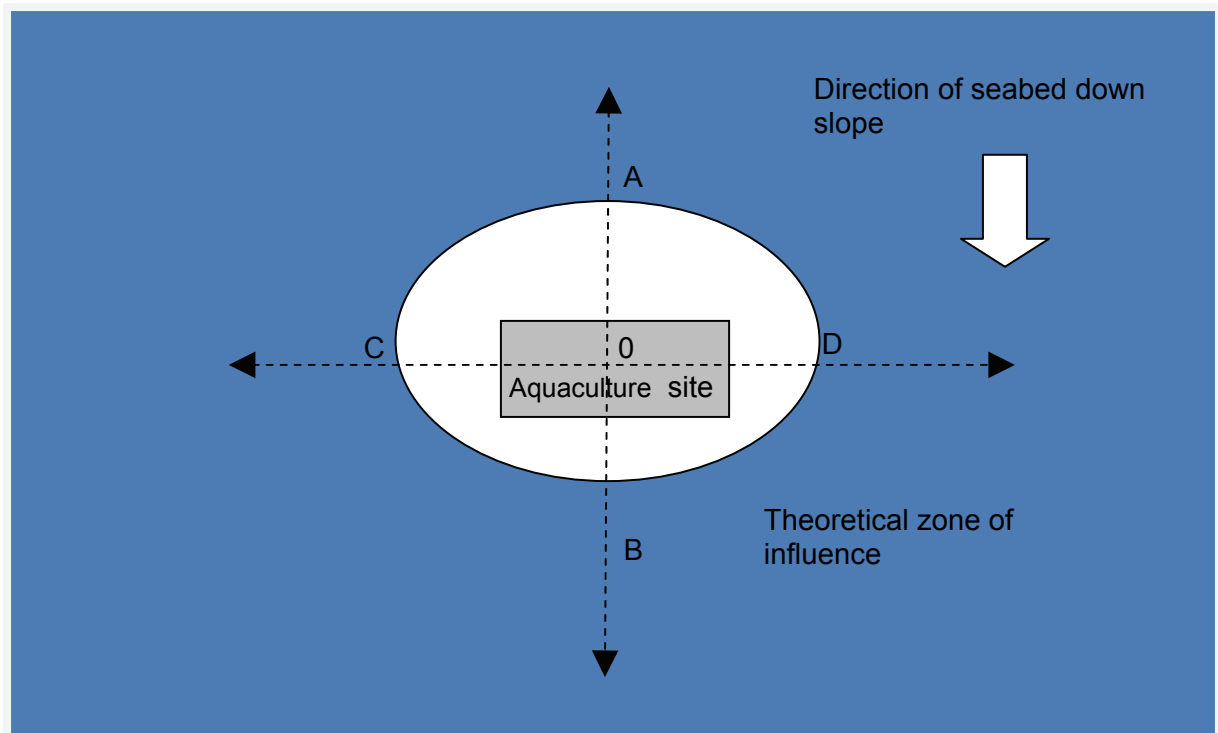


Figure 68: Received level modelling at a site with significant slope.

5.1.3 Sound Exposure Level Injury Criteria

Data represented in this range prediction model are for a SEL level integrated across 1 second. The criteria used by Southall *et al.* (2007), however, are for a cumulative exposure over a 24 hour period. Assessing this requires knowledge of the animals' movements within a sound field so that the cumulative exposure experience by an animal can be summed up over the total exposure duration. The current model could provide the acoustic data required for such an exercise given data for an animal's location and movements within the sound field. We do not know how different species would move in the noise field around a fish farm. However, some examples of cumulative exposures for stationary, fleeing and transiting animals for other noise sources have been presented in Gordon *et al.* (2007); Theobald *et al.* (2009) and Lepper *et al.* (2010).

Here we will calculate exposure for an animal that is assumed to stay at a fixed distance from the ADD.

The total cumulative SEL exposure (SEL_{cum}) can be estimated at that range where:

$$SEL_{cum} = SEL_{1s} + 10 \log(t_{ds}) \text{ in total time } t(s)$$

Where t_{ds} is the duty cycle exposure time (total time 'on' in seconds) in total time t , SEL_{1s} is the estimated received level exposure over 1 second from received level model output. Figure 68 shows an example of model output for exposure time versus distance from source. Exposure is based on an animal at fixed distance from source and the time taken for exposure to reach the user defined threshold (e.g. an injury threshold) and duty cycle (t_{ds}) is shown. Model output data are plotted for each device type sediment type, water depth and functional hearing group.

5.1.4 Model outputs

Model outputs for Terrecos ADD with differing SEL Threshold inputs corresponding to different species (pinnipeds and harbour porpoise)

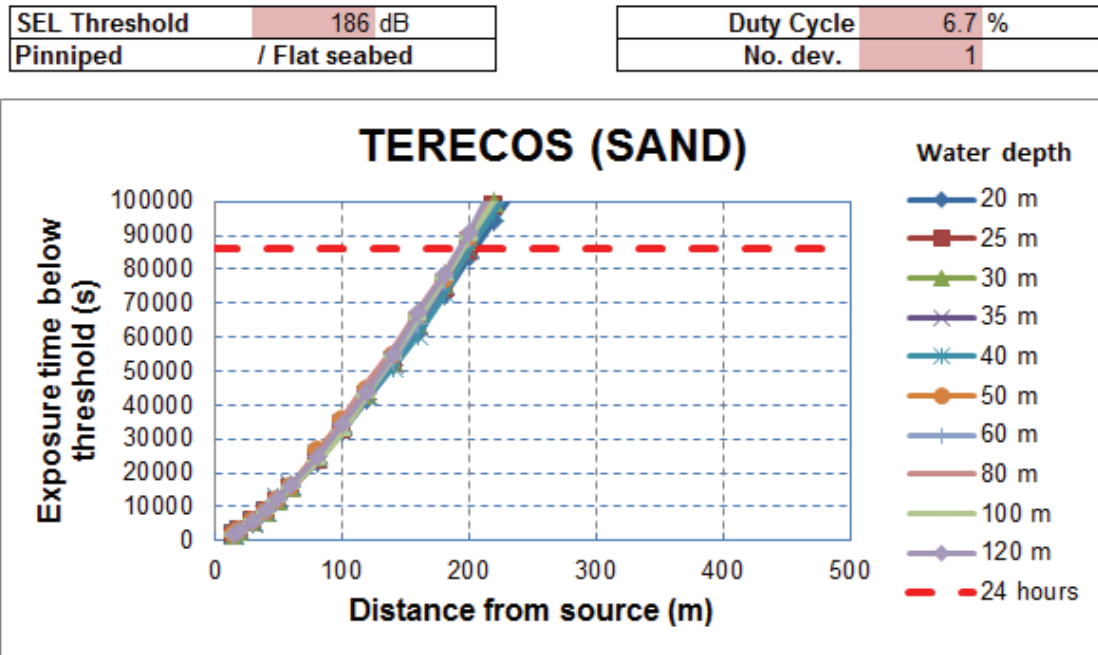


Figure 69a: Example output for time for exposure to reach the injury threshold of 186 dB re 1 $\mu\text{Pa}^2\text{s}$ for a pinniped for a single Terrecos system versus distance for multiple water depths.

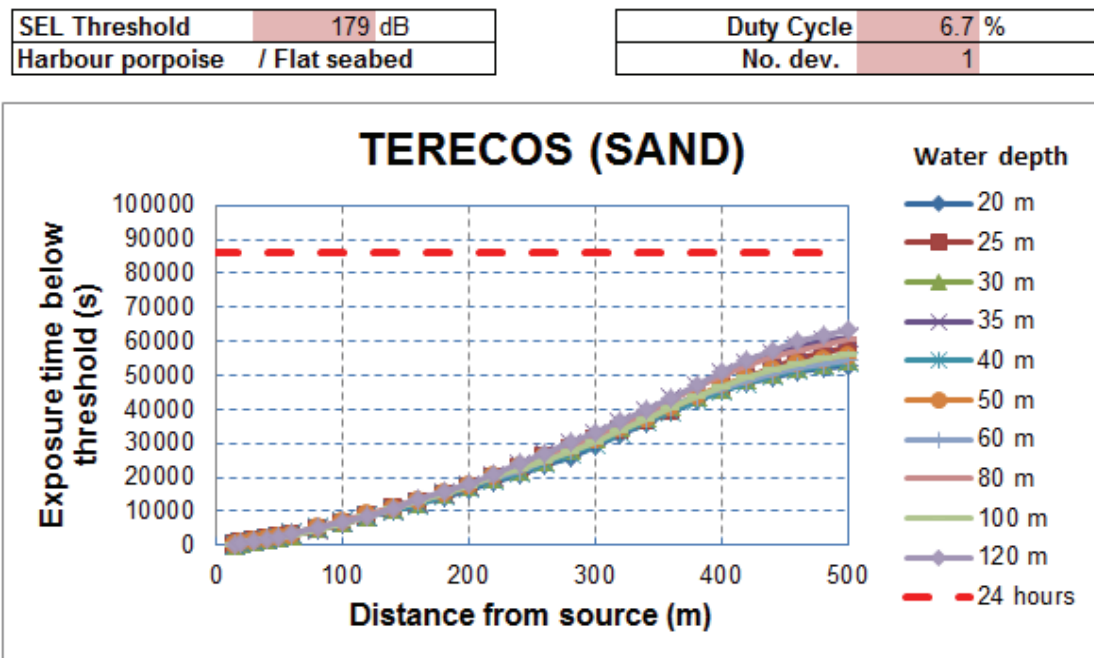


Figure 69b: Example output for time for exposure to reach the injury threshold of 179 dB re 1 $\mu\text{Pa}^2\text{s}$ for a harbour porpoise for a single Terrecos system versus distance for multiple water depths.

Further information for Figures 69a/69b: [Device type: Terrecos, Sediment type: Sand, Seabed slope: flat/down slope, duty cycle: 6.7% (note: a 6.7% duty cycle represent the

potential worse case based on manufactures information of an 8 second burst every two minutes. Other programs in system could reduce duty cycle to 1.3% using a 200 ms pulse every 15 seconds. This lower duty cycle in turn would increase time before an injury threshold was reached at a fixed distance)]. Dashed red line shows an exposure duration equivalent to 24 hours.

Figure 69a and 69b shows predictions for a Terecos device for both seals and porpoises respectively. For a seal the threshold would be exceeded if the seal remained at 100 m for around 9 hours or spent an entire 24 hour period within 200 m. For a porpoise, the threshold at 100 m would be exceeded after about 2.5 hours and the safe range for 24 hour exposure was beyond the 500 m in the model based on a 6.7% duty cycle. It should be noted that a 6.7% duty cycle represent the potential worse case based on manufactures information of an 8 second burst every two minutes. Other programmes in system would reduce duty cycle to 1.3% using a 200 ms pulse every 15 seconds. This lower duty cycle in turn would increase time before an injury threshold was reached at a fixed distance. In the case of a harbour porpoise for a sandy seabed the injury threshold would be reached in less than 24 hours for ranges less than 200 m at the lower duty cycle compared to greater than 500 m at the higher duty cycle.

Model outputs for Ace Aquatec ADD with differing SEL Threshold inputs corresponding to different species (pinnipeds and harbour porpoise).

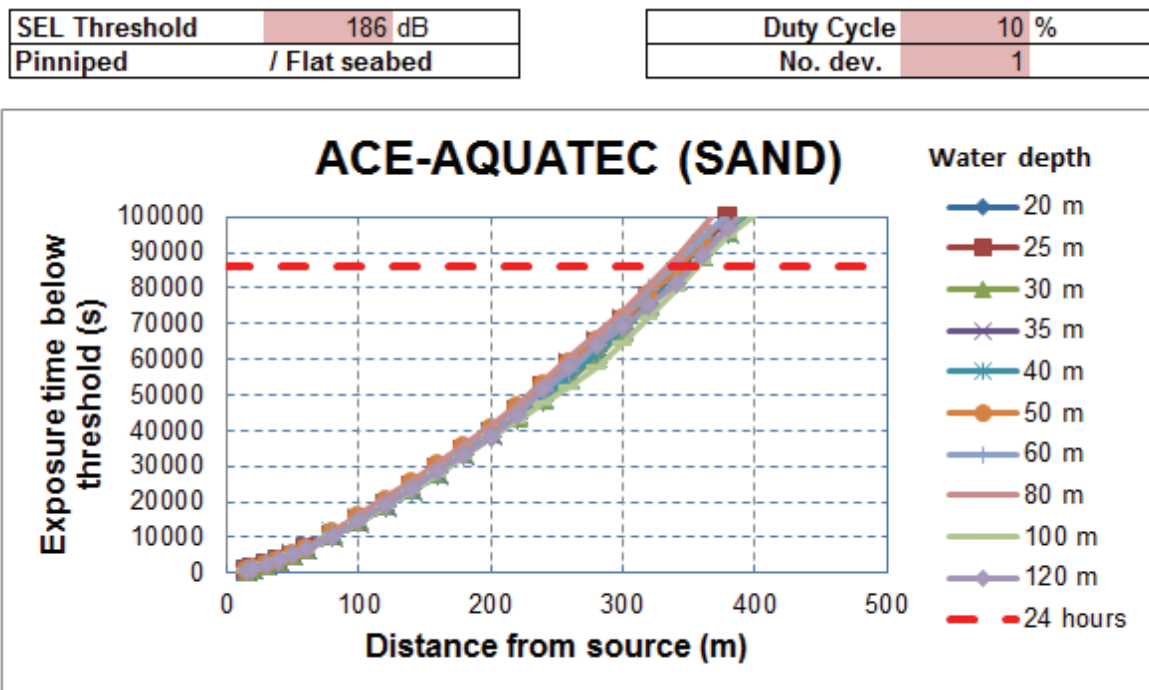


Figure 70a: Example output for time for exposure to reach the injury threshold of 186 dB re 1 $\mu\text{Pa}^2\text{s}$ for a pinniped for a single Ace Aquatec system versus distance for multiple water depths.

SEL Threshold	179 dB
Harbour porpoise	/ Flat seabed

Duty Cycle	10 %
No. dev.	1

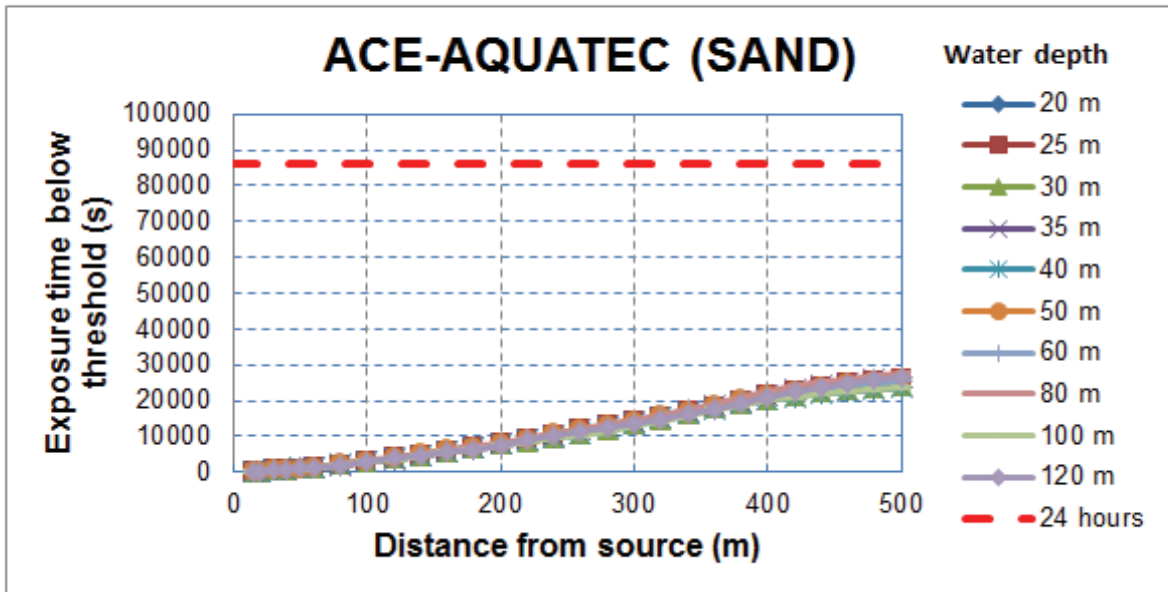


Figure 70b: Example output for time for exposure to reach the injury threshold of 179 dB re 1 $\mu\text{Pa}^2\text{s}$ for a harbour porpoise for a single Ace Aquatec system versus distance for multiple water depths.

Further information for Figures 70a/70b [Device type: Ace Aquatec, Sediment type: Sand, Seabed slope: flat/down slope, duty cycle: 10%. (note: a 10% duty cycle represent the potential worse case based on manufactures information of 72, 5 second bursts per hour. The device may be programmed to use lower duty cycles, increasing time before an injury threshold was reached at a fixed distance. The manufactures also offers a triggered system option where acoustic output should only occur when an animal causes movement of the net. However the extent of use of such systems in Scottish waters in unknown)]. Dashed red line shows an exposure duration equivalent to 24 hours.

Figure 70a and 70b shows similar plots for an Ace-Aquatec ADD. This provides a higher acoustic dose compared to the Terecos system. The injury threshold for a seal at 100 m would be exceeded after around 3 hours and the threshold range for 24 hour exposure is around 350 m. As with the Terecos system the example data shown represents a worse case duty cycle based on manufactures information of 72, 5 second bursts per hour (10%). The system allows programming of lower numbers of burst per hour lowering this duty cycle and therefore increasing time for reaching an injury threshold at a fixed distance.

Model outputs for Airmar ADD showing changed in cumulative exposure with differing number of devices.

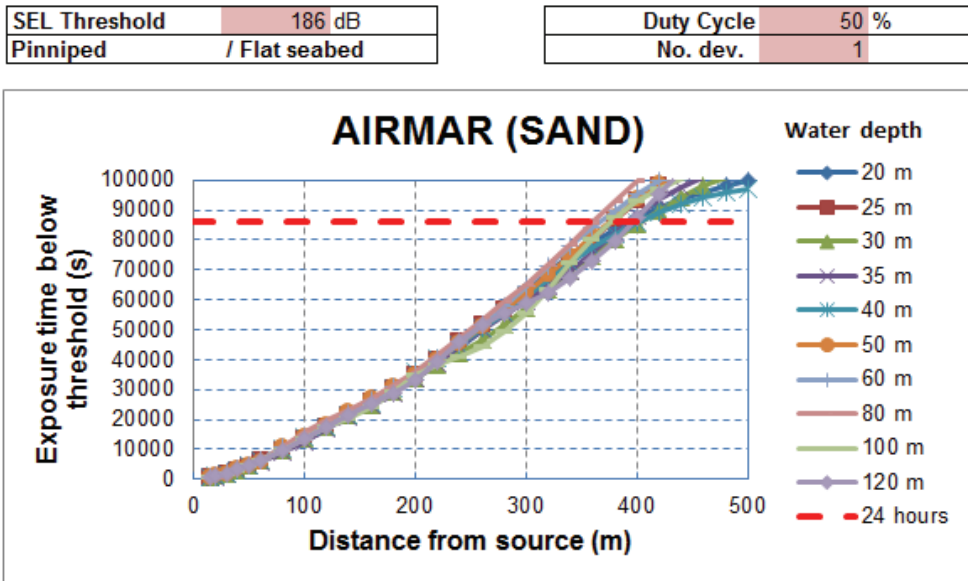


Figure 71a: Example output for time for cumulative exposure to reach the injury threshold for a pinniped of 186 dB re $1 \mu\text{Pa}^2\text{s}$ for a single Airmar system versus distance for multiple water depths.

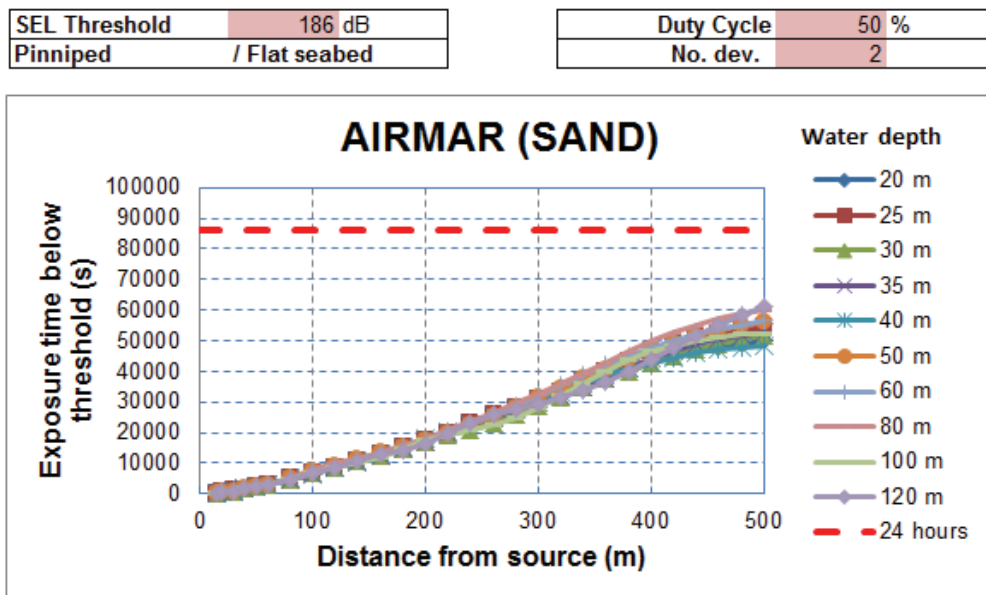


Figure 71b: Example output for time for cumulative exposure to reach the injury threshold for a pinniped of 186 dB re $1 \mu\text{Pa}^2\text{s}$ for exposure from two Airmar system versus distance for multiple water depths.

SEL Threshold	186 dB
Pinniped	/ Flat seabed

Duty Cycle	50 %
No. dev.	3

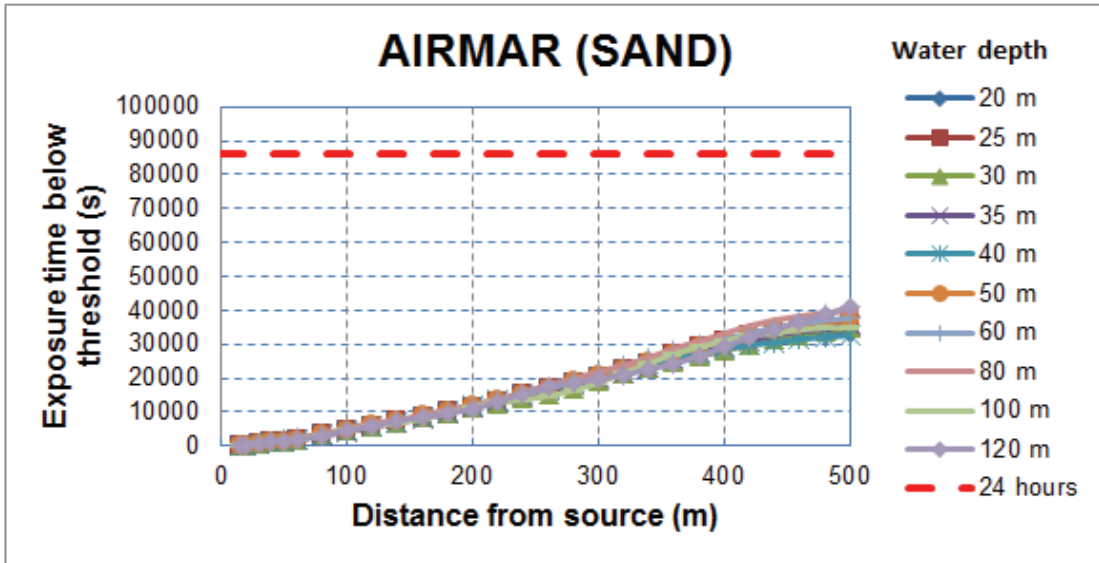


Figure 71c: Example output for time for cumulative exposure to reach the injury threshold for a pinniped of 186 dB re $1 \mu\text{Pa}^2\text{s}$ for exposure from three Airmar system versus distance for multiple water depths.

Further information for Figures 71a,71b,71c - [Sediment type: Sand, Seabed slope: flat/down slope.[Duty cycle: 50%.] Dashed red line shows an exposure duration equivalent to 24 hours.]

Figure 71a, b & c presents similar plots with one to three simultaneously fired Airmar devices for exposure to seals. A seal at 100 m would exceed the threshold after about 3.3 hours for a single device with time decreasing pro rata to 1.6 and 1.1 hours when two and three devices were operational at the site. With single device animals remaining at 400 m for 24 hours would reach the threshold for injury.

SEL Threshold	179 dB
Harbour porpoise	/ Flat seabed

Duty Cycle	50 %
No. dev.	1

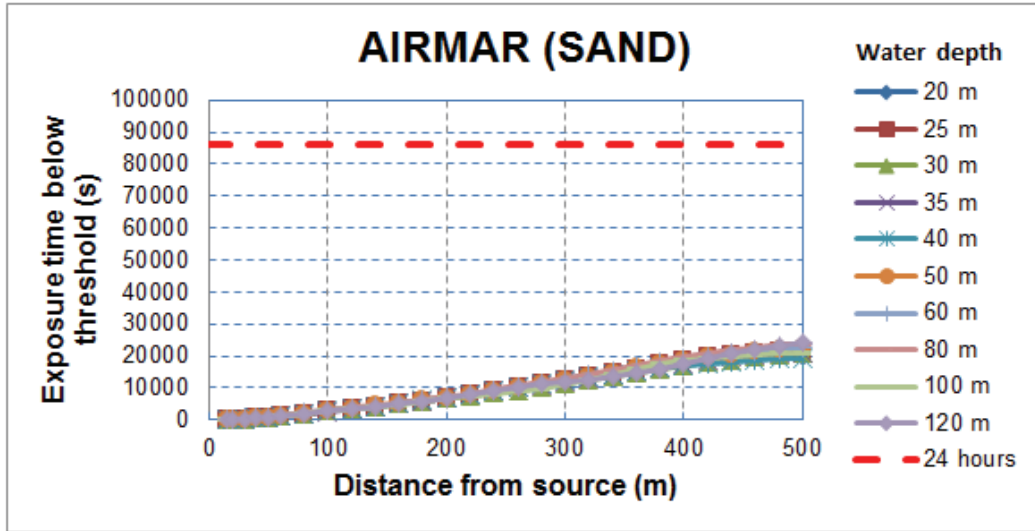


Figure 72a: Example output for time for cumulative exposure to reach the injury threshold for a harbour porpoise of 179 dB re 1 $\mu\text{Pa}^2\text{s}$ for a single Airmar system versus distance for multiple water depths. [Duty cycle: 50%].

SEL Threshold	179 dB
Harbour porpoise	/ Flat seabed

Duty Cycle	50 %
No. dev.	2

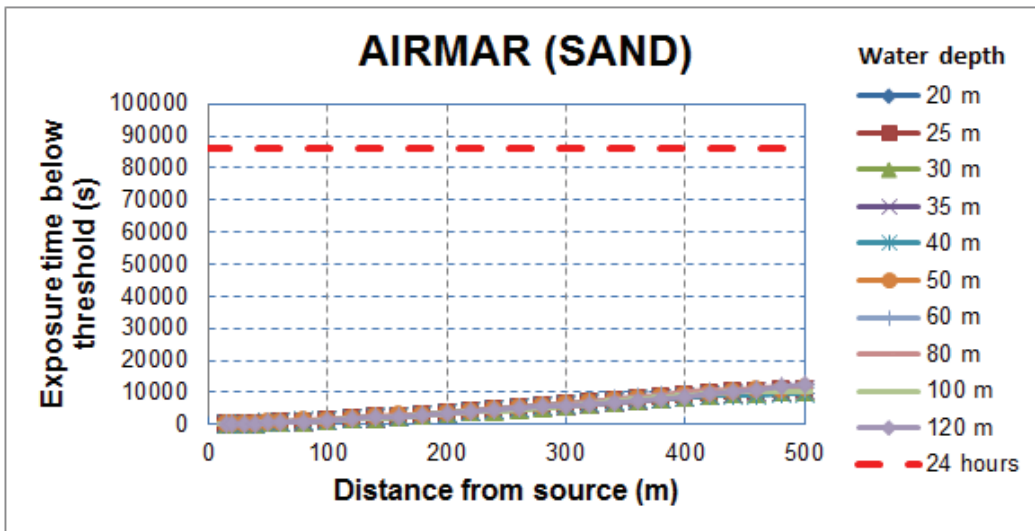


Figure 72b: Example output for time for cumulative exposure to reach the injury threshold for a harbour porpoise of 179 dB re 1 $\mu\text{Pa}^2\text{s}$ for exposure from two Airmar systems versus distance for multiple water depths. [Duty cycle: 50%].

SEL Threshold	179 dB
Harbour porpoise / Flat seabed	

Duty Cycle	50 %
No. dev.	3

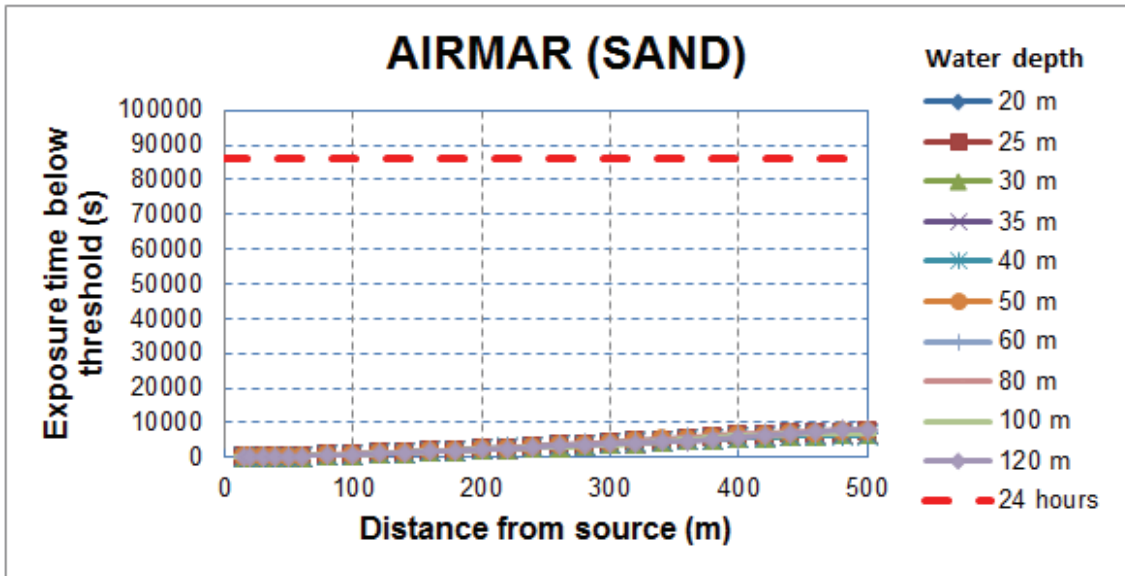


Figure 72c: Example output for time for cumulative exposure to reach the injury threshold for a harbour porpoise of 179 dB re 1 $\mu\text{Pa}^2\text{s}$ for exposure from three Airmar system versus distance for multiple water depths. [Duty cycle: 50%].

SEL Threshold	179 dB
Harbor porpoise / Flat seabed	

Duty Cycle	2 %
No. dev.	3

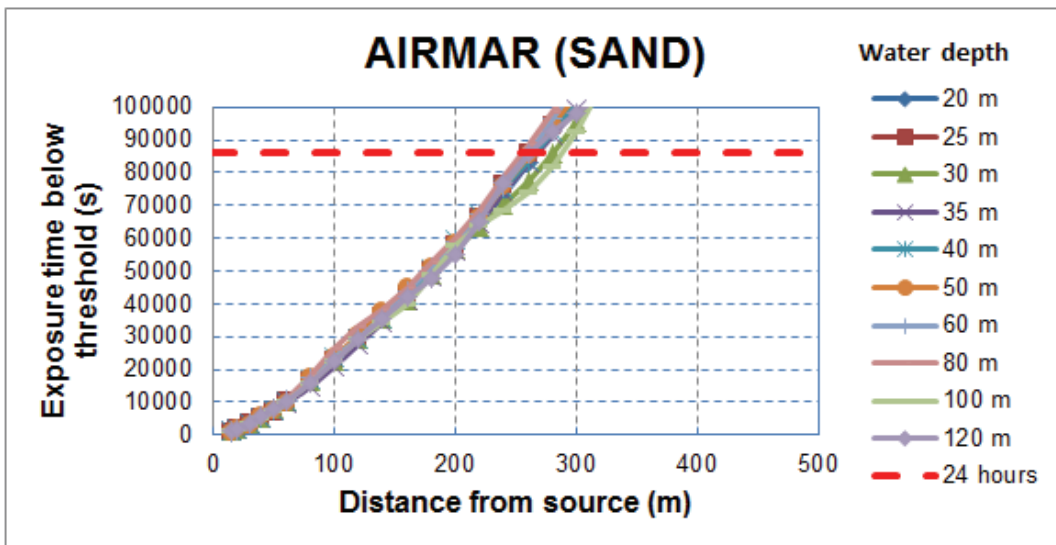


Figure 72d: Theoretical output for time for cumulative exposure to reach the injury threshold for a harbour porpoise of 179 dB re 1 $\mu\text{Pa}^2\text{s}$ for exposure from three Airmar system at a duty cycle of 2%. [Note: this is a theoretical case the use of a 2% duty cycle in Airmar systems in Scottish waters is not known of].

[Sediment type: Sand, Seabed slope: flat/down slope]. Dashed red line shows an exposure duration equivalent to 24 hours.]

Figures 72 a-c shows plots for Airmar devices and porpoises in cases with between 1 and 3 operating systems respectively. (We provide these plots for this devices because there is a trend for multiple Airmar ADDs to be deployed at sites.) Time to reach threshold declines pro rata with number of devices deployed. At 500 m the injury threshold is reached after approximately 5.5, 2.75 or 1.8 hours for sites with one, two or three devices respectively.

The potential to vary the Airmar system duty cycle is unknown and all current data indicates an approximate 50% duty cycle for operational systems as shown in Figures 71 and 72 a-c. However, using the model, the output shown in figure 72d indicates a reduction of duty cycle from 50% to 2% would for 3 simultaneously operating Airmar devices increase exposure times at a fixed distance before reaching injury levels. Figure 72d shows a theoretical case where the injury criteria for a harbour porpoise would not be met at ranges greater than 300 m in less than 24 hours using a lower 2% duty cycle.

These models do indicate that porpoises are more susceptible to hearing damage than seals. However, we know from field observations that seals may often spend several hours within hundreds of meters of active ADDs at fish farm sites and when predation events take place at fish farms with ADDs, seals must expose themselves to very high levels of sound. By contrast, porpoises have been observed to strongly avoid ADDs. This will serve to reduce the risk of injury though it should be noted that complete exclusion has not been demonstrated beyond the ranges at which long exposures might result in injury according to these models.

The movement assumption in these models, that animals are maintaining a fixed range from ADDs, is of course completely unrealistic. There are also a host of other uncertainties in the model. One of these is whether or not ADDs should be considered to be pulsed or continuous sound sources as envisaged in Southall *et al.* (2007). The thresholds for PTS vary by 7 dB between pulsed and continuous categories. Given these uncertainties these model outputs should not be considered to be firm predictions but rather contributing to an exploratory exercise that can help to put bounds on our concerns.

Bearing these caveats in mind, the risk that ADDs will cause hearing damage in marine mammals appears to be a real one that cannot be discounted. Animal behaviour remains the most significant source of uncertainty. Observations that seals will remain at fish farm sites with active ADDs for many hours at a time suggest the risk might be particularly high for this group.

5.6 Note on Model Update and Development

The current model incorporates the three most common ADD types in Scottish waters and likely encountered environments (water depths 20-120 m) and sediment types ranging from sand, silt-sand, silt and silt-clay. The model / database is organized such that propagation losses are device independent allowing source characteristics of future systems to be added at later dates as data becomes available. The user definition also allows emerging impact criteria to be automatically incorporated and functional hearing group frequency weighting applied. In cases where complex bathymetries exist, case by case detailed modelling should be considered to fully assess potential received levels and corresponding zones of influence.

The use of techniques such as range averaging were imperative to the generation of a generic model, however, it should be noted that this approach provides a mean level likely to occur at a site and actual levels are likely to be highly variable (greater and lower than mean) both spatially (distance from source) and temporally due to the complex interference fields present at higher frequencies in shallow water environments. However, the broadband nature of many of these devices will also tend to average out stronger field structures and

rapid variations leaving making the range averaged techniques a reasonable approximation for most cases.

The largest uncertainties in models of SEL impacts arise from lack of knowledge of marine mammal movements at and around farm sites with active ADDs. Photo-ID studies in conjunction with photogrammetry or laser range finding can provide information on the residence patterns of seals at farm sites and put some bounds on their movements.

Impact thresholds lower than ones used in this study are likely to occur at longer ranges from the source and the extension of the current model to greater ranges would be advise to capture potential effects at longer ranges.

6. CONCLUSIONS

The criteria for noise induced injury in marine mammal proposed by Southall *et al.* (2007) are the most well developed and are becoming widely accepted. The metrics used in the Southall *et al.* (2007) noise exposure criteria include zero-peak sound pressure level and sound exposure level thresholds. Using data from a survey of the most commonly used ADD systems, estimates of the equivalent SEL Source Level in third octave bands integrated across 1 second were made. Analysis showed that propagation loss at fish farm sites would depend on water depth, sediment type, surface roughness, sea bed slope and device type.

Using a source-image model propagation losses were estimated for four general sediment types (sand, sandy-silt, silt and silt-clay), a range of water depths (20-120m) and for different seabed slopes for third octave band centre frequencies from 2-40 kHz. These data were then compiled into an interactive database with source characteristics for the Airmar, Ace Aquatec and Terecos devices. Using this database broadband SEL received level versus range were estimated for a variety of scenarios with differing water depth and sediment type and seabed slope typical of Scottish fish farm sites. These estimates were then frequency weighted using the functional hearing groups proposed by Southall *et al.* (2007) described as low, medium and high frequency cetacean and pinnipeds in water. Analysis showed that for the three most commonly used ADD systems the medium and high frequency cetaceans and pinnipeds in water could be functionally grouped. However, the data showed slightly lower exposure and therefore lower impact ranges predicted for low frequency cetaceans due to more limited high frequency hearing capability.

A model was then developed to estimate range to exceed user defined thresholds for one second SEL levels given, site depth, sediment type, seabed slope and device type and the functional hearing group of the subject. Consideration of cumulative exposure thresholds depends on both received levels and exposure time. To model these data on an animal's position and movements within the predicted sound field is required, but these data are lacking. Here, we have modelled one movement scenario and tested cumulative SEL for animals maintaining a fixed range from an ADD. While this is an unrealistic assumption the outputs help to put some bounds on concerns. Additional model inputs allow testing of system duty cycle and number of devices per site.

These simulations provide a range of predictions, but they suggest that seals may be at risk of suffering auditory injury if they remain within 100s of metres of an ADD sound source for several hours. Observations of seals around fish farms suggest that animals may spend extended periods at these types of ranges, suggesting the risk of hearing damage cannot be excluded.

Porpoises are more vulnerable to auditory damage than seals and other small cetaceans. They seem to show strong avoidance (of Airmar devices at least). If this holds generally then concerns for porpoises may focus on longer term exposures at greater ranges (which are not covered by the propagation models predicted here) and of course the long range disturbance and habitat exclusion that has already been shown for this species.

There is insufficient data to inform the extent to which behavioural change is affected by received noise level, or for the use of sound fields from this report to provide reliable predictions of ranges for behavioural effects at specific Scottish fish farm sites. However, sufficient data does exist for responses to one ADD type, for regulators to be able to move forward in assessing whether this level of habitat exclusion and disturbance of a European Protected Species is of concern. Further field studies should be undertaken to measure the extent of responses to other ADD types used in Scotland.

7. REFERENCES

- Ainslie, M.A. 2010. *Principles of sonar performance modelling*. Springer Verlag Berlin. ISBN: 978-3-540-87661-8, table 10.1, p.525.
- Ainslie M.A. and McCole, J.G. 1998. A simplified formula for viscous and chemical absorption in sea water. *Journal of the Acoustical Society of America*, 103(3), pp.1671-1672.
- Ainslie, M.A., Harrison, C.H. and Burns, P.W. 1994. Reverberation modelling with INSIGHT. *Proceedings of the Institute of Acoustics*, 16(6), pp.105-112.
- Akamatsu, T., Hatakeyama, Y., Kojima, T., and Soeda, H. 1994. Echolocation rates of two harbour porpoises (*Phocoena phocoena*), *Marine Mammal Science*. (10), pp.401–411.
- ANSI S1.1-1986 (ASA 65-1986). 1993. Specifications for Octave-Band and Fractional-Octave-Band Analogue and Digital Filters, *Journal of the Acoustical Society of America*, NY.
- ASCOBANS. 2006. *Proceedings of the 5th Meeting of the Parties to ASCOBANS*, In 5th Meeting of the Parties of ASCOBANS. The Netherlands.
- Au, W.W.L. 2004. Echolocation signals of wild dolphins. *Acoustical Physics*, (50), pp.454-462.
- Aubrey, F.T., Thomas, J.A. and Kastelein, R.A. 1988. Low-frequency underwater hearing sensitivity in belugas, *Delphinapterus leucas*. *Journal of the Acoustical Society of America*, 84(6), pp. 2273-2275.
- Bjørge, A., Thompson, D., Hammond, P., Fedak, M., Bryant, E., Aarefjord, H., Roen, R. and Olsen, M. 1995. Habitat use and diving behaviour of harbour seals in a coastal archipelago in Norway. *Whales, seals, fish and man*, Ed. A.S. Blix, L. Wallace and O. Ulltang.
- Booth, C.G. 2010. *Impacts of Commercial Aquaculture Acoustic Devices on harbour porpoises west of Scotland*. Ph. D. University of St Andrews.
- Brekhovskikh, L.M. and Lysanov, Y. 2003. *Fundamentals of Ocean Acoustics*. AIP Press Springer Verlag Berlin.
- Burns, W. 1973. *Noise and Man*. 2nd ed. London, John Murray.
- Barros, N.B. and Myrberg, A.A. 1987. Prey detection by means of passive listening in bottlenose dolphins (*Tursiops truncatus*). *Journal of the Acoustical Society of America*, 82, S65 - S65.
- Carter, C. 2007. *Marine renewable energy devices: A collision risk for marine mammals*. University of Aberdeen.
- Coates, R. 1988. An Empirical Formula for Computing the Beckmann-Spizzichino Surface Reflection Loss Coefficient. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 35(4), pp.522-523.
- Collins M.C. 1988, Benchmark calculation for higher-order parabolic equations. *Journal of the Acoustical Society of America*, 87(4), pp.1535-1538.
- EUNIS. 2010. *European Union Nature Information System*. [online] Available at <<http://eunis.eea.europa.eu>>

- Francois, R.E. and Garrison, G.R. 1982a. Sound absorption based on ocean measurements: Part 1: Pure water and magnesium sulfate contributions. *Journal of the Acoustical Society of America*, 72(3), pp.896-907.
- Francois, R.E. and Garrison, G.R. 1982b. Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America*, 72(6), pp.1876-1890.
- Gannon, D.P., Barros, N.B., Nowacek, D.P., Read, A.J., Waples, D.M. and Wells, R.S. 2005. Prey detection by bottlenose dolphins (*Tursiops truncatus*): an experimental test of the passive-listening hypothesis. *Animal Behaviour*, 69, pp.709 - 720.
- Goodson A.D. and Sturtivant, C.R. 1996. Sonar Characteristics of the harbour porpoise (*Phocoena phocoena*): source levels and spectrum. *ICES Journal of Marine Science*, 53, pp. 465-472.
- Gordon, J. and Northridge, S. 2002. Potential impacts of Acoustic Deterrent Devices on Scottish Marine Wildlife. *Scottish Natural Heritage Commissioned Report F01AA404*.
- Gordon, J., Thompson, D., Gillespie D, Lonergan, M., Calderan, S, Jaffey, B. and Todd V. 2007. *Assessment of the potential for acoustic deterrents to mitigate the impact on marine mammals of underwater noise arising from the construction of offshore wind farms: technical report*. COWRIE DETER-01-2007.
- Hafner, G.W., Hamilton, C.L., Steiner, W.W., Thompson, T.J. and Winn, H.E. 1979. Signature information in the song of the humpback whale. *Journal of the Acoustical Society of America*, 66, pp.1-6.
- Haller D.R. and Lemon D.D. 1994. *Acoustic source levels of Airmar and PRA seal-scarers*. Department of Fisheries and Oceans. Contract Report No. XSA FP941-3-8025/00/A. p.52.
- Hamilton, E.L. 1980. Geoacoustic modelling of the sea floor, *Journal of the Acoustical Society of America*, 68(5), pp.1313-1340.
- Harrison, C.H. and Harrison, J.A. 1995. A simple relationship between frequency and range averages for broadband sonar. *Journal of the Acoustical Society of America*, 97(2), pp.1314-1317.
- Hastie, G.D., Wilson, B. and Thompson, P.M. 2006. Diving deep in a foraging hotspot: acoustic insights into bottlenose dolphin dive depths and feeding behaviour. *Marine Biology*, 1(148), pp.1181-1188.
- Jacobs, S.R. and Terhune, J.M. 2002. The effectiveness of acoustic harassment devices in the Bay of Fundy, Canada: seal reactions and a noise exposure model. *Aquatic Mammals*, 28, pp.147-158.
- Janik, V. 2000. Food-related bray calls in wild bottlenose dolphins (*Tursiops truncatus*). *Proceedings of the Royal Society of London Series, Biological Sciences* 267, p.923-927.
- Janik, V. 2009. Acoustic communication in delphinids. *Advances in the Study of Behavior*, 40, pp.123-157.
- Jefferson, T.A. and Curry, B.E. 1996. Acoustic methods of reducing or eliminating marine mammal-fishery interactions: Do they work? *Ocean & Coastal Management*, 31, pp.41-70.

Jensen, F.B., Kuperman, W. A., Porter, M. B. and Schmidt H. 2000. *Computational Ocean Acoustics, 2nd Edition*. Springer-Verlag, ISBN: 1-56396-209-8.

Johnson C.S. 1967. Sound detection thresholds in marine mammals. *Marine Bioacoustics II*. Oxford: Pergamon, pp.247-260.

Johnston, D.W. 2002. The effect of acoustic harassment devices on harbour porpoises (*Phocoena phocoena*) in the Bay of Fundy, Canada. *Biological Conservation*, 108, pp.113 – 118.

Joint Nature Conservation Committee, Natural England and Countryside Council for Wales 2010. *The protection of marine European Protected Species from injury and disturbance. Guidance for the marine area in England and Wales and the UK offshore marine area*. Draft Guidance Document. p.118.

Kastak, D. and Schusterman, R.J. 1998. Low-frequency amphibious hearing in pinnipeds: methods, measurements, noise and ecology. *Journal of the Acoustical Society of America*, 103, pp.2216-2228.

Kastelein, R.A., Bunschoek, P., Hagedoorn, M. and Au, W.W.L. 2002. Audiogram of a harbour porpoise (*Phocoena phocoena*) measured with narrow-band frequency modulated signals. *Journal of the Acoustical Society of America*, 112, pp.334-344.

Kastelein, R.A., Hagedoorn, M., Au, W.W.L. and de Haan, D. 2003. Audiogram of a striped dolphin (*Stenella coeruleoalba*). *Journal of the Acoustical Society of America*, 113, pp. 1130-1137.

Kastelein R.A., Van der Heul, S., Van der Veen, J., Verboom, W. C., Jenneing, N., De Haan, D. and Reijnders, P. 2007. Effects of commercially-available acoustic alarms, designed to reduce small cetacean by-catch in gillnet fisheries, on the behaviour of North Sea fish species in a large tank. *Marine Mammal Research*, 64(2).

Kastelein R., Wensveen, P., Hoek, L. and Terhune, J.M. 2009. Underwater hearing sensitivity of harbour seals (*Phoca vitulina*) for narrow noise bands between 0.2 and 80 kHz, *Journal of the Acoustical Society of America*, 126 (1). pp.476-483.

Kastelein, R.A., Hoek, L., Jennings, N., de Jong, C.A.F., Terhune, J.M. and Dieleman, M. 2010. Acoustic mitigation devices to deter marine mammals from pile driving areas at sea: audibility & behavioural response of a harbour porpoise & harbour seals. *COWRIE Ref: SEAMAMD-09, Technical Report*, 68. ISBN 978-0-9565843-7-3.

Kinsler. L.E., Frey A.R., Coppens A.B. and Sanders J.V. 2000. *Fundamentals of acoustics*. 4rd ed. John Wiley & Sons, Inc. ISBN: 9778-0-471-84789-2.

Lepper, P.A., Turner, V.L.G., Goodson, A.D. and Black, K.D. 2004. Source Levels and Spectra Emitted by Three Commercial Aquaculture Anti-Predation Devices. *Proceedings of the Seventh European Conference on Underwater Acoustics, Seventh European Conference on Underwater Acoustics*. Delft, The Netherlands, ISSN 90 5986 080 2, 1039-1044.

Lepper, P.A., Robinson, S.P., Ainslie, M.A., Theobald, P.D. and de Jong, C.A.F. 2010. Assessment of cumulative Sound Exposure Levels (SEL) for marine piling events *Proceedings from the Second International Conference on the effects of noise on aquatic life*. Cork, Ireland.

- Linley, A., Laffont, J.K., Wilson, B., Elliot, M., Perez-Dominguez, R. and Burdon, D. 2009. *Offshore and coastal renewable energy: Potential ecological benefits and impacts of large-scale offshore and coastal renewable energy projects*, N.E.R.C, 124.
- Lucke, K., Lepper, P.A., Hoeve, B., Everaarts, E., van Elk, N. and Siebert, U. 2007. Perception of low-frequency acoustic signals by a harbour porpoise (*Phocoena phocoena*) in the presence of simulated offshore wind turbine noise. *Aquatic Mammals*, 33, pp.55-68.
- Lucke, K., Siebert, U., Lepper, P.A. and Blanchet, M.A. 2009. Temporary shift in masked hearing thresholds in a harbour porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *Journal Acoustical Society of America*, 125(6). ISSN 10.1121/1.3117443, 4060-4070.
- Maggi, A. L. and Duncan, A J. 2010. *Underwater Acoustic Propagation Modelling software AcTUP V2.2L*. Centre for Marine Science and Technology (CMST), Curtin University of Technology in Australia.
- Medwin, H. and Clay, C. 1988. *Fundamentals of Acoustical Oceanography*, Academic Press, Boston.
- MMC. 2007. *Marine Mammals and Noise: A Sound Approach to Research and Management. A Report to Congress from the Marine Mammal Commission*. Marine Mammal Commission, Bethesda, Maryland.
- Møhl, B. 1968. Auditory sensitivity of the common seal in air and water. *Journal of Auditory Research*, 8, pp.27-38.
- Møhl, B. 1981. *Masking effects of noise; their distribution in time and space. The question of sound from icebreaker operations*. Proceedings from a workshop. N.M. Peterson, editor. Arctic Pilot Project, Calgary, Alberta. 259-266.
- Morton, A. 2000. Occurrence, photo-identification and prey of Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) in the Broughton Archipelago, Canada 1984-1998. *Marine Mammal Science* 16, pp.80-93.
- Morton, A.B. and Symonds, H.K. 2002. Displacement of Orcinus orca by high amplitude sound in British Columbia, Canada. *ICES Journal of Marine Science*, 59, pp.71-80.
- Nedwell, J.R., Brooker, A.G., Bryant, S.A.H. and Barham, R.J. 2010. *Measurements of Underwater Noise Generated by Acoustic Mitigation Devices*. Subacoustech Environmental Report No. E238R0122 to COWRIE. ISBN: 978-0-9565843-2-8
- Northridge, S.P., Gordon, J.G., Booth, C., Calderan, S., Cargill, A., Coram, A., Gillespie, D., Lonergan, M. and Webb, A. 2010. *Assessment of the impacts and utility of acoustic deterrent devices*. Final Report to the Scottish Aquaculture Research Forum, project code SARF044.
- Olesiuk, P.F., Nichol, L.M., Sowden, M.J. and Ford, J.K.B. 2002. Effect of the sound generated by an acoustic harassment device on the relative abundance and distribution of harbour porpoises (*Phocoena phocoena*) in retreat passage, British Columbia. *Marine Mammal Science*, 18, pp.843-862.
- Otani, S. 2001. Diving behaviour and swimming speed for free ranging harbour porpoise *phocena phocena*. *Marine Mammal Science*, 16(4), pp.811-814.

Popov, V.V., Supin, A.Y., Wang, D., Wang, K., Dong, L. and Wang S. 2011. Noise-induced temporary threshold shift and recovery in Yangtze finless porpoises *Neophocaena phocaenoides asiaeorientalis*. *Journal of the Acoustical Society of America*, 130(1), pp.574-584.

Porter, M. B. 2010. *The BELLHOP manual and user guide*.

Quick, N.J., Middlemas, S.J. and Armstrong, J.D. 2004. A survey of anti-predator controls at marine salmon farms in Scotland. *Aquaculture*, 230, pp.169-180.

Rendell, L. and Whitehead, H. 2004. Do sperm whales share coda vocalizations? Insights into coda usage from acoustic size measurement, *Animal Behaviour*. 67, pp.865-874.

Richardson, W.J., Greene, C.R.J., Malme, C.I. and Thomson D.D. 1995. *Marine mammals and noise*. San Diego: Academic Press.

Ridgway, S.H. and Joyce, P.L. 1975. Studies on seal brain by radiotelemetry. *Publications of the International Council for the Exploration of the Sea: Report and minutes of meetings*. 169, pp.81-91.

Robinson, S.P., Theobald, P.D., Hayman, G., Wang, L.S. Lepper, P.A., Humphrey, V. and Mumford, S. 2011. *Measurement of noise arising from marine aggregate dredging operations*. MALSF. ISBN 978 0907545 57 6.

Ross, A. 1988. *Controlling nature's predators on fish farms*. Report for the Marine Conservation Society. 96

Schulz, T.M., Whitehead, H., Gero, S. and L. Rendell. 2008. Overlapping and matching of codas in vocal interactions between sperm whales: insights into communication function, *Animal Behaviour*, 76, pp.1977-1988.

Shapiro, A.D., Tougaard, J., Jorgensen, P.B., Kyhn, L.A., Balle, J.D., Bernardez, C., Fjalling, A., Karlsen, J. and Wahlberg, M. 2009. Transmission loss patterns from acoustic harassment and deterrent devices do not always follow geometrical spreading predictions. *Marine Mammal Science*, 25, pp.53-67.

Shrimpton, J.H. and Parsons, E.C.M. 2000. A review of the environmental threats to cetaceans in West Scotland. 52nd Meeting of the International Whaling Commission. Scientific Committee of the IWC, Australia.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene C.R., Kastak, Jr., D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A. and Tyack P.L. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations, *Aquatic Mammals*, 33, (4), pp.411-509.

Szymanski, M.D., Bain, D.E., Kiehl, K., Pennington, S., Wong, S. and Henry, K.R. 1999. Killer whale (*Orcinus orca*) hearing: Auditory brainstem response and behavioural audiograms. *Journal Acoustical Society of America*, 106, pp.1134-1141.

Tappert, F.D., 1977. The parabolic approximation method. Wave propagation and underwater acoustics. Lecture notes in Physics, 70, Springer, New York.

Taylor, V.J., Johnston, D.W. and Verboom, W.C. 1997. Acoustic harassment device (AHD) use in the aquaculture industry and implications for marine mammals. Proceeding Symposium on Bio-Sonar and Bioacoustics. Loughborough University. p.10

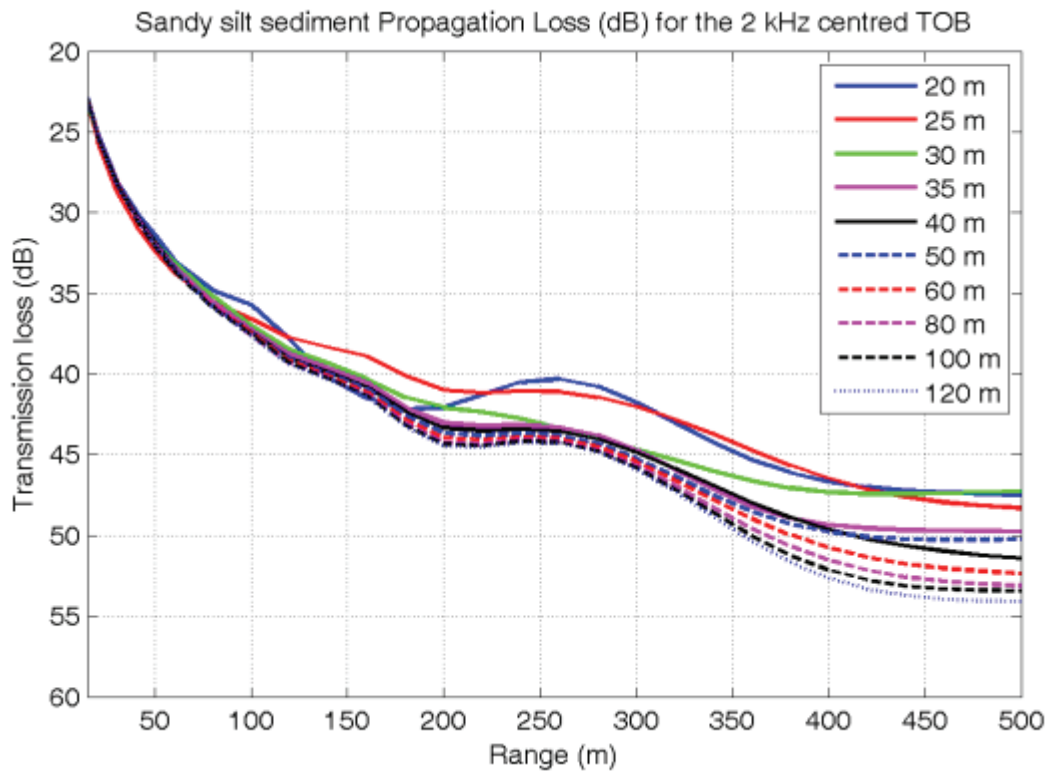
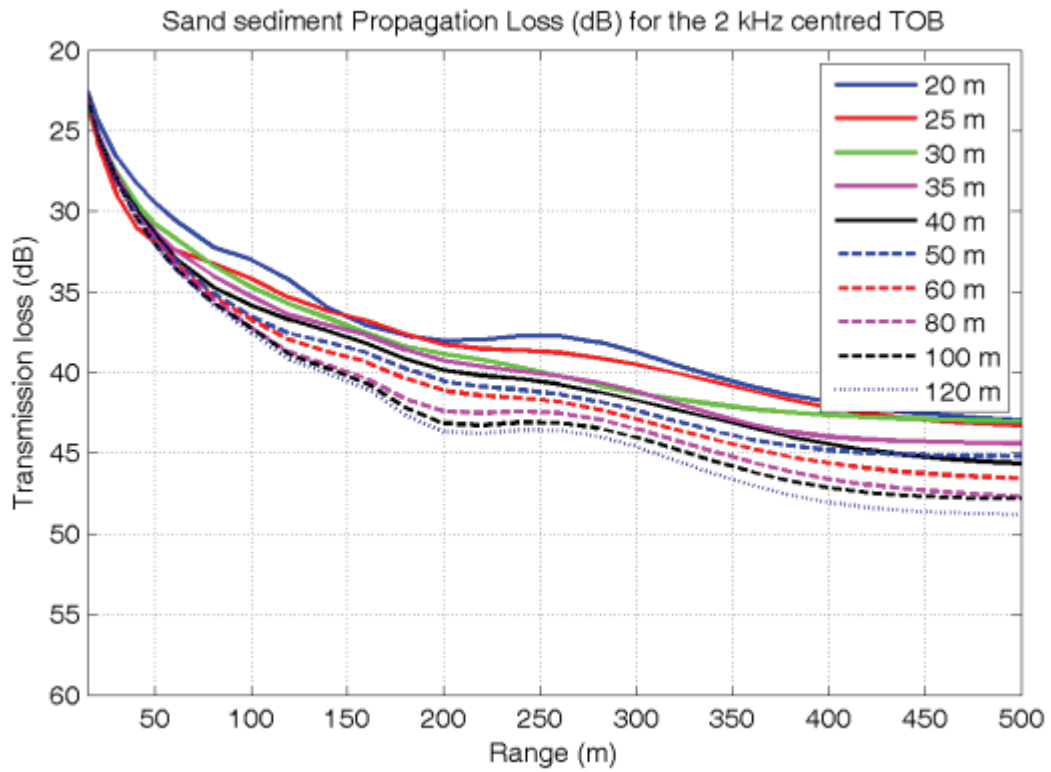
- Terhune, J.M. and Ronald, K. 1972. The harp sea (*Pagophilus groenlandicus*) (Erxleben, 1777). III., The underwater audiogram. *Canadian Journal of Zoology*. 50, pp.565-569.
- Terhune, J.M. and Ronald, K. 1975. Underwater hearing sensitivity of two ringed seals (*Pusa hispida*). *Canadian Journal of Zoology*, 53, pp.227-231.
- Theobald, P.D., Lepper, P.A., Robinson, S.P. and Hazelwood, R.A. 2009. Cumulative noise exposure assessment for marine using Sound Exposure Level as a metric". Proceedings of the 3rd International Conference & Exhibition on Underwater Acoustic Measurements: Technologies & Results. Napflion, Greece. ISBN; 978-960-98883-4-9.
- Tyack, P.L. 2007. Marine mammal noise exposure criteria: Initial scientific recommendations, *Aquatic Mammals*. 33(1), p.521.
- Urick, R.J. 1983. *Principles of Underwater Sound*, Peninsula Publishing, New York.
- Yelverton, J.T., Richmond, D.R., Fletcher, E.R. and Jones, R.K. 1973. Safe distances from underwater explosions for mammals and birds. Final Technical Report DNA3114T. Lovelace Foundation for Medical Education and Research.
- Yelverton, J.T., Richmond, D.R., Hicks, W., Saunders, K. and Fletcher, E.R. 1975. The relationship between fish size and their response to underwater blast. Final Technical Report DNA 3677T. Lovelace Foundation for Medical Education and Research,
- Yelverton, J.T., Richmond, D. R., Jones, R. K. and Fletcher, E. R. 1976. A review of the treatment of underwater blast injuries. Final Technical Report A553430. Lovelace Foundation for Medical Education and Research.
- Yurk, H. and Trites, A.W. 2000. Experimental attempts to reduce predation by harbour seals on out migrating juvenile salmonids, *Transactions of the American Fisheries Society* 129, pp.1360–1366.

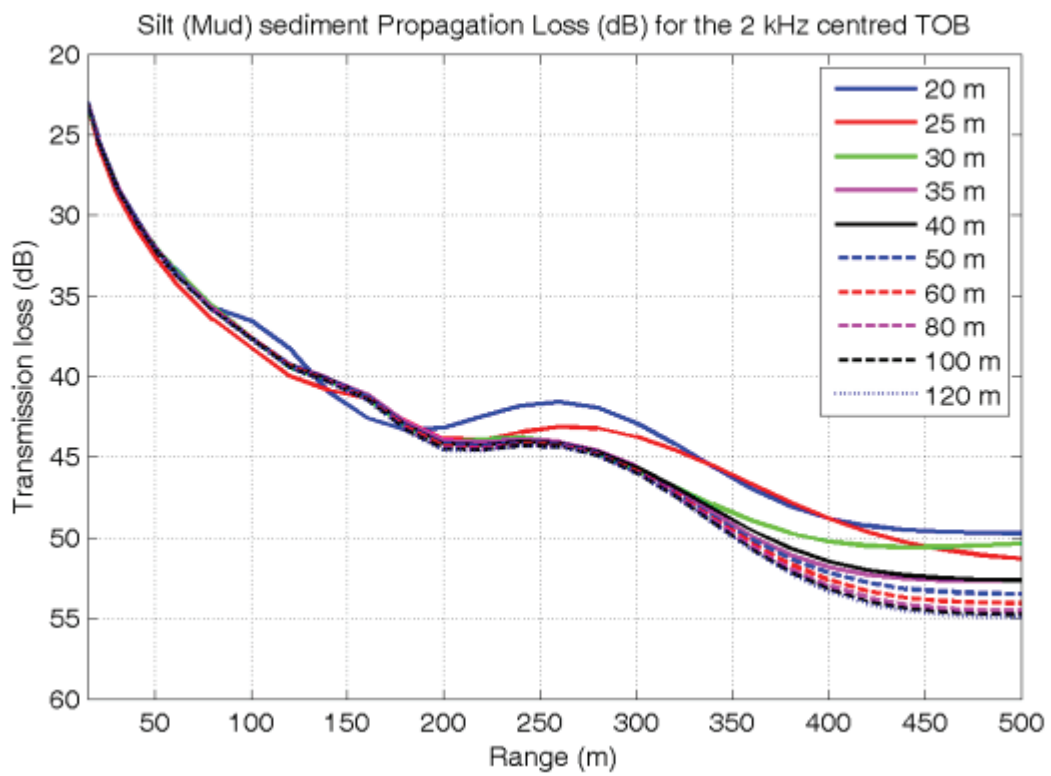
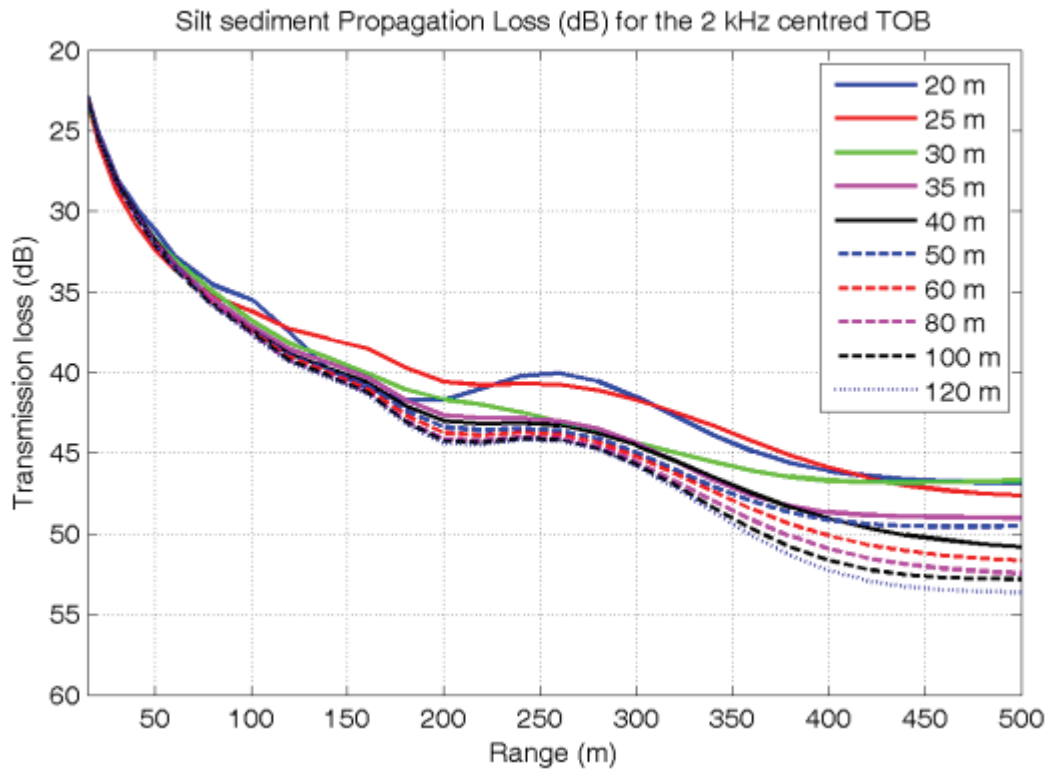
8. GLOSSARY

ADD	Acoustic Deterrent Device (see AHD)
AHD	Acoustic Harassment Device (see ADD)
Duty cycle	Ratio of period 'on' to period 'off'
EL	Ecologic Ltd
EUNIS	European Union Nature Information System
HWDT	Hebridean Whale and Dolphin Trust
GIS	Global Information System
LU	Loughborough University
Multi-path	Arrival of direct and reflected signals at a fixed point
PE	Parabolic Equation
PL	Propagation Loss (see TL)
Phon	A unit of apparent loudness
RAMGeo	An acoustic propagation model based on the parabolic equation
RL	Receive Level
SMRU	Sea Mammal Research Unit
SMRU Ltd.	Sea Mammal Research Unit Ltd.
SNH	Scottish Natural Heritage
SL	Source Level (usually expressed in dB re 1 μ Pa.m \pm 1 dB (RMS))
TL	Transmission Loss see Propagation Loss (PL)
UK HO	United Kingdom Hydrographic Office
RMS	Root Mean Square
SEL	Sound Exposure Level (dB)
Spectrogram	A frequency versus time plot with intensity shown as colour
SPL	Sound Pressure Level (dB)
Tonal Blocks	Continuous blocks of signals at a signal frequency
TOB	Third Octave Bands

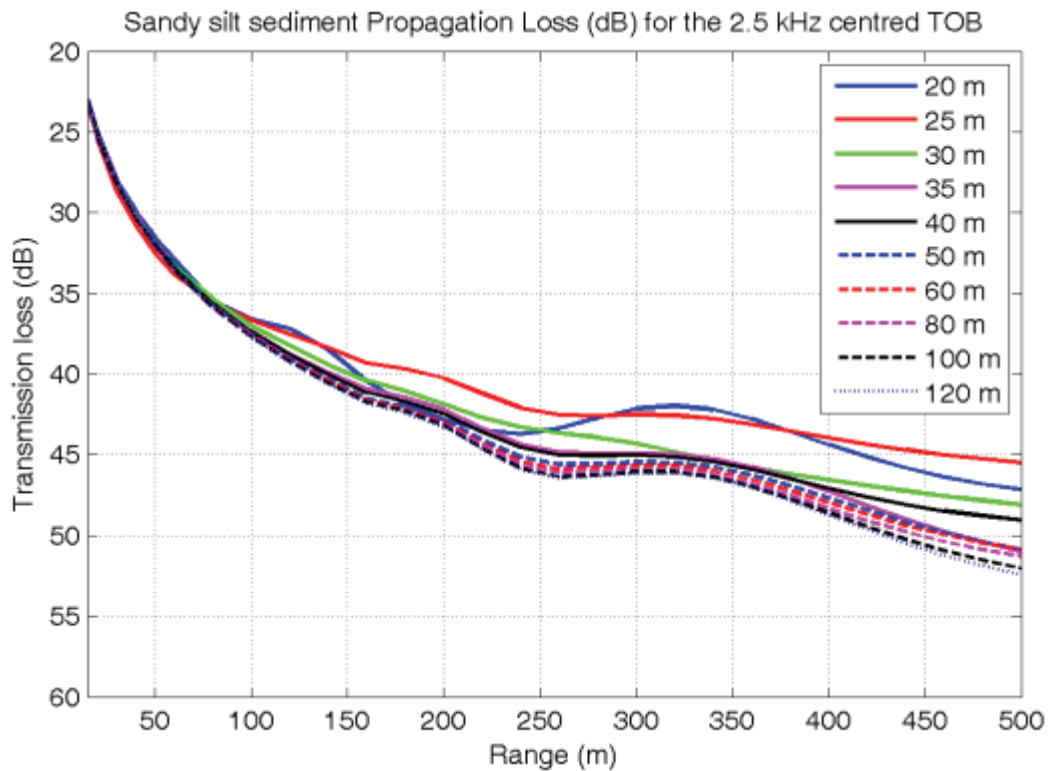
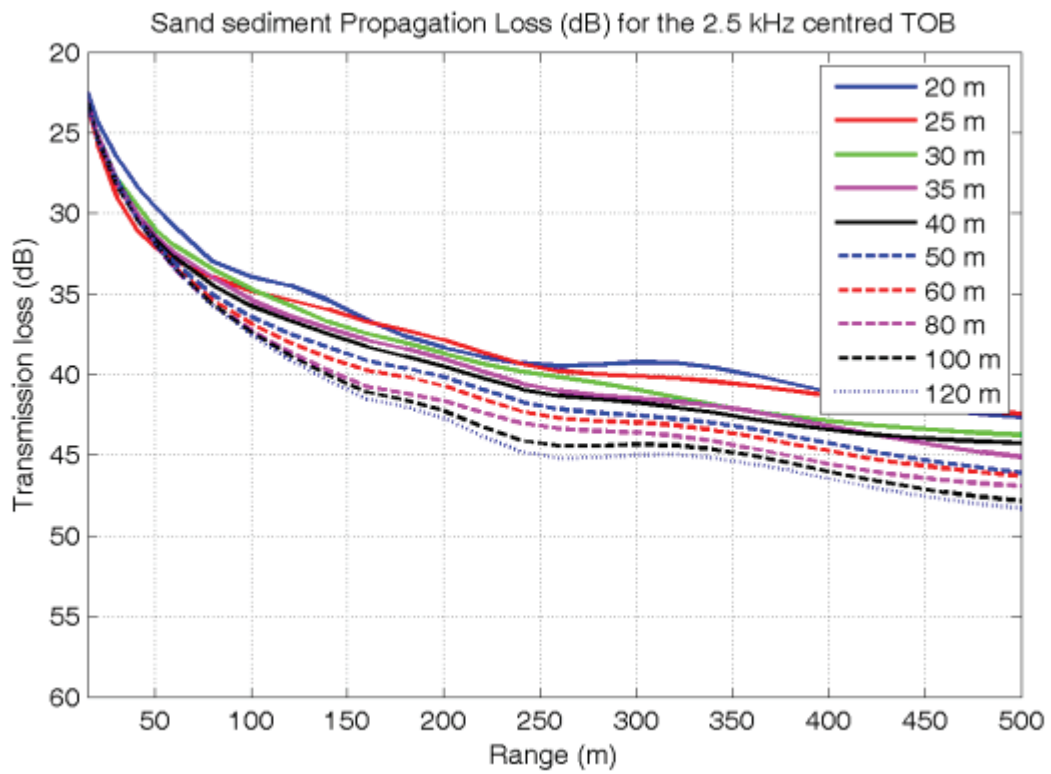
ANNEX 1

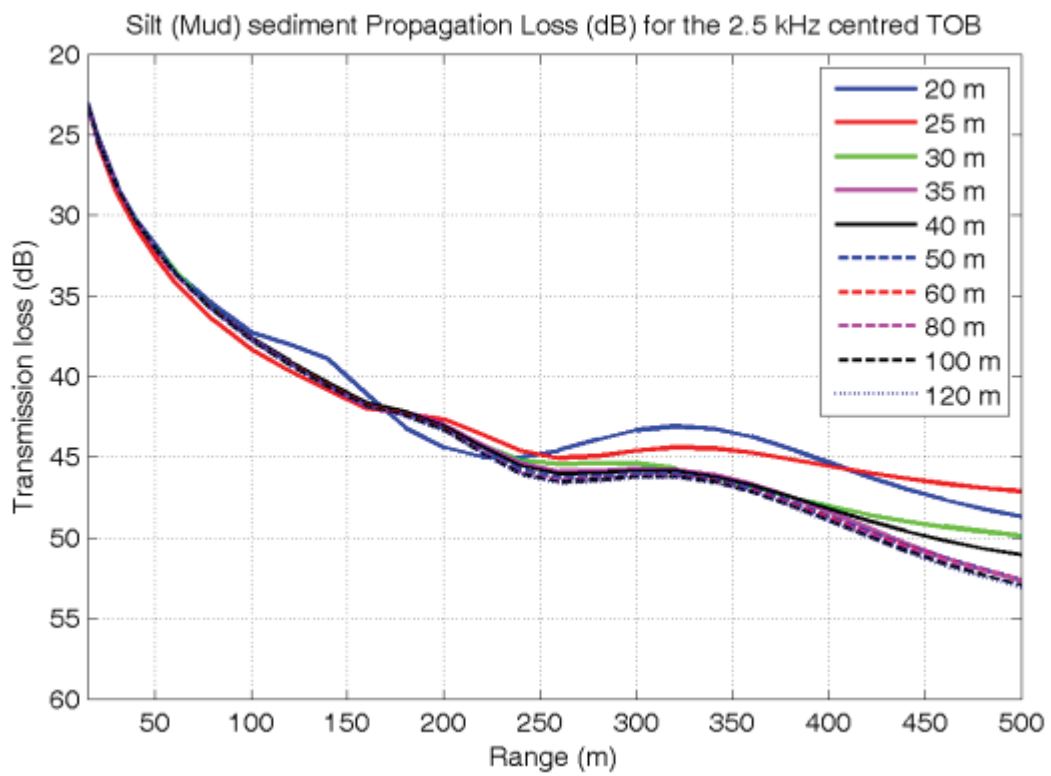
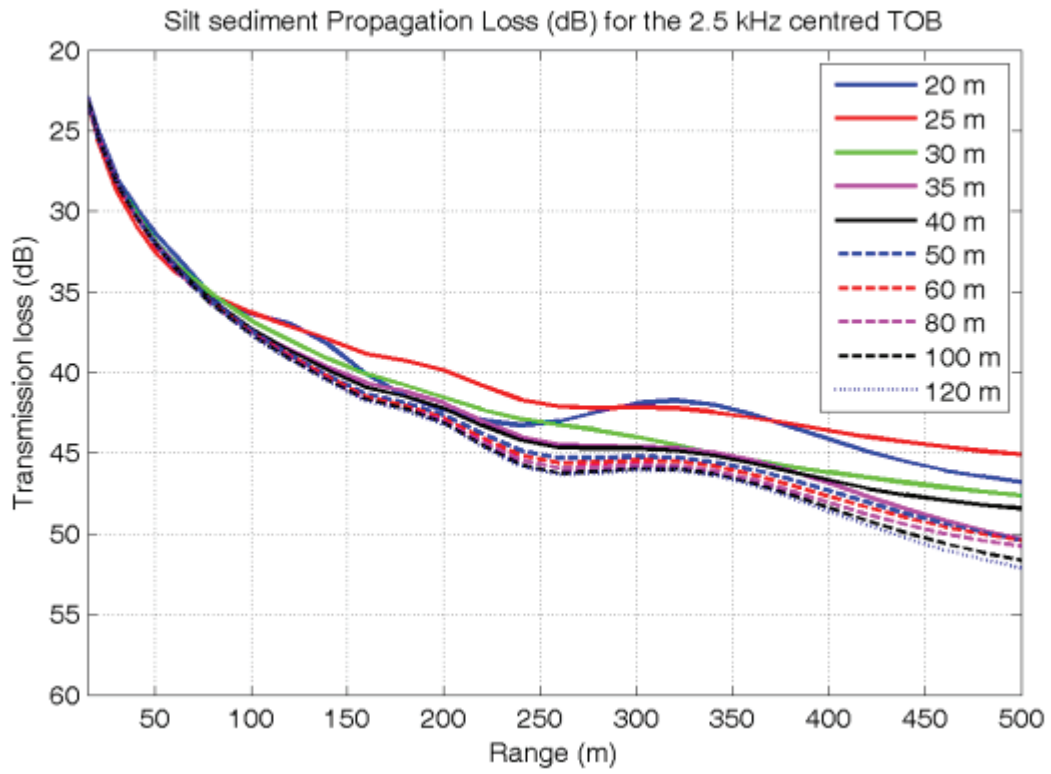
2 kHz



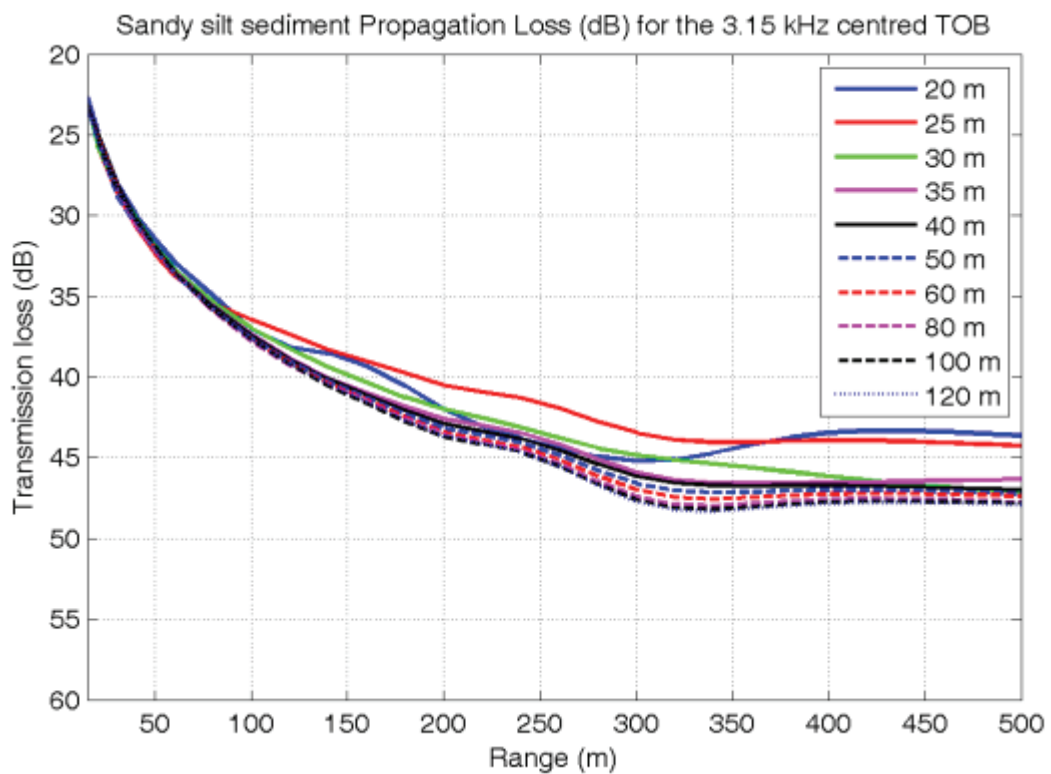
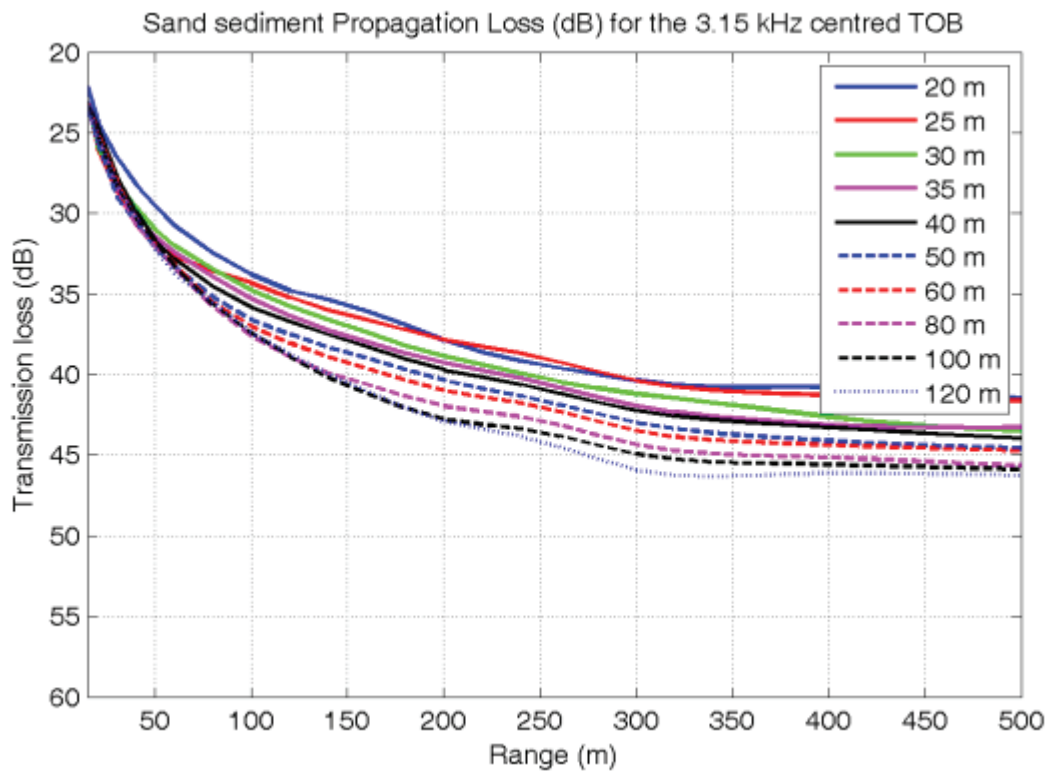


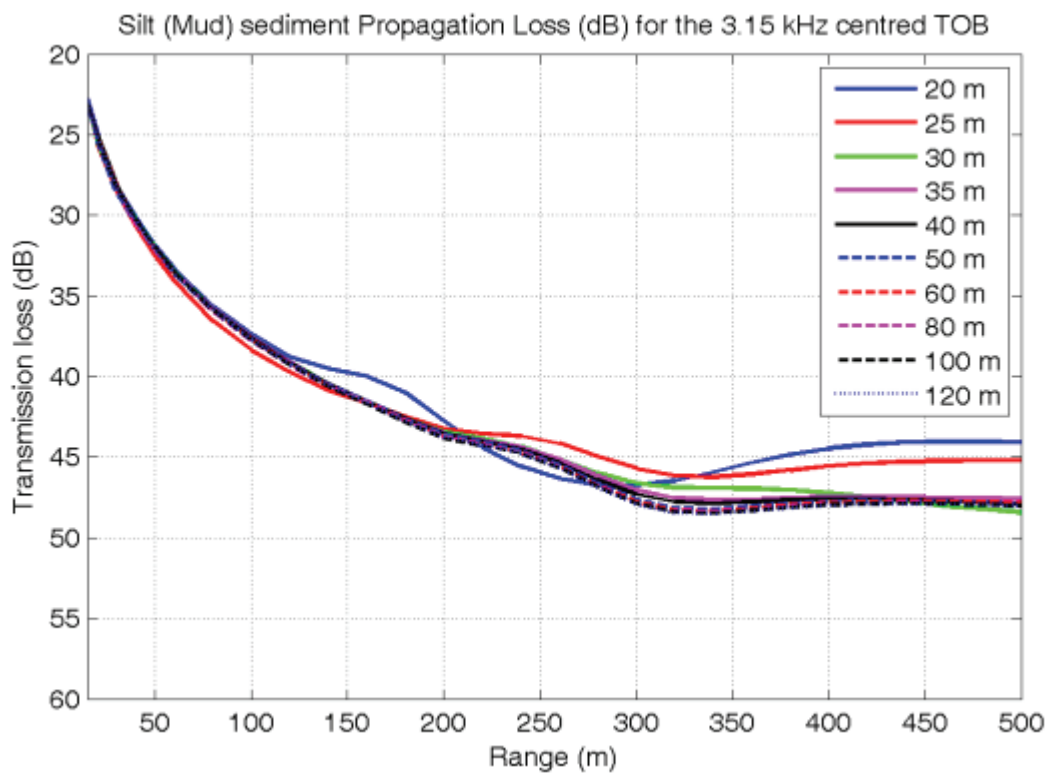
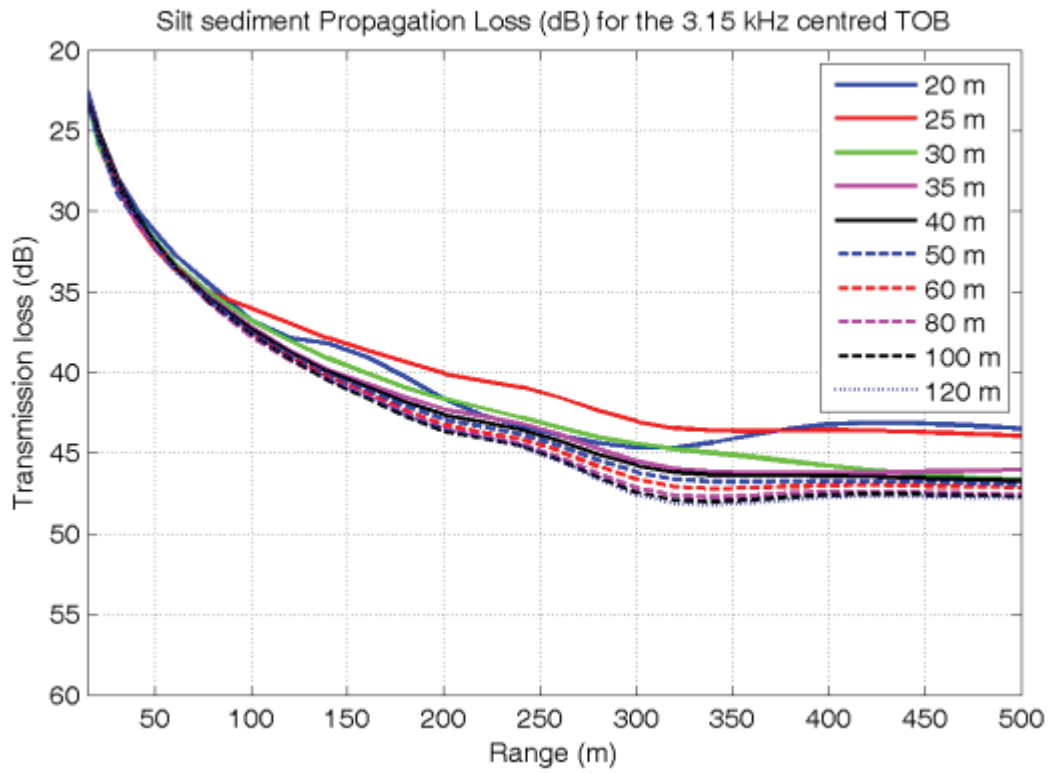
2.5 kHz



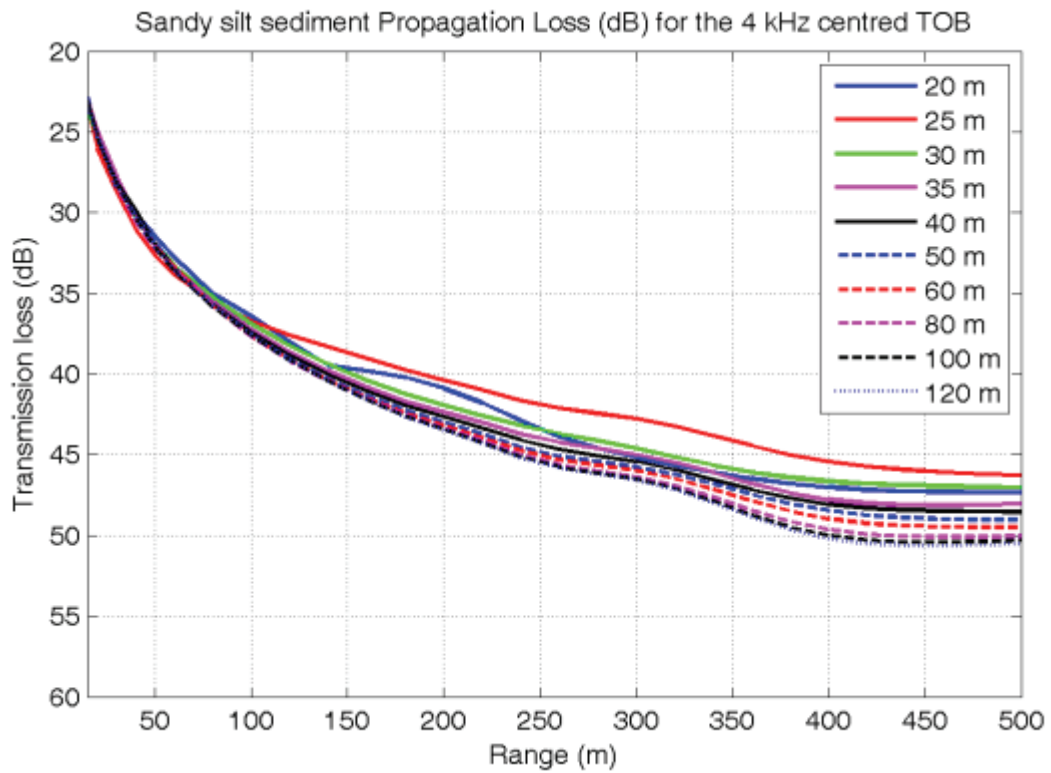
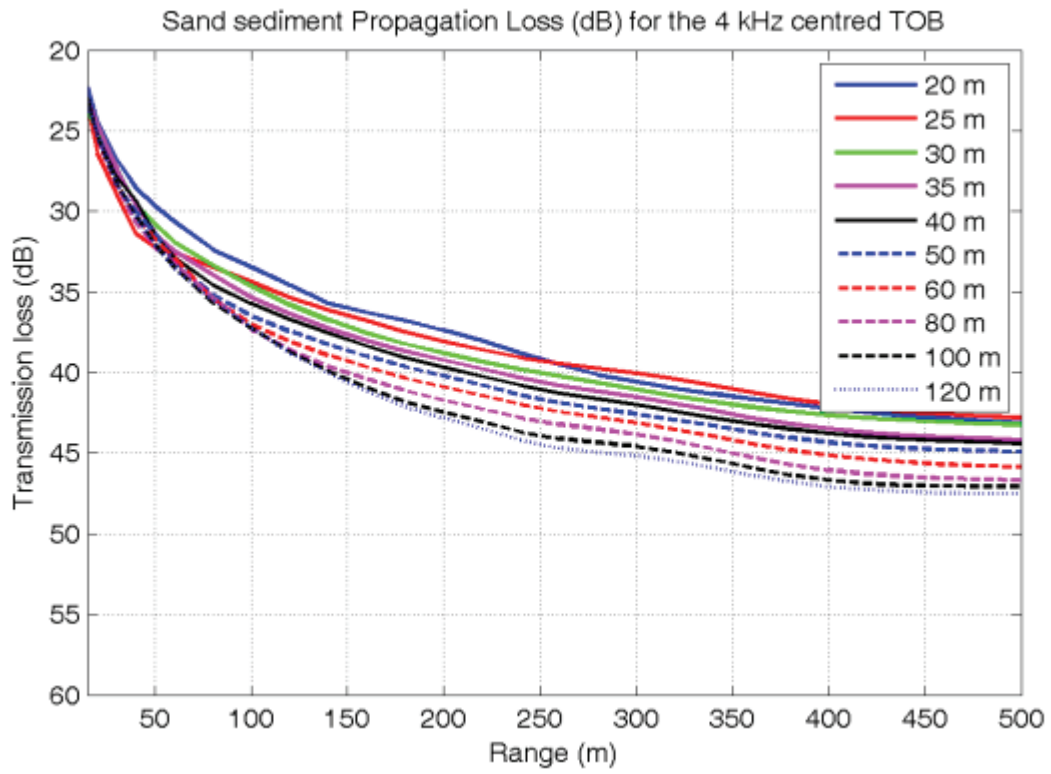


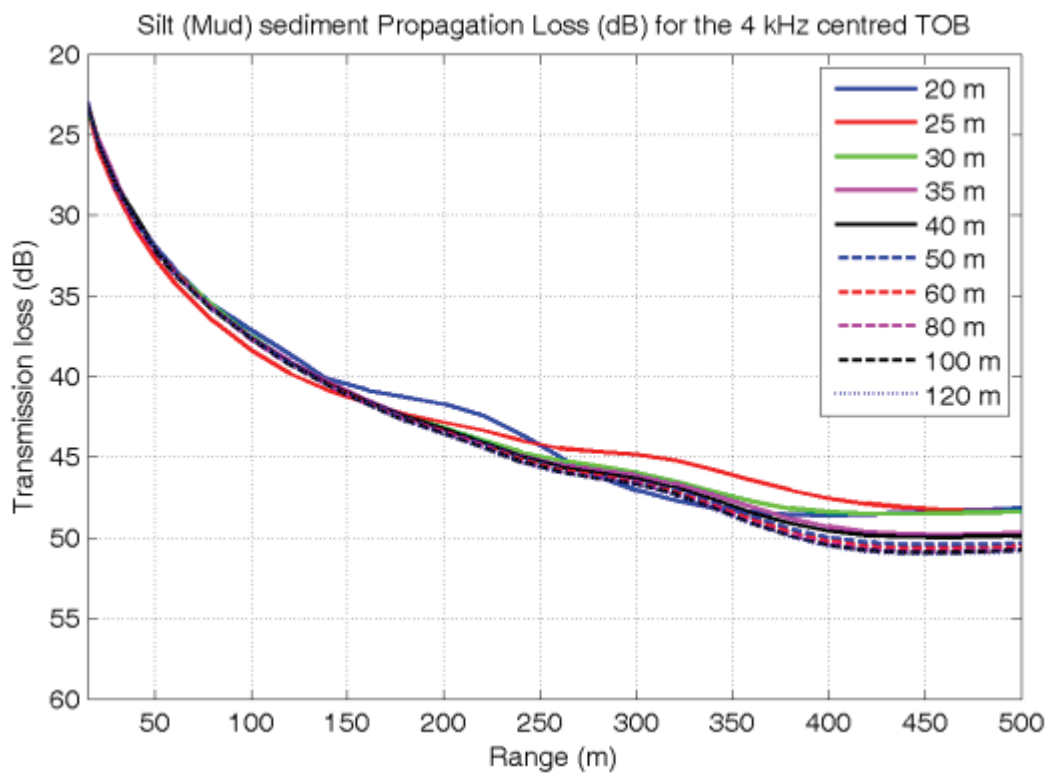
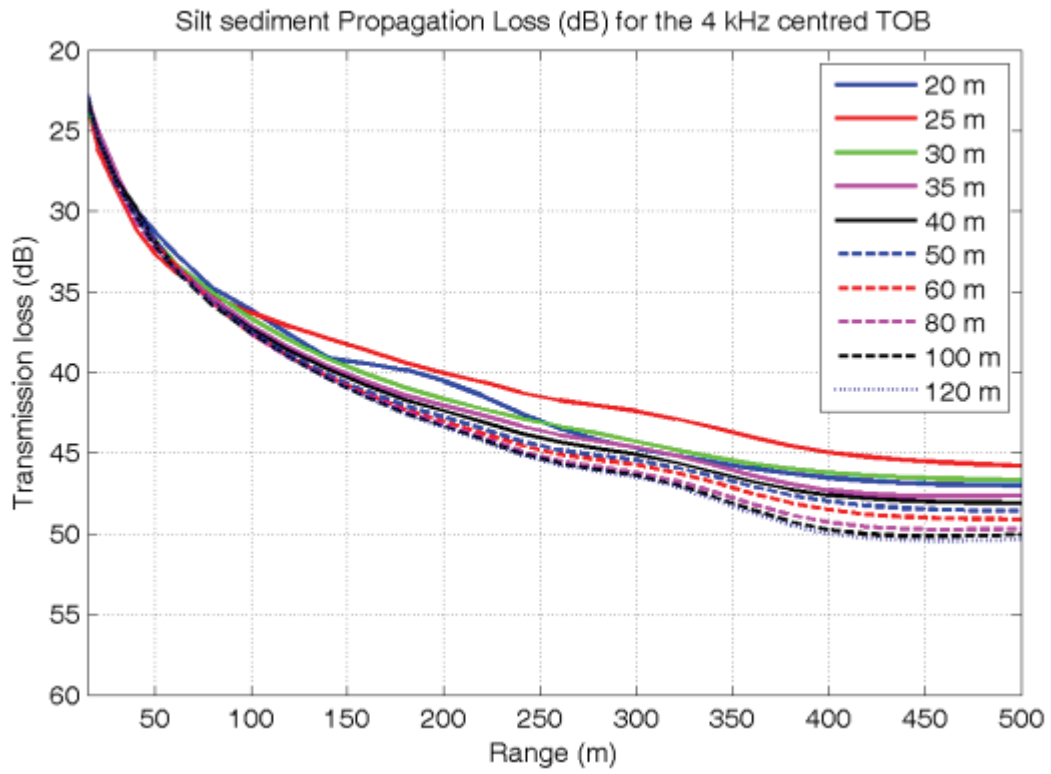
3.15 kHz



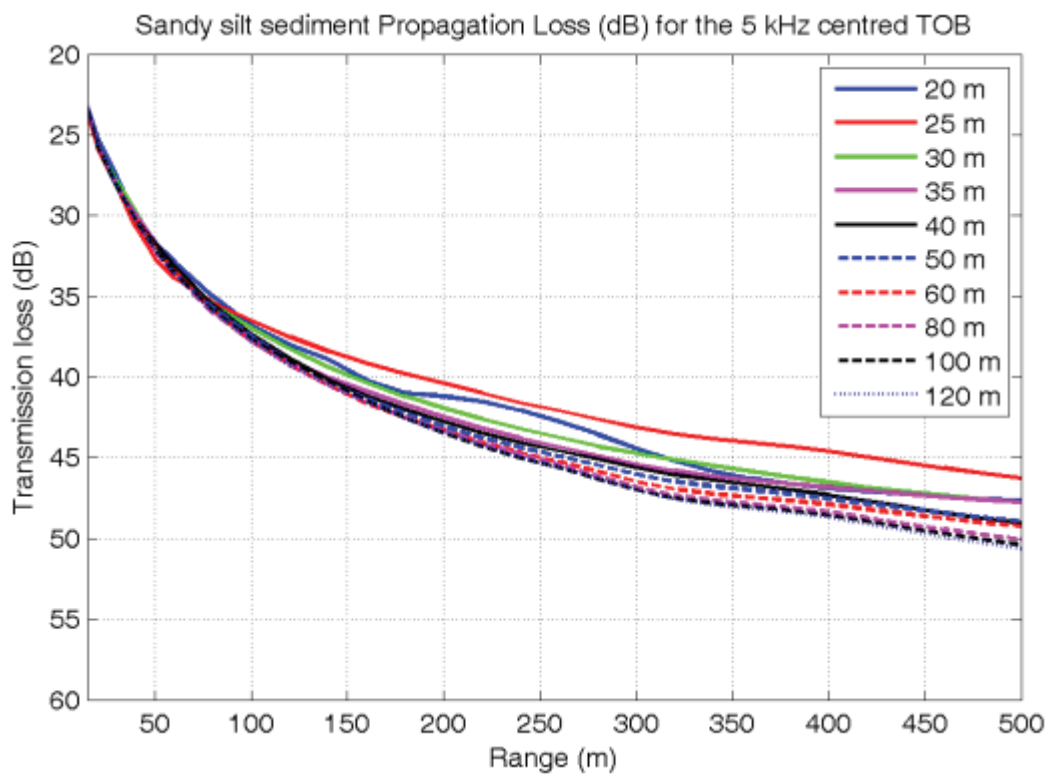
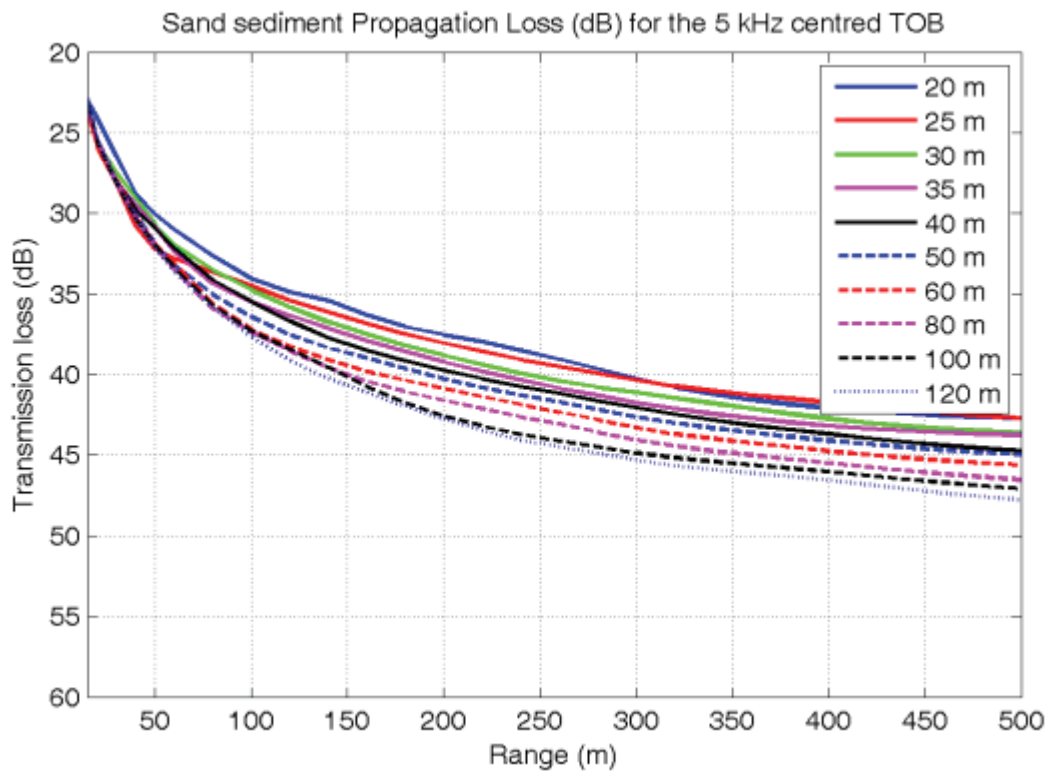


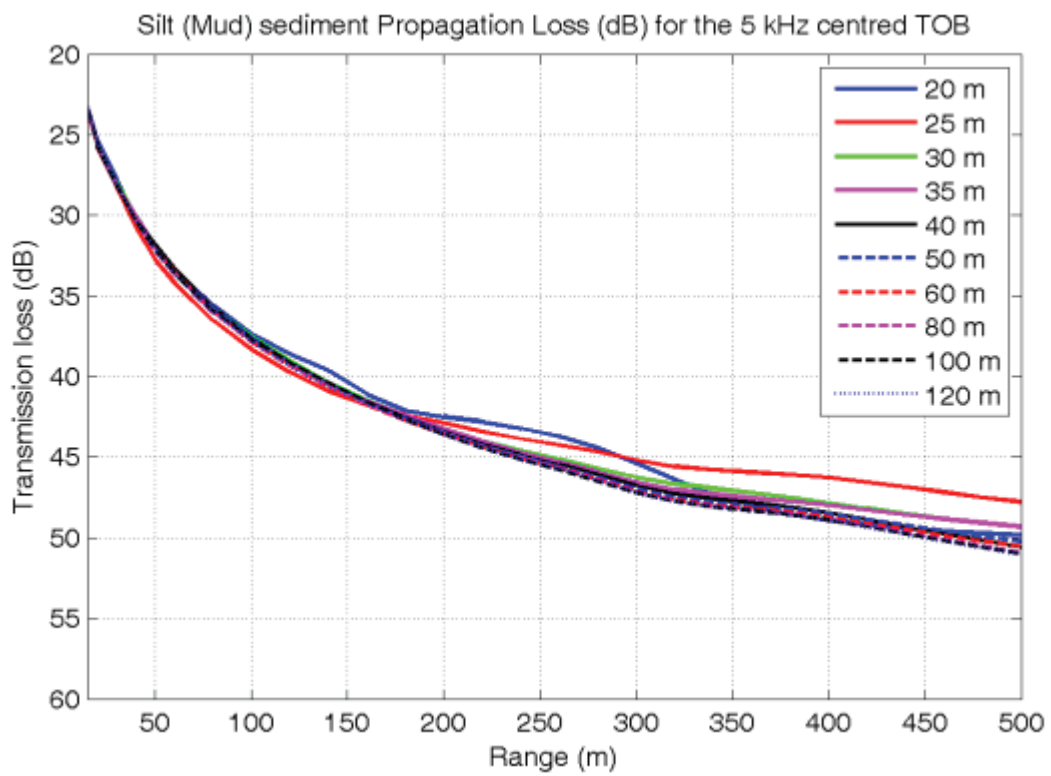
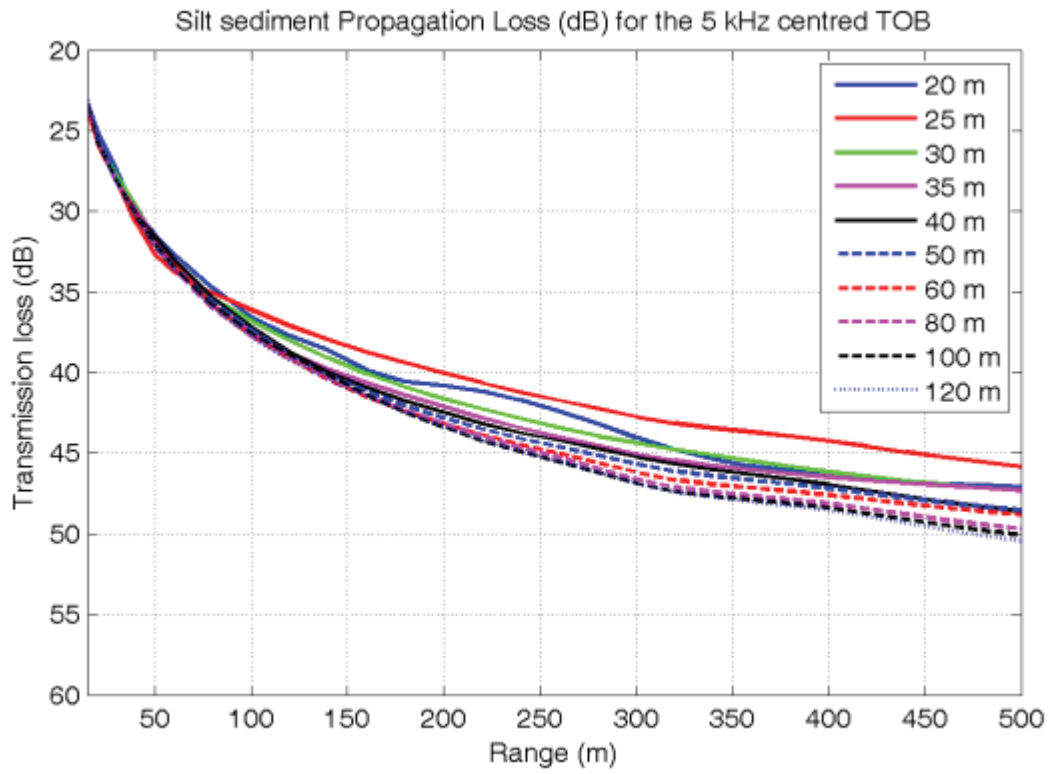
4 kHz



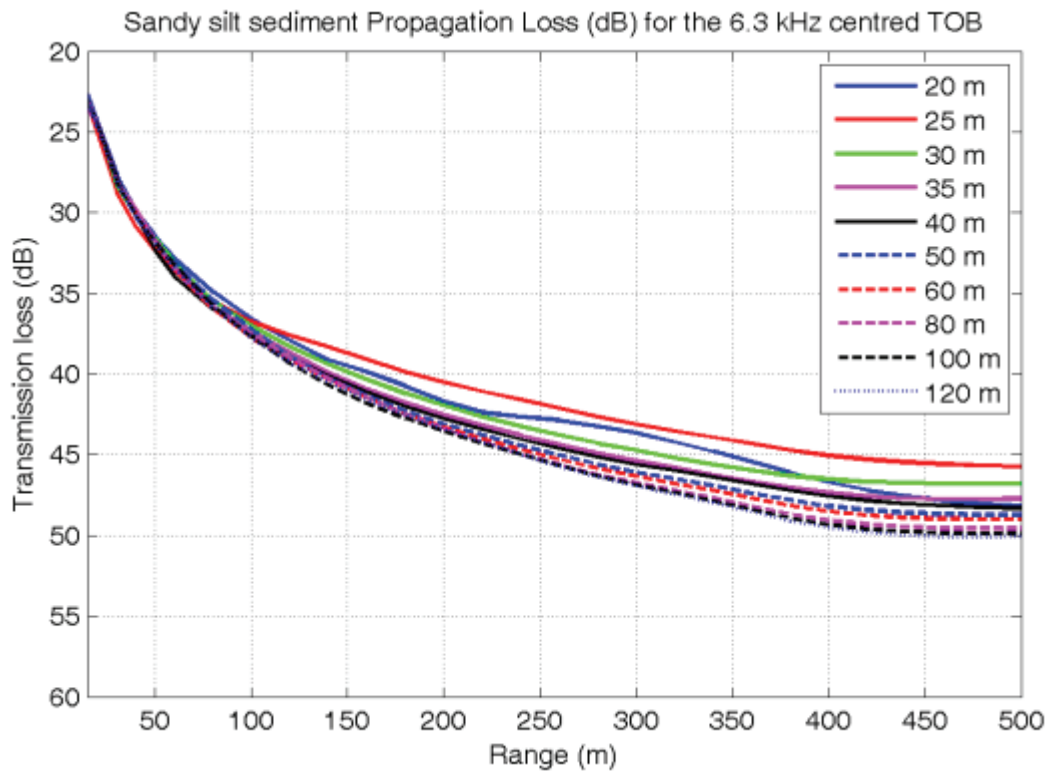
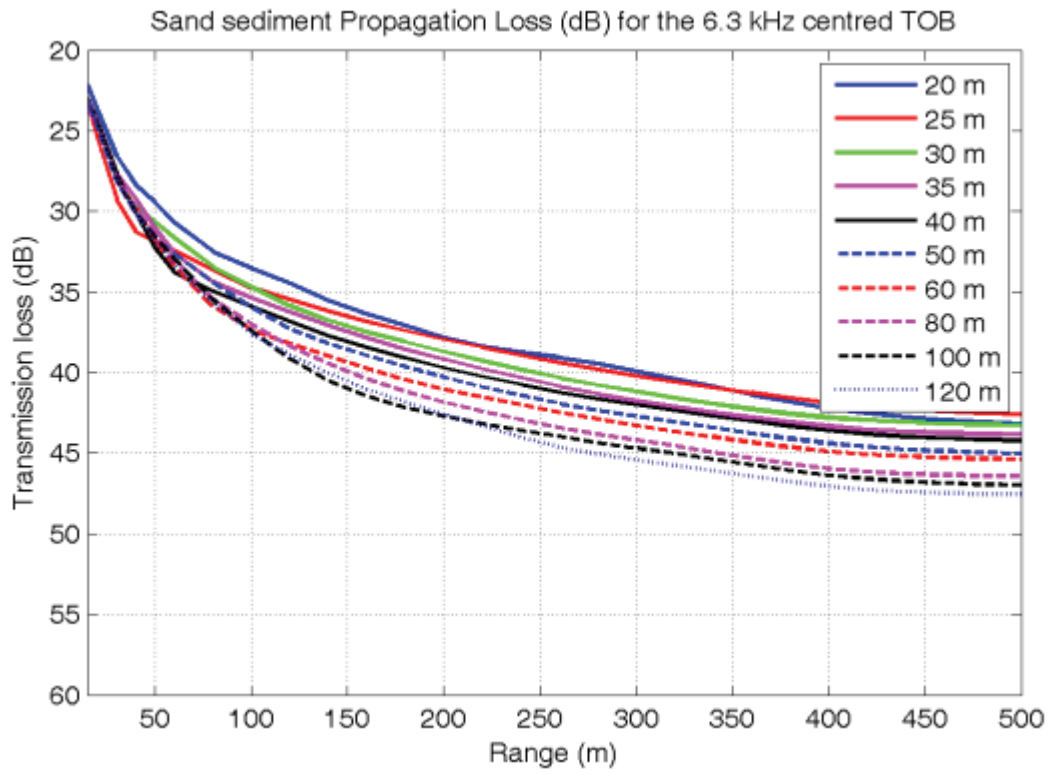


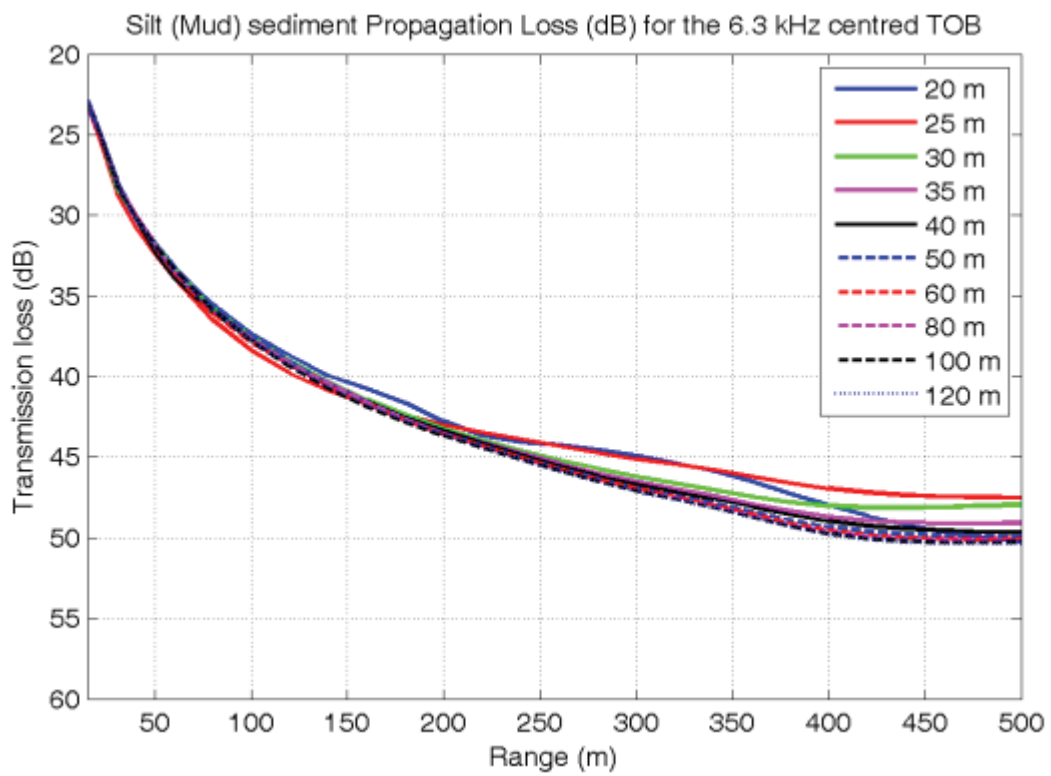
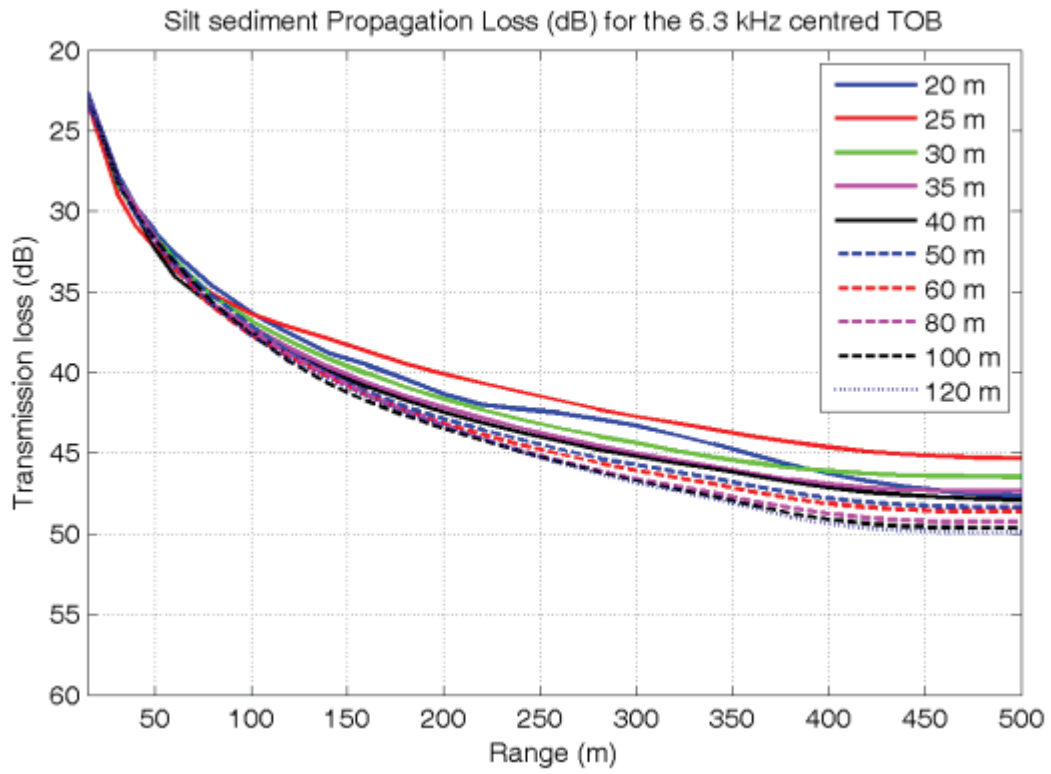
5 kHz



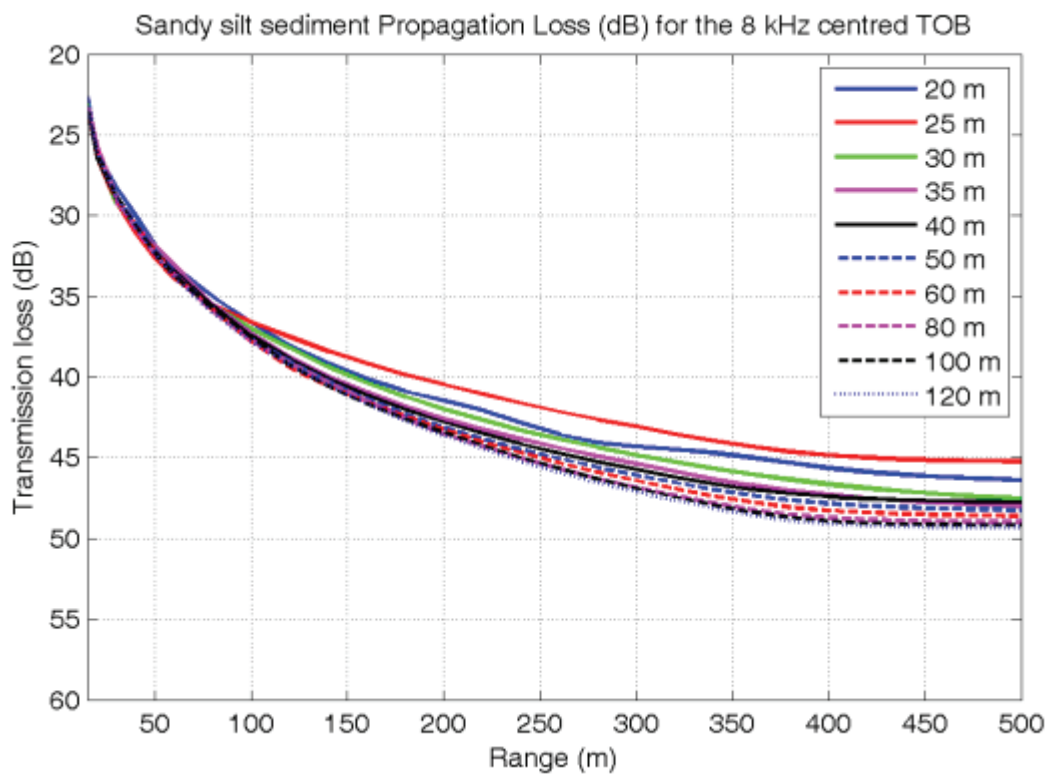
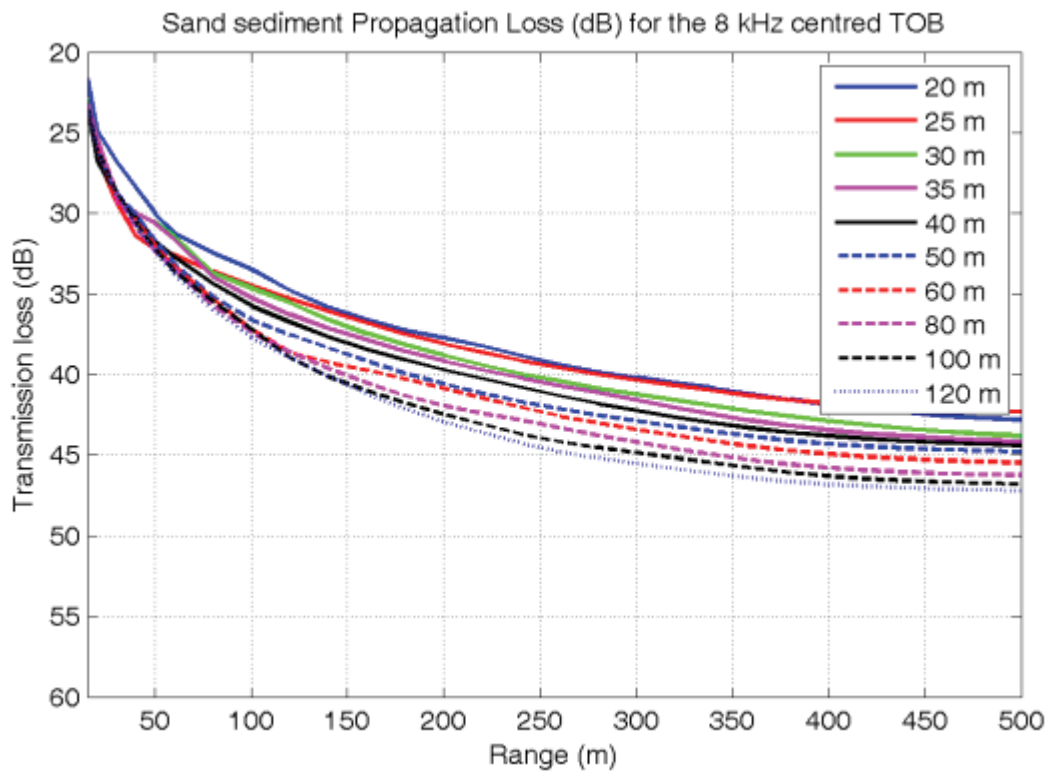


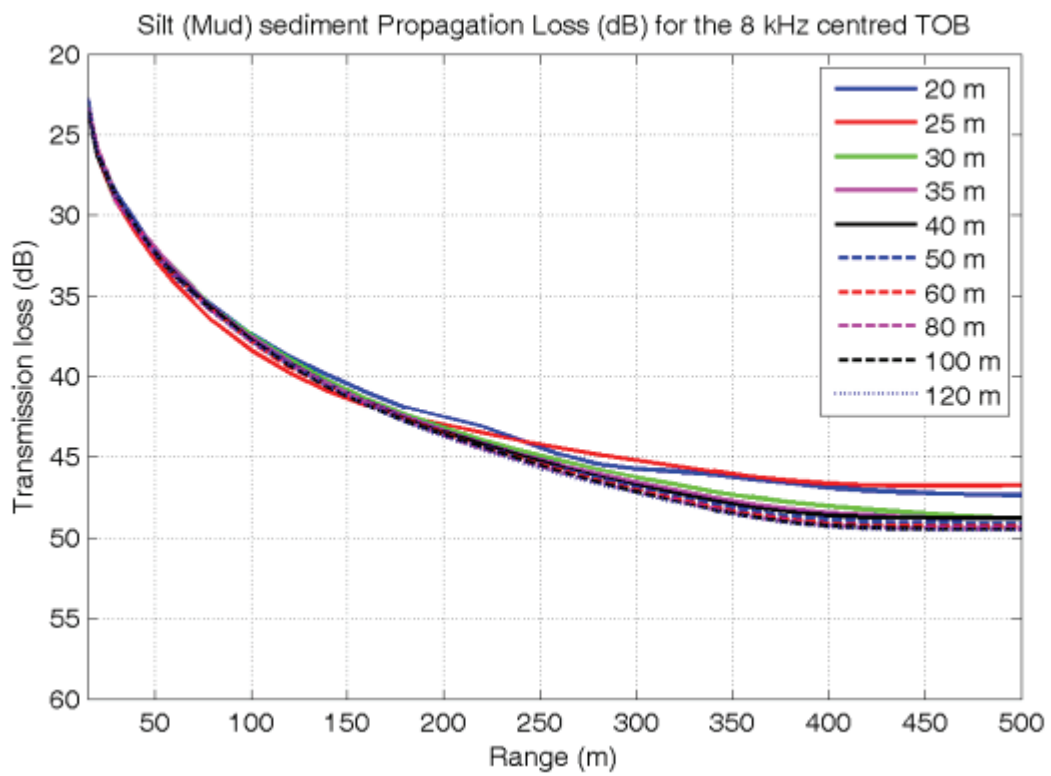
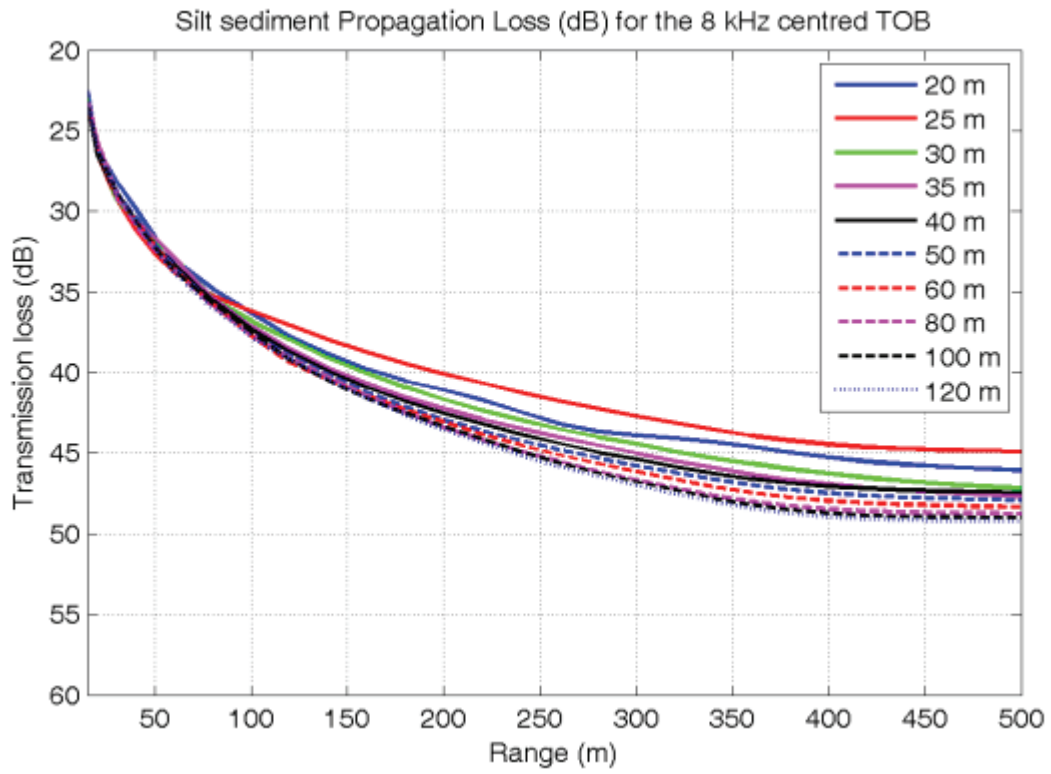
6.3 kHz



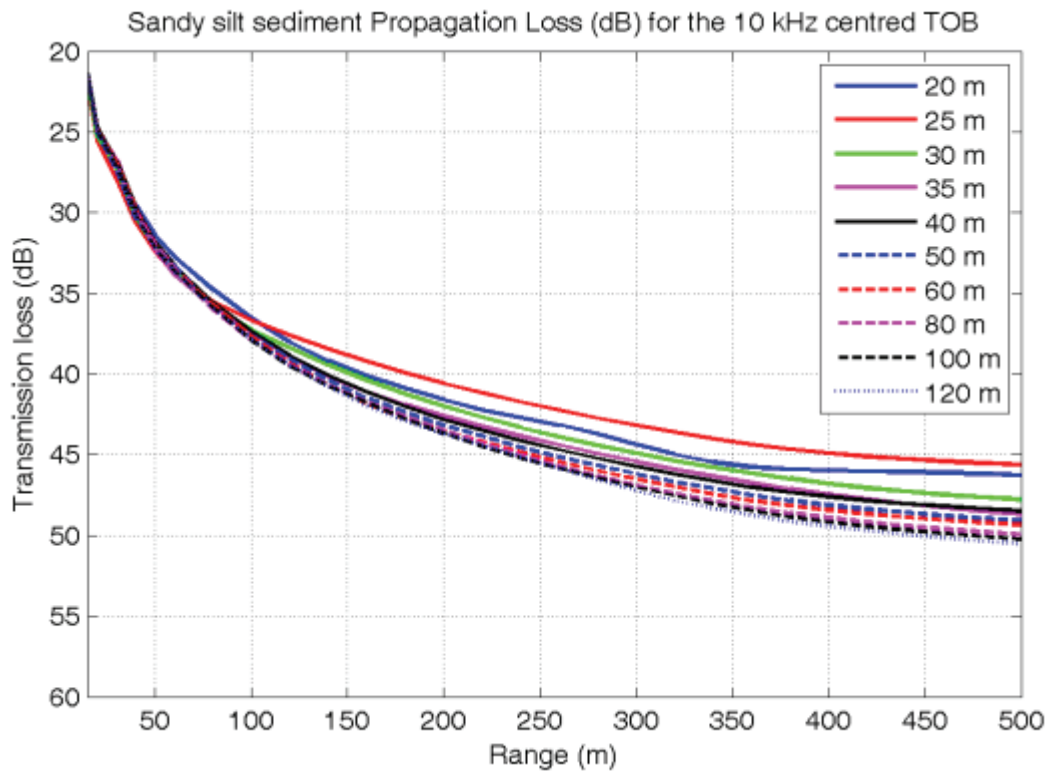
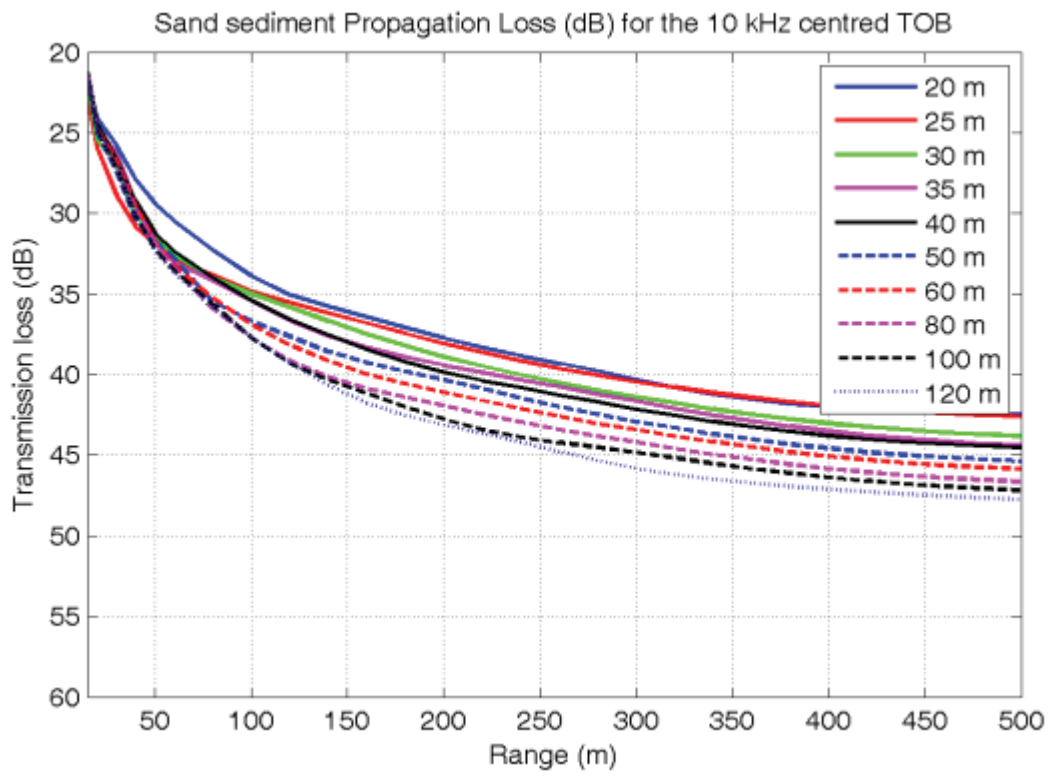


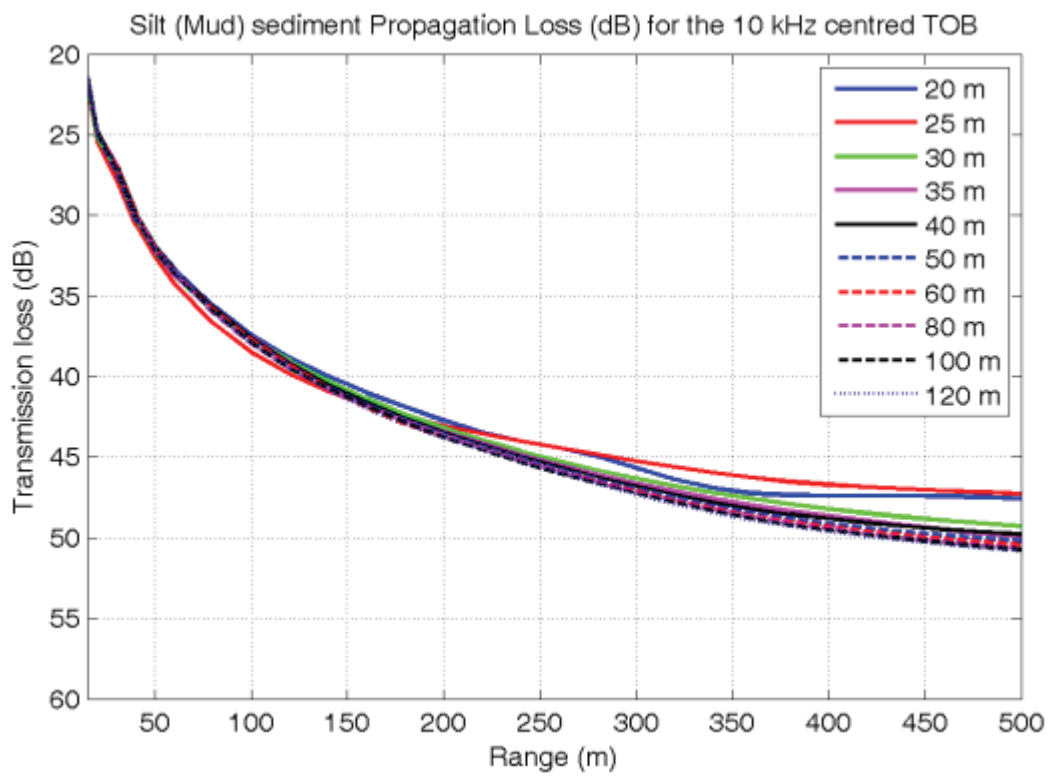
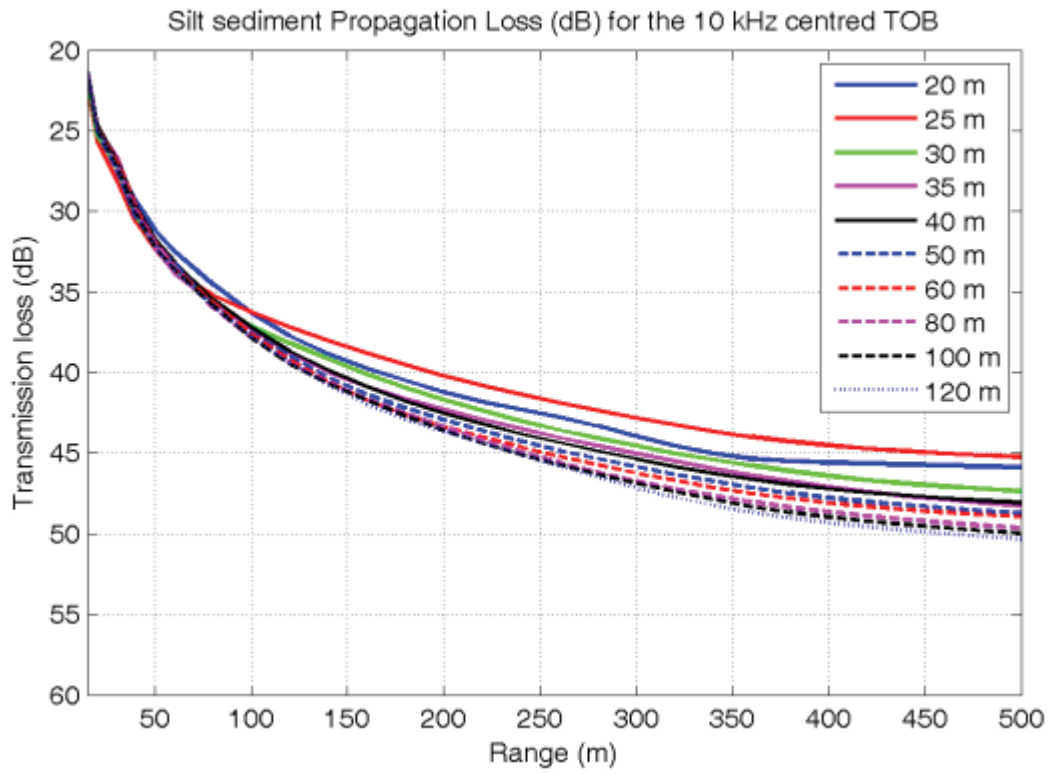
8 kHz



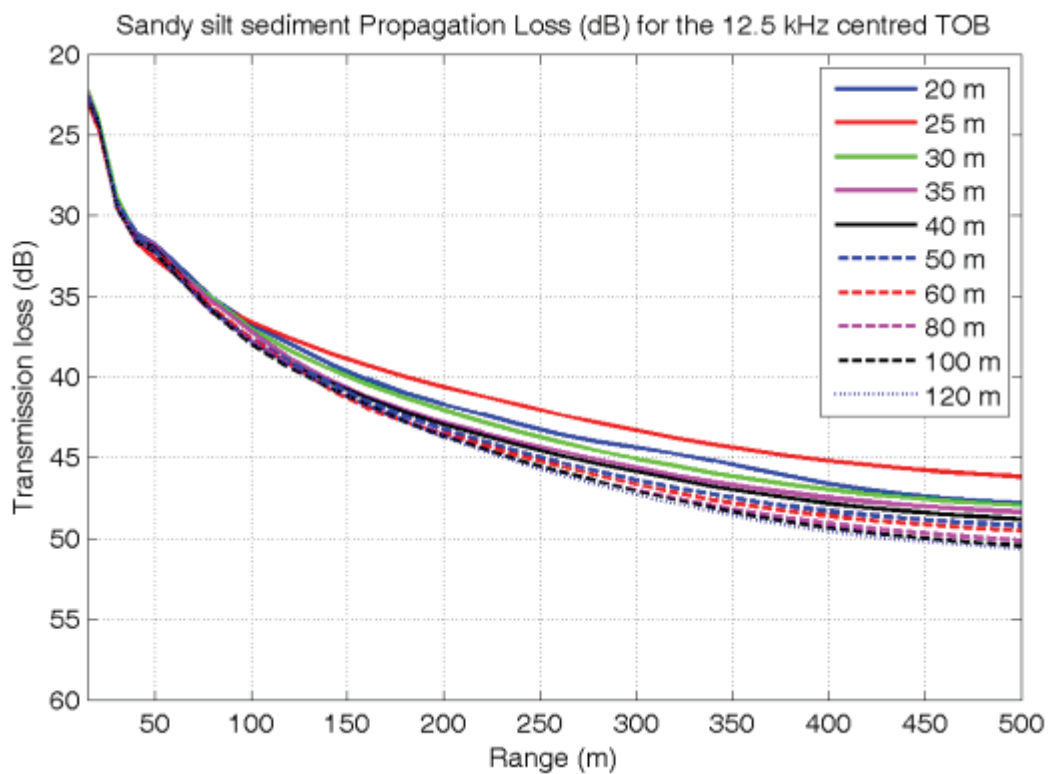
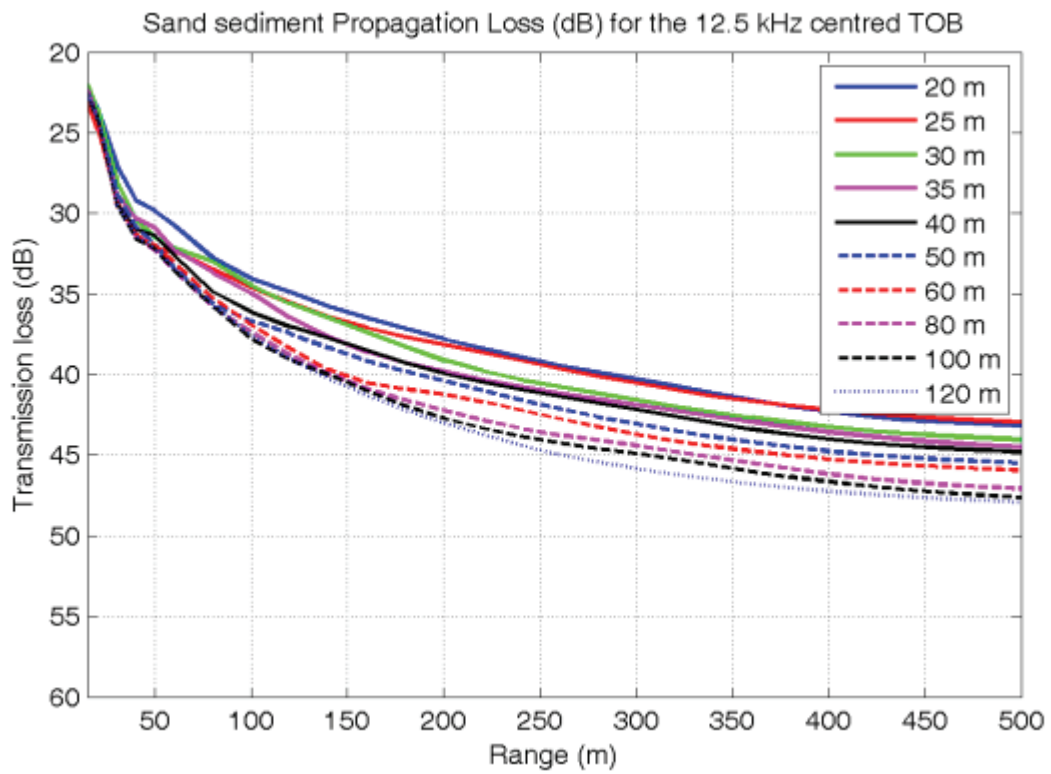


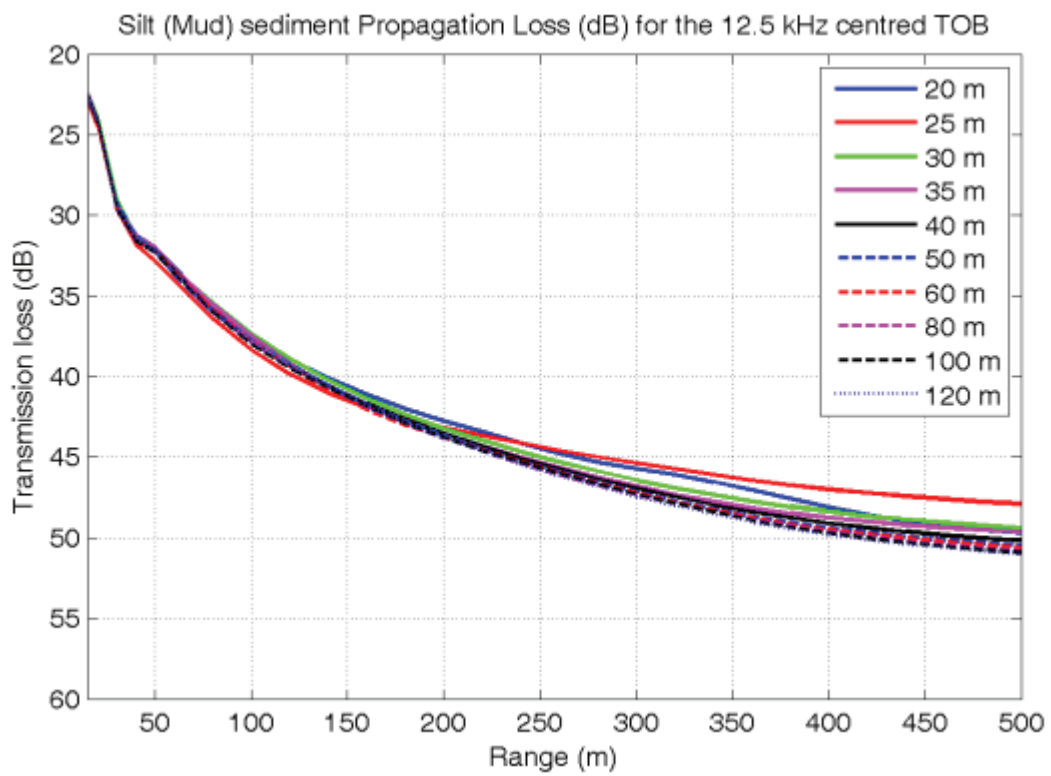
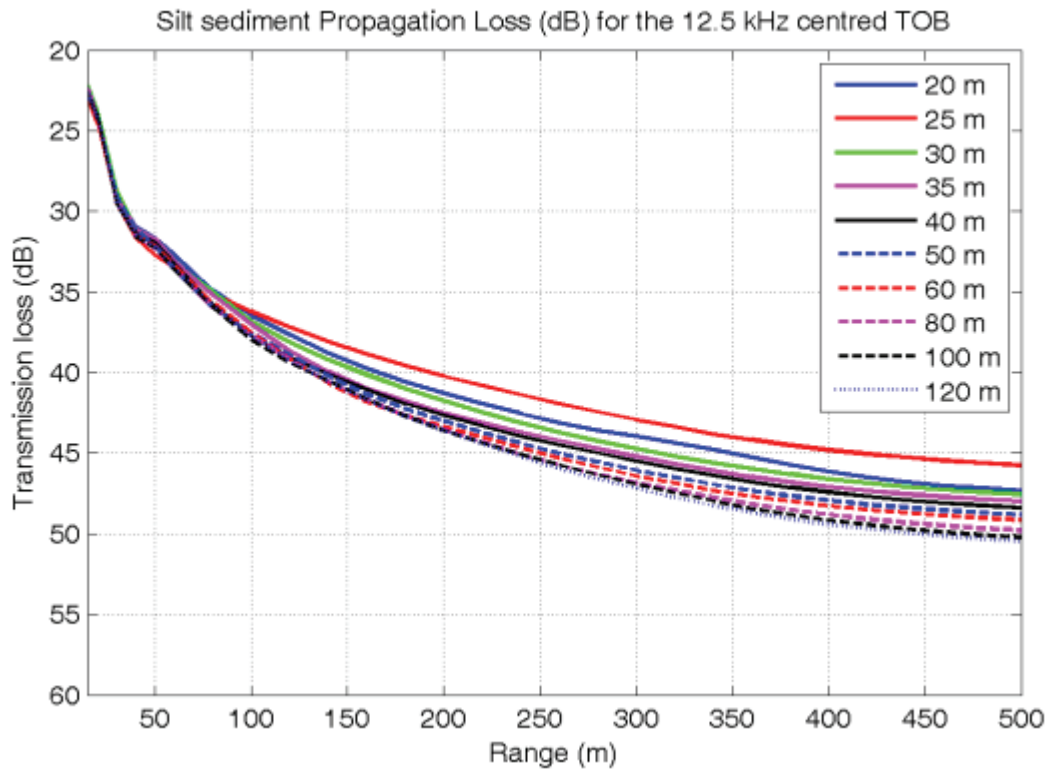
10 kHz



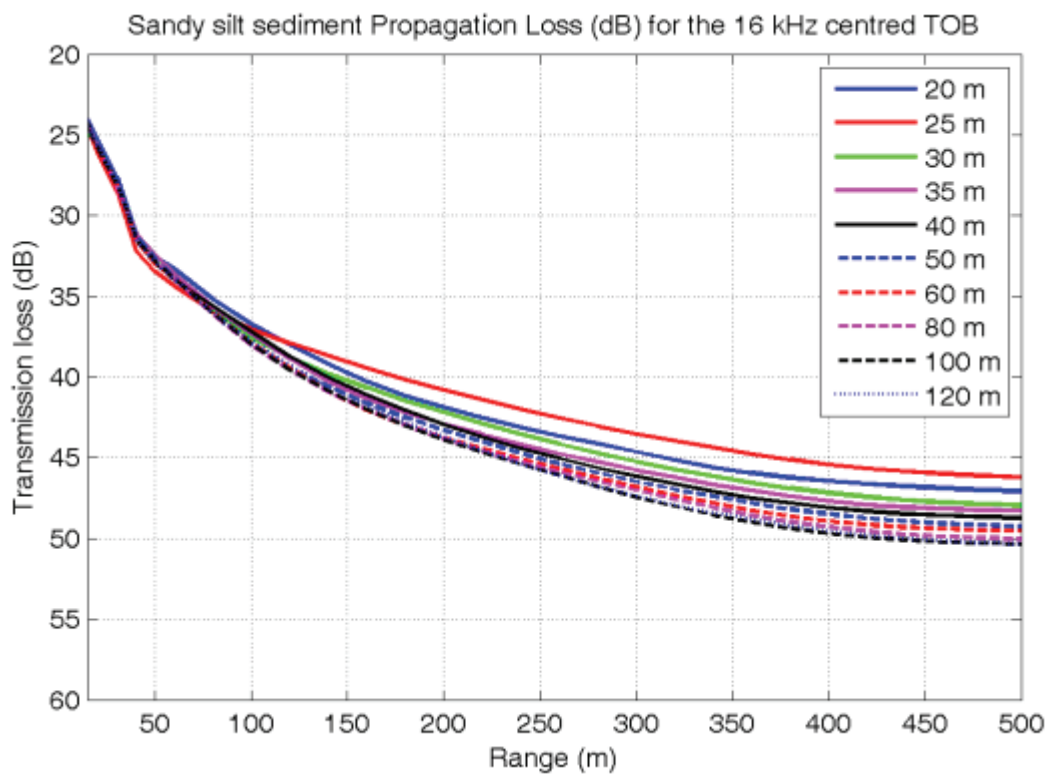
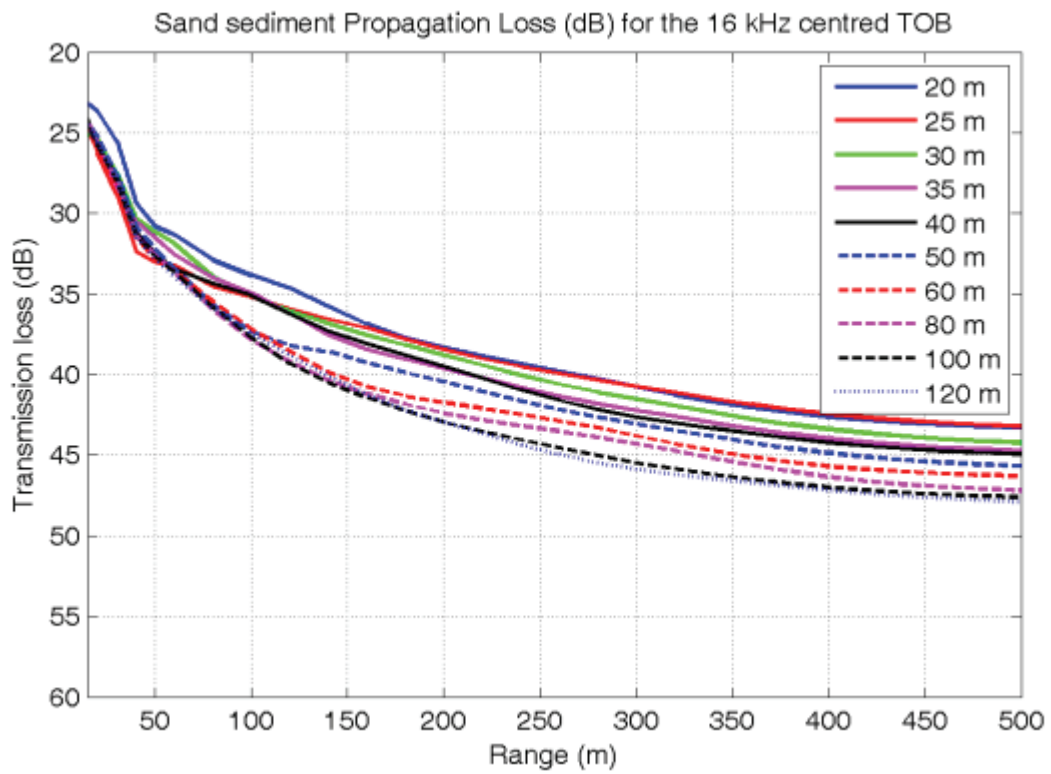


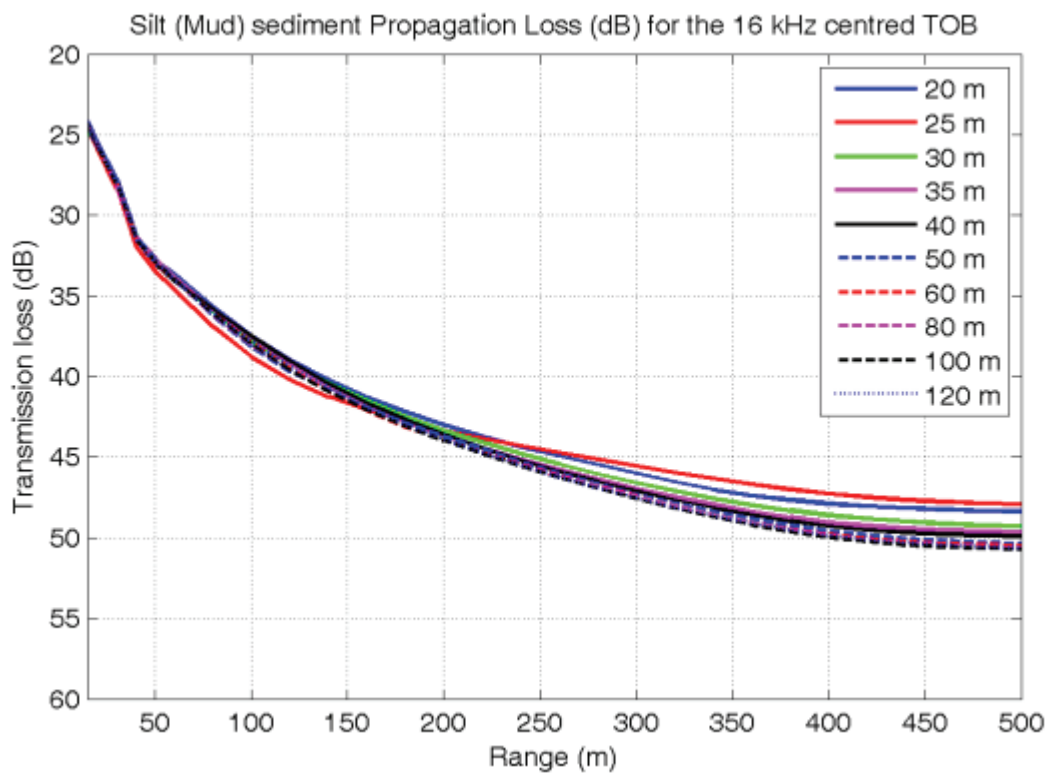
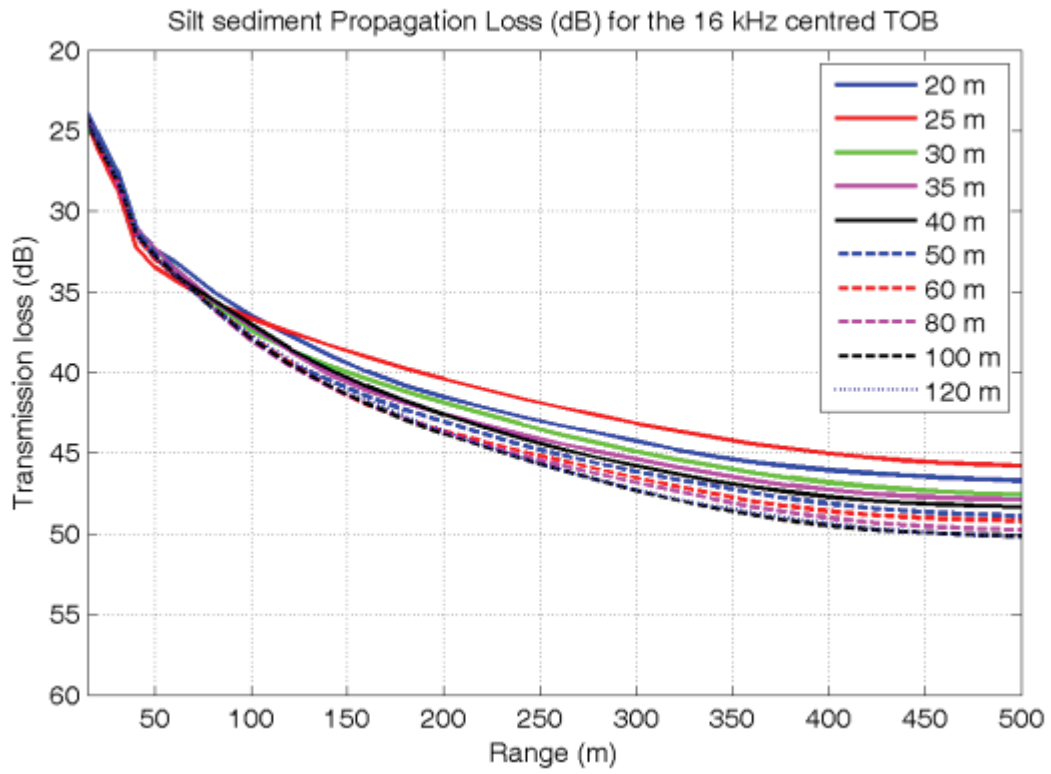
12.5 kHz



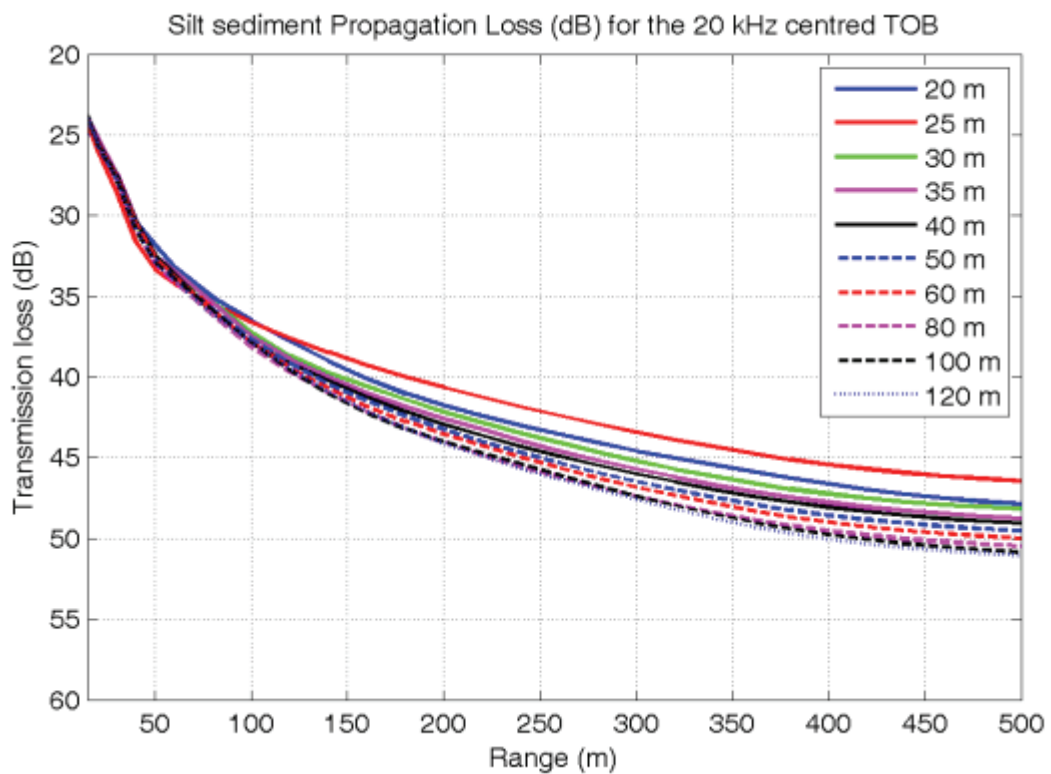
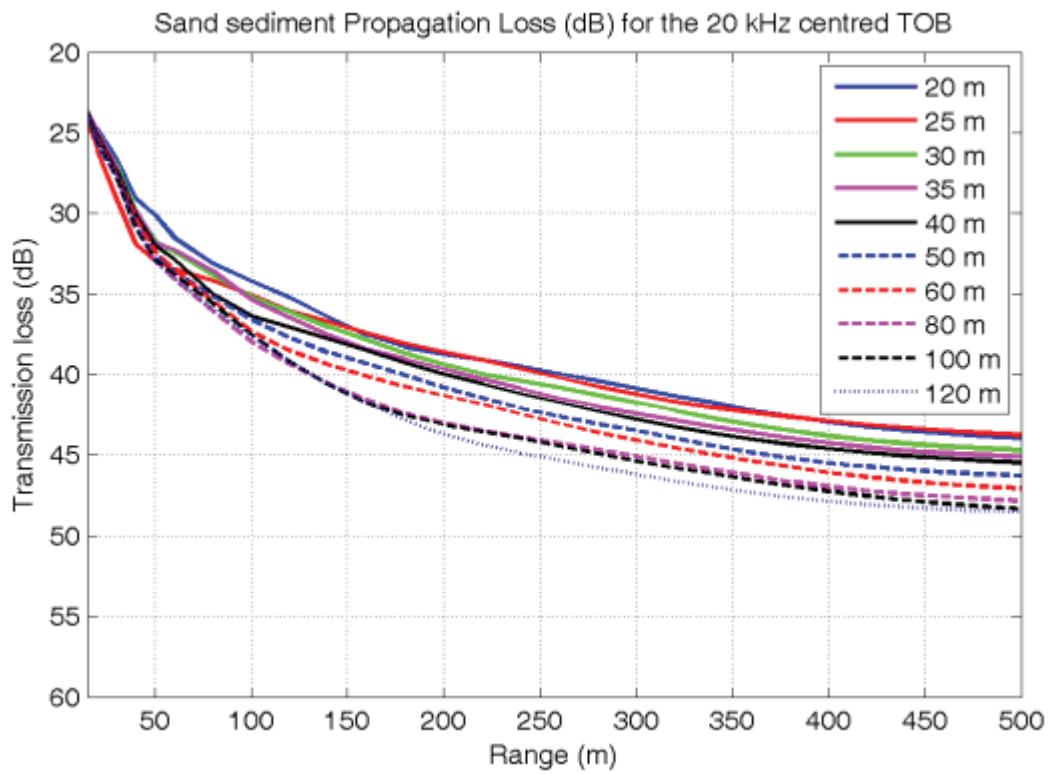


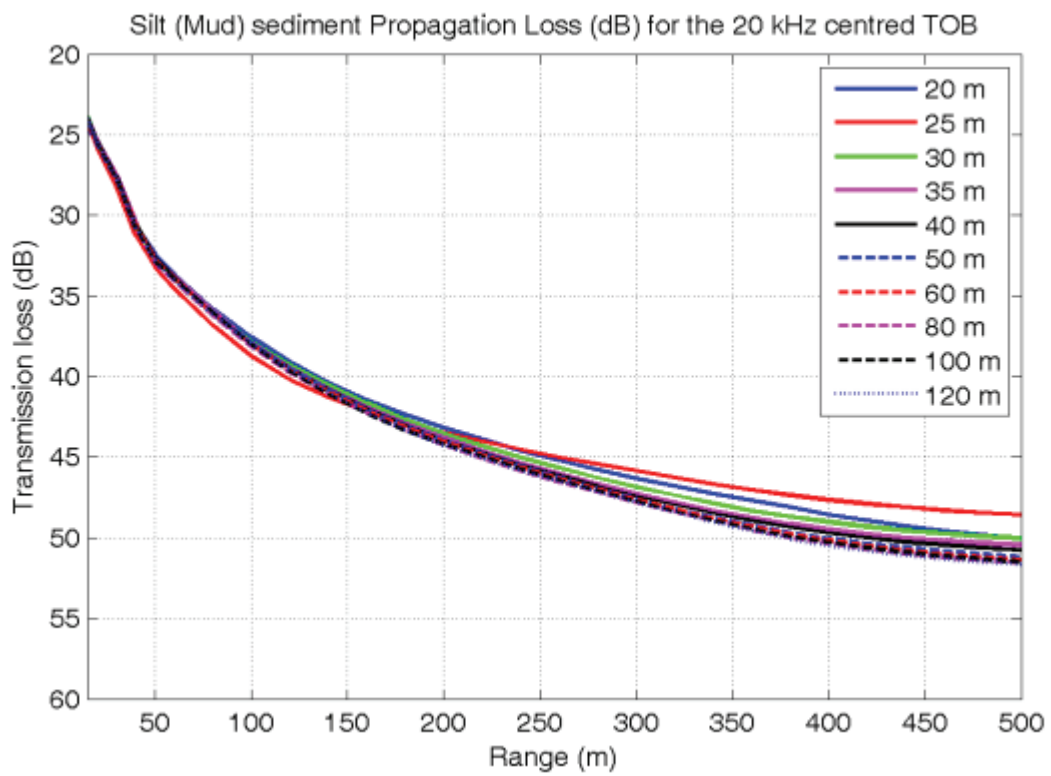
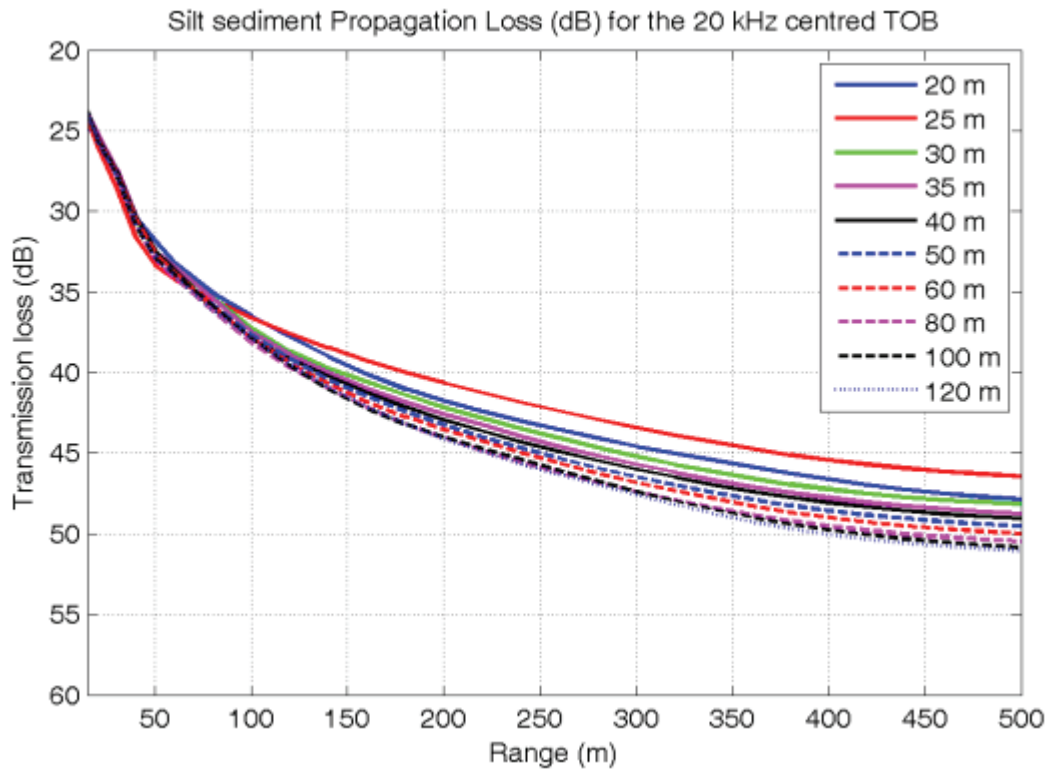
16 kHz



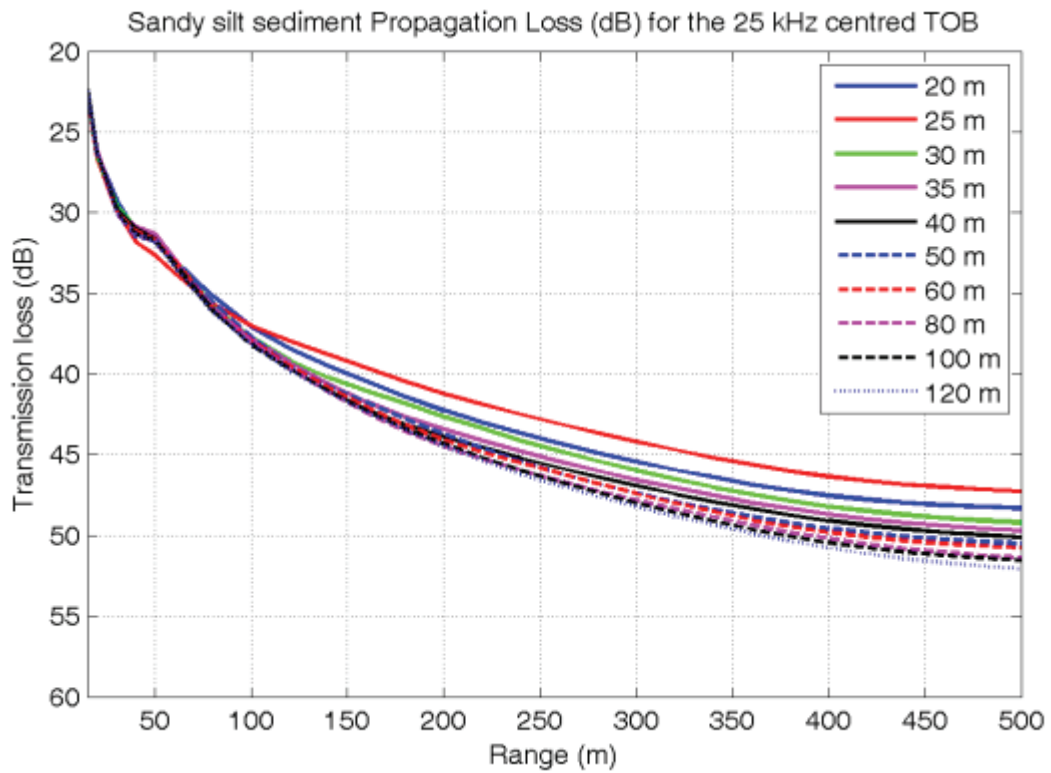
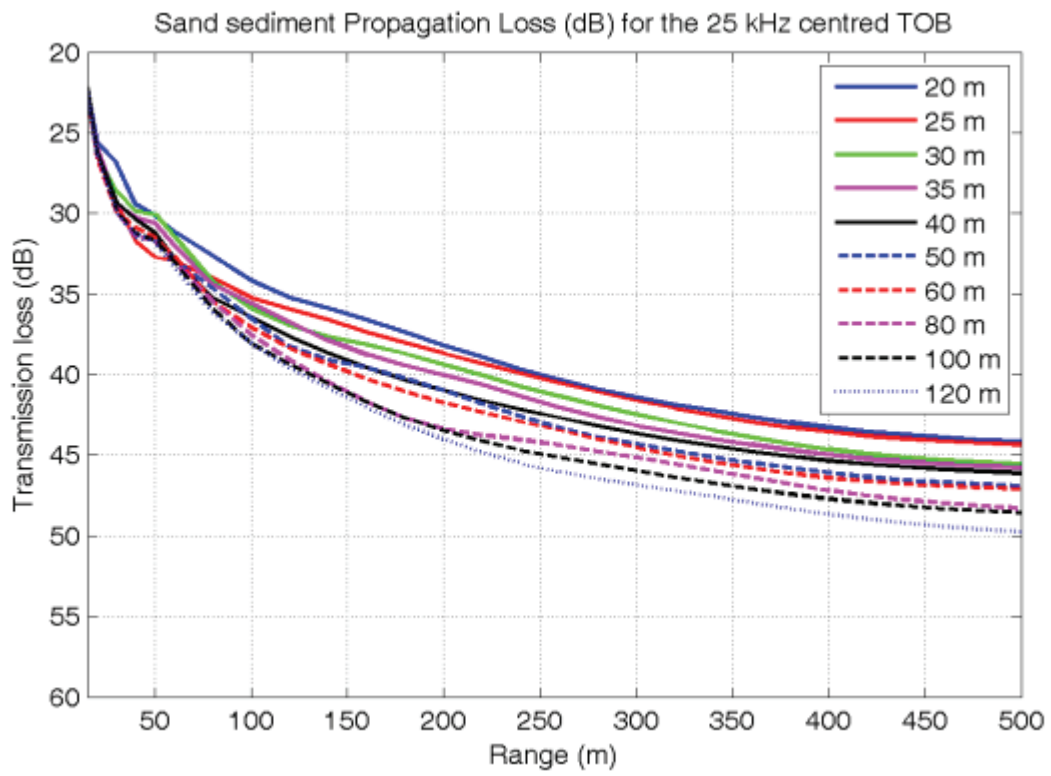


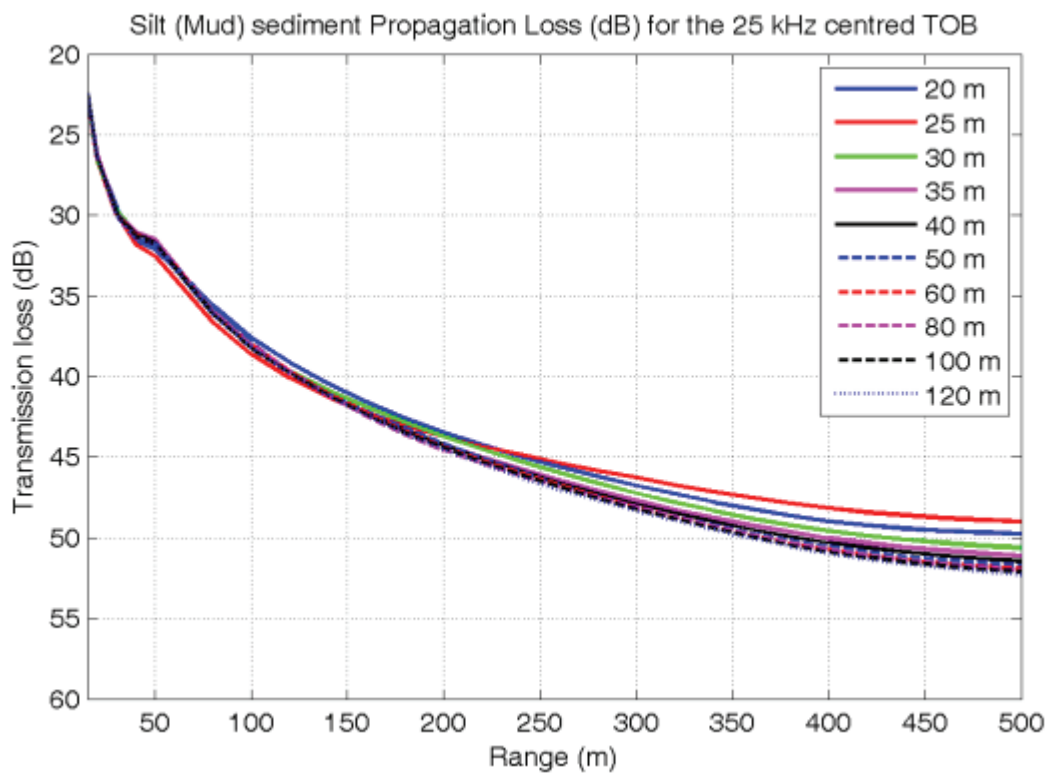
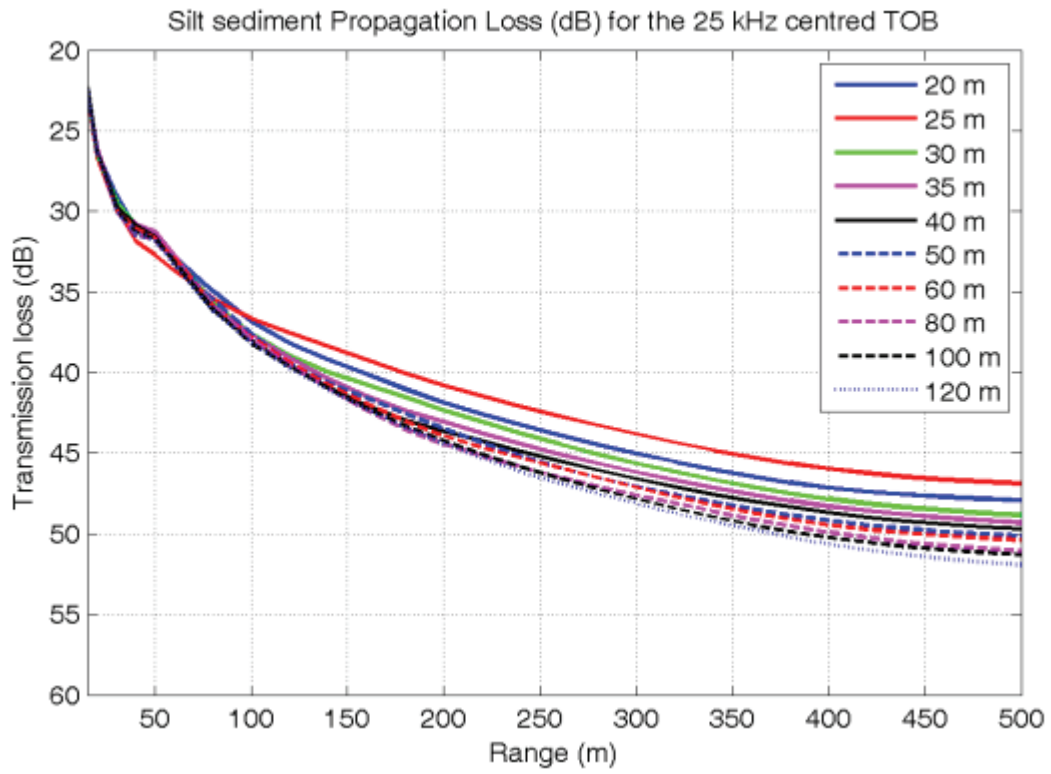
20 kHz



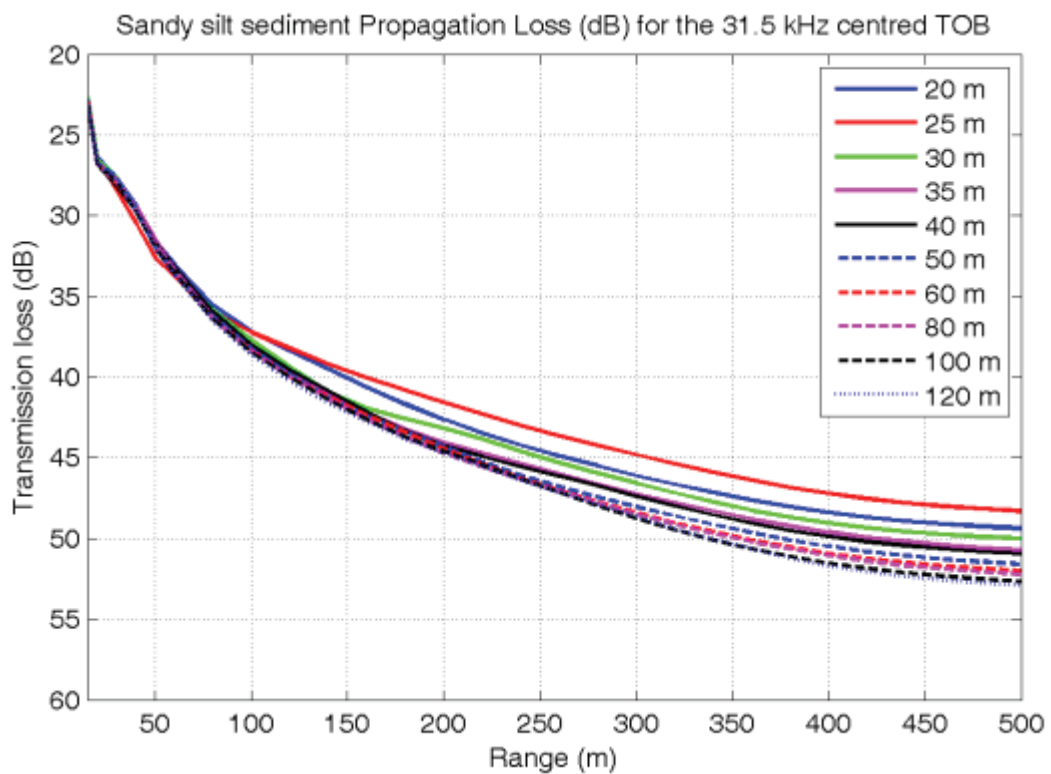
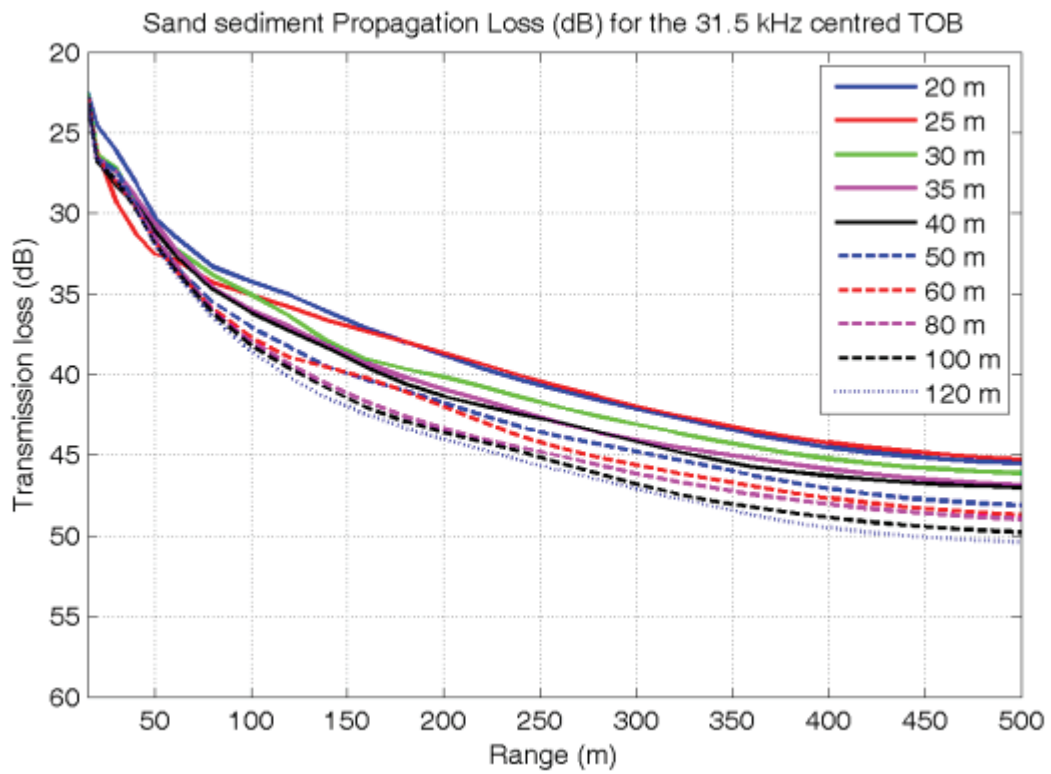


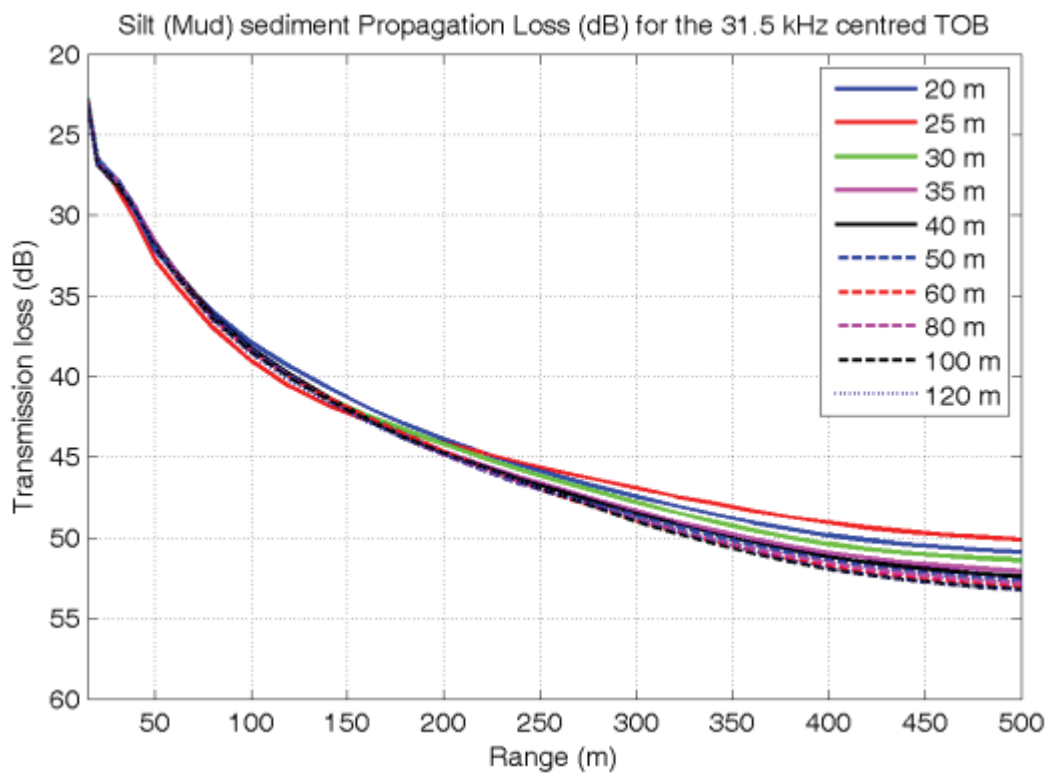
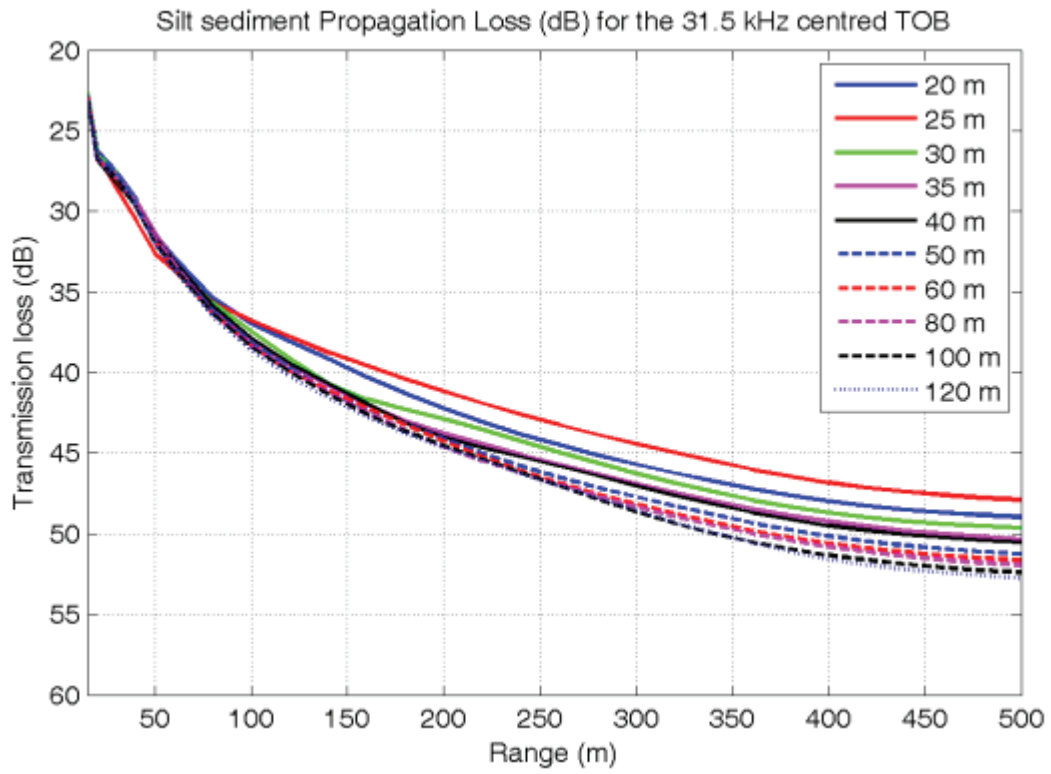
25 kHz



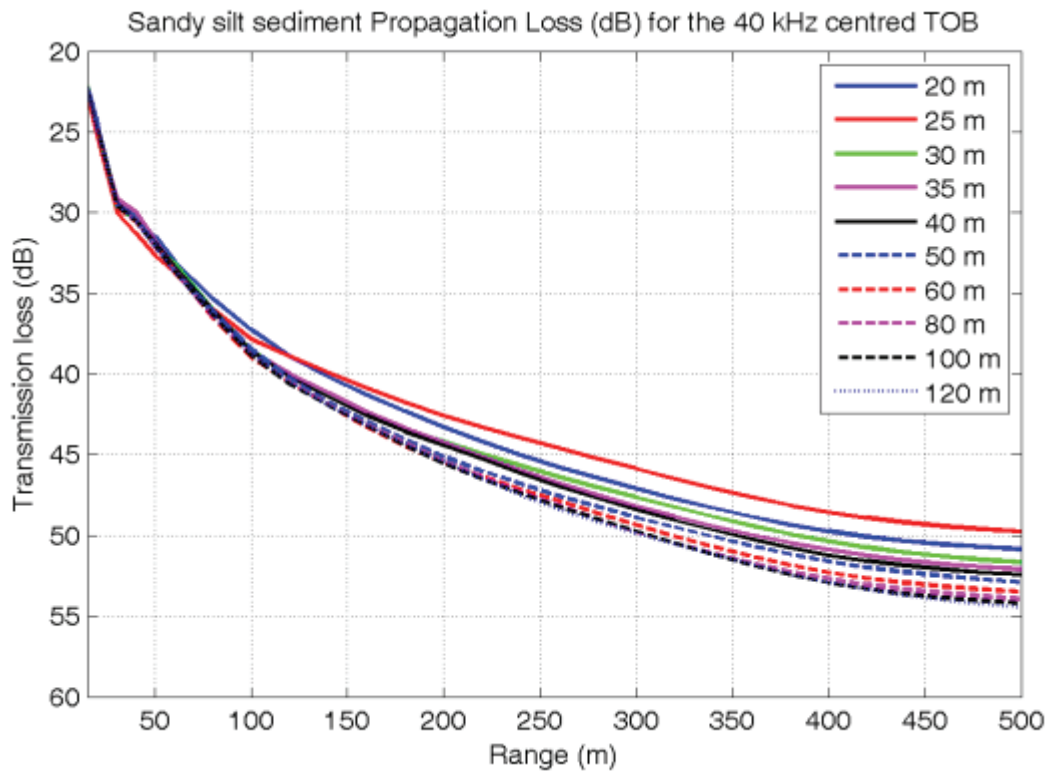
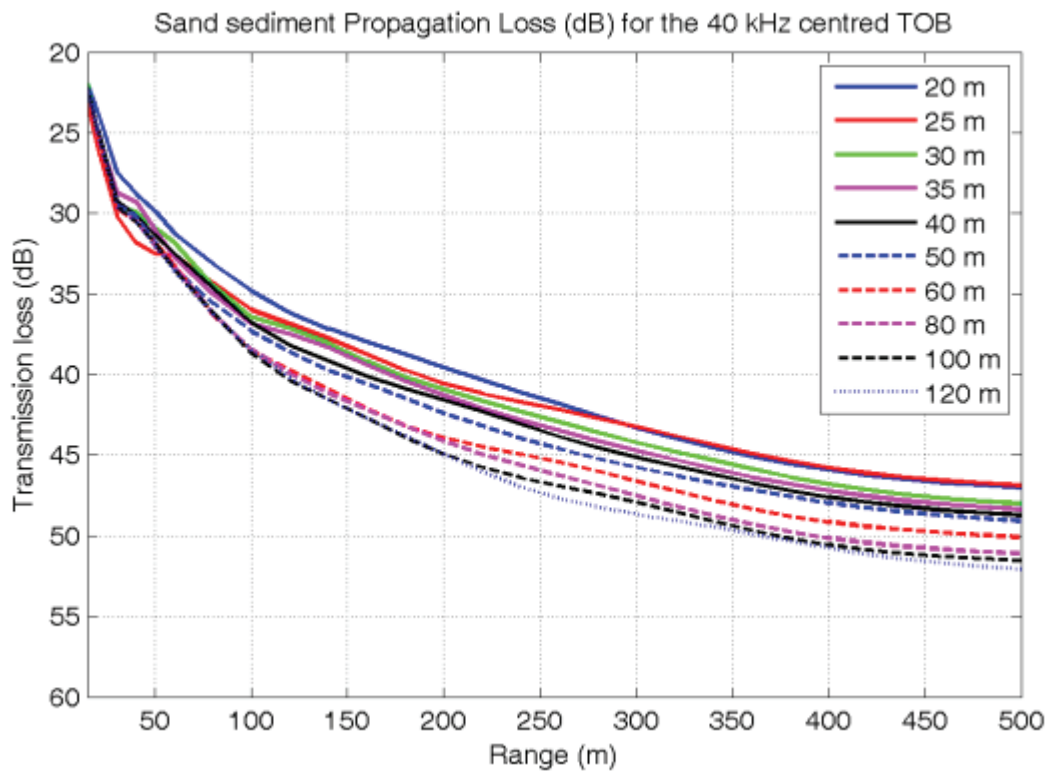


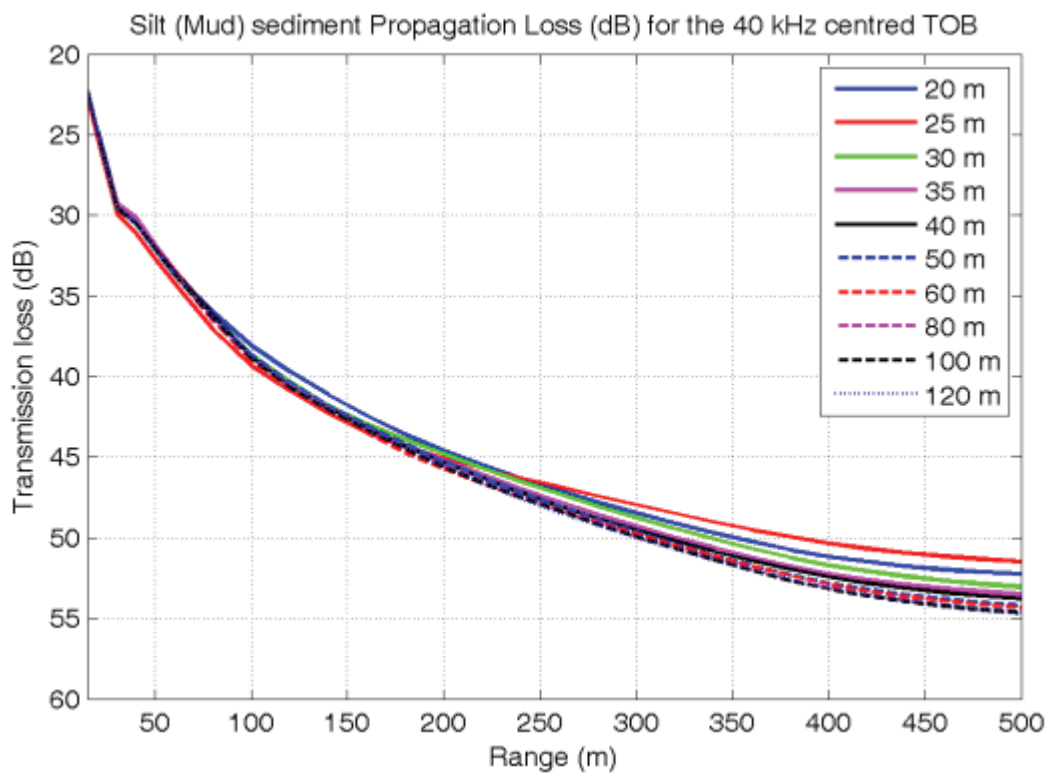
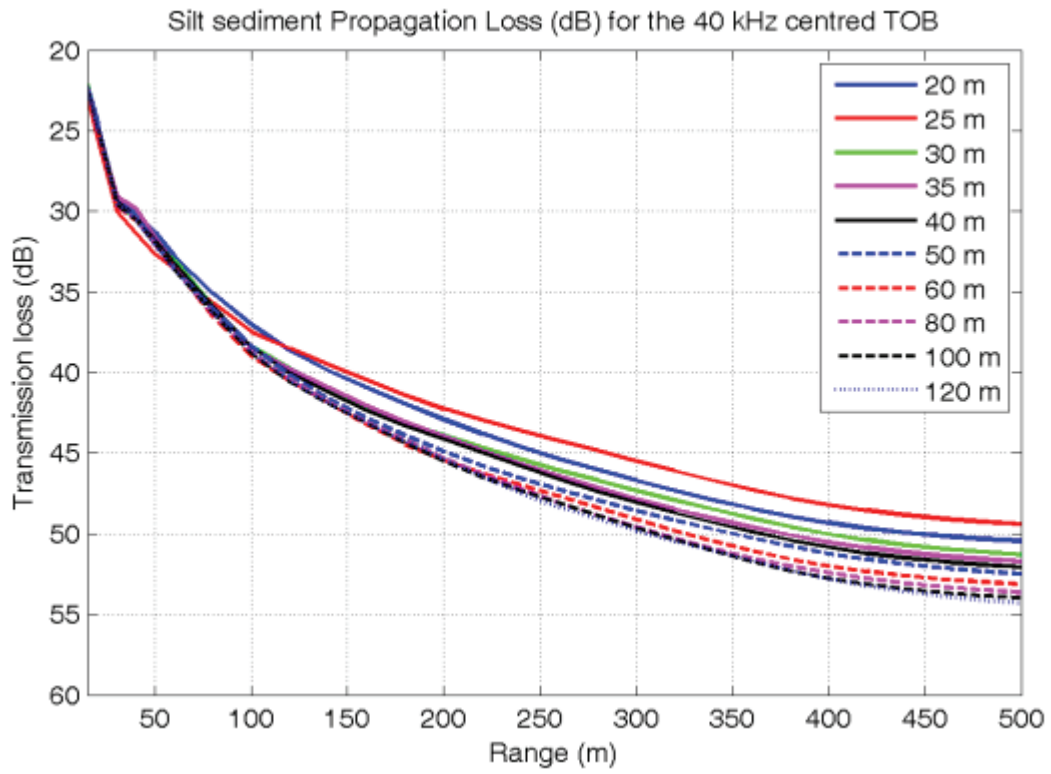
31.5 kHz





40 kHz





www.snh.gov.uk

© Scottish Natural Heritage 2014
ISBN: 978-1-85397-871-5

Policy and Advice Directorate, Great Glen House,
Leachkin Road, Inverness IV3 8NW
T: 01463 725000

You can download a copy of this publication from the SNH website.



Scottish Natural Heritage
Dualchas Nàdair na h-Alba

All of nature for all of Scotland
Nàdar air fad airson Alba air fad