SMRU Limited
Scottish Oceans Institute
New Technology Centre
North Haugh
ST ANDREWS
Fife KY16 9SR
www.smru.co.uk
http://soi.st-andrews.ac.uk/

FTOWDG SAFESIMM Noise Impact Assessment – Seals and Bottlenose dolphins (Neart na Gaoithe).

Authors: Carol Sparling, Catriona Harris, Carl Donovan and Lorenzo Milazzo

Date: **9th March 2012**

Report code: **SMRU-MRP-2012-004**

This report is to be cited as: *Sparling, Harris, Donovan, and Milazzo ,* **FTOWDG SAFESIMM Noise Impact Assessment – Seals and Bottlenose dolphins (Neart na Gaoithe).** *Report number SMRU-L-MRP-2012-004* to *Mainstream, March, 2012* (unpublished).

Lead Scientist: **Carol Sparling**

Project Manager: **Carol Sparling**

Scientific QA: **John Harwood/Gordon Hastie**

For its part, the Buyer acknowledges that Reports supplied by the Seller as part of the Services may be misleading if not read in their entirety, and can misrepresent the position if presented in selectively edited form. Accordingly, the Buyer undertakes that it will make use of Reports only in unedited form, and will use reasonable endeavours to procure that its client under the Main Contract does likewise. As a minimum, a full copy of our Report must be appended to the broader Report to the client.

Table of contents

List of figures

List of tables

Introduction

Pile driving during the construction of offshore wind turbines has the potential to produce levels of noise in the marine environment which may have a detrimental effect on marine animals. SMRU Ltd were contracted by the Forth and Tay Offshore Developers Group to assess the potential impacts of pile driving at multiple development sites on local marine mammal populations during the construction of wind farms in the region.

A detailed description of the potential effects of pile driving noise on marine mammals is out with the scope of this report; however we are concerned with two main types of impact. The first is auditory injury leading to a reduction in the hearing abilities of animals (permanent and temporary threshold shift) and the second is the elicitation of behavioural responses to sound which result in animals being displaced away from areas around the piling activities.

The assessment approach combines three key pieces of quantitative information to estimate the number of animals likely to be affected by each type of impact: 1) the predicted spatial pattern and extent of underwater noise produced by piling activities, 2) the spatial pattern of abundance of marine mammals across the area of potential impact, and 3) the way in which animals are predicted to move in response to sound.

This report presents the results of these modelling exercises for both species of seal (harbour seal and grey seal) and for bottlenose dolphins for 1) pile driving at the Neart Na Gaoithe site alone and 2) pile driving at the Neart Na Gaoithe site concurrent with pile driving at the Inch Cape site and Firth of Forth Round 3 sites.

1 Methodology

The SAFESIMM (Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna) algorithm is a software tool for estimating the potential effects of anthropogenic noise on marine fauna. SAFESIMM can also be used to compare the effectiveness of different strategies for mitigating the effects of anthropogenic sound by determining the risk associated with these strategies under a range of scenarios. For example, a proposed sound producing activity can be analysed with SAFESIMM to determine the likely effects of changes in operational parameters (such as the activity location and time of year, or the source level, frequency and duty cycle of the sound production) on the risk to marine mammals (please see Appendix One for full details of the algorithm).

1.1 Physical Effects:

The main physical effect on marine mammals that is likely to occur as a result of turbine construction is Permanent Threshold Shift (PTS). This involves a permanent impairment in hearing sensitivity at a particular frequency caused by exposure to excessive sound levels. There have been no direct experiments on marine mammals to determine what sound levels may cause PTS. Rather, these levels have been estimated by determining what sound levels are required to cause a temporary threshold shift (TTS) and then estimating what additional sound exposure would be required to cause PTS by inference from the results of experiments with small mammals. Southall *et al*. (2007)

used this approach to derive interim recommendations of the sound levels that could cause PTS in different groups of marine mammals. They also developed a series of weighting functions (M-weightings) that could be used to take account of the hearing sensitivities of four different marine mammal groups (low frequency cetaceans, mid-frequency cetaceans, high frequency cetaceans and pinnipeds). The authors recommend the following values for the onset of PTS based on M-weighted Sound Exposure Levels (SELs) for both pulsed (such as those produced during pile driving) and non-pulsed sounds (such as vessel noise or that produced during cable laying):

Cetaceans = Pulsed (198dB), Non-pulsed (215dB)
Pinnipeds = Pulsed (186dB), Non-pulsed (203dB)

They also recommended a similar set of values for the onset of TTS:

Cetaceans = Pulsed (183dB), Non-pulsed (195dB)
Pinnipeds = Pulsed (171dB), Non-pulsed (183dB)

However, exposure to SELs at or above these levels does not mean that an animal is certain to experience TTS or PTS, because the onset of threshold shift is a probabilistic phenomenon. The data from Finneran *et al.* (2005) that were used by Southall *et al*. (2007) to develop the TTS values for mid-frequency cetaceans indicate that ~18-19% of exposures to an SEL of 195 dB re 1 µPa^2.s^{-1} resulted in measurable TTS. SAFESIMM therefore uses a series of dose-response relationships derived from Finneran *et al.*'s work to determine the likely effect of sound exposure on the different marine mammal groups. These dose-response relationships are shown in Figure **1** Dose-response curves used within SAFESIMM to relate the probability of Temporary Threshold Shift (black curves) and Permanent Threshold Shift (red curves) to M-weighted Sound Exposure Level (SEL) for cetaceans and pinnipeds exposed to pulsed and non-pulsed sounds. In these relationships, the probability that an animal which is exposed to an SEL equivalent to the threshold values recommended by Southall *et al.* (2007) will experience PTS or TTS is set at 0.18, and that probability increases as the SEL increases.

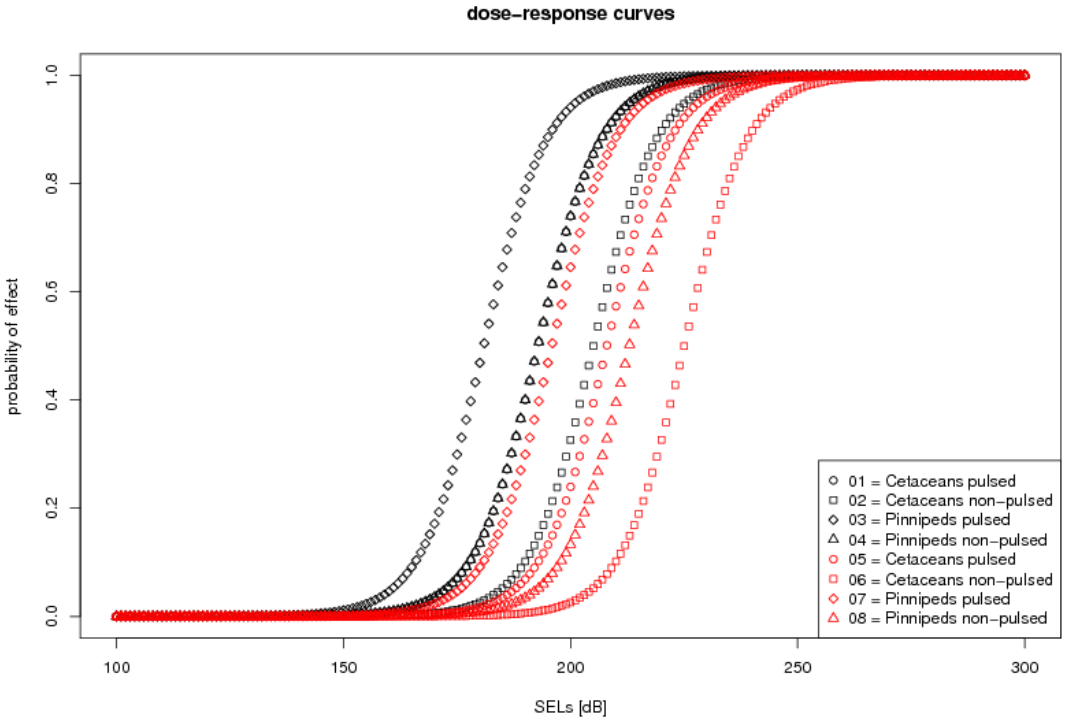

Figure 1 Dose-response curves used within SAFESIMM to relate the probability of Temporary Threshold Shift (black curves) and Permanent Threshold Shift (red curves) to M-weighted Sound Exposure Level (SEL) for cetaceans and pinnipeds exposed to pulsed and non-pulsed sounds.

SAFESIMM provides estimates of the number of animals of each species of marine mammal that may experience PTS and TTS from a particular sound field by simulating the three dimensional movements of thousands of simulated animals through this field, based on known characteristics of the diving and swimming behaviour of each species, and recording the cumulative SEL of each simulated individual. The species-specific PTS and TTS dose-response curves are then used to convert each individual's SEL into a probability that it will experience PTS or TTS. The initial locations of these simulated animals are chosen at random, although the density of simulated animals in any grid cell is proportional to the expected density provided by the animal density data. The actual number of animals predicted to experience PTS and TTS at individual locations is then calculated by scaling these simulated values using estimates of the expected densities of all marine mammal species at each location.

The density data for grey seals and harbour seals used in the simulations were provided by the Sea Mammal Research Unit at a resolution of 5km^2 (SMRU Ltd 2011: FTWODG seal baseline report)(Figure **2** and Figure **3**). This grid was converted into a 0.083 degree grid for incorporation into SAFESIMM. The density estimate for bottlenose dolphins was derived from Quick and Cheney (2011) and was applied over all 0.08 grid cells which overlapped with the areas surveyed. This resulted in a uniform density estimate of 0.35 dolphins/km^2 Figure 4).

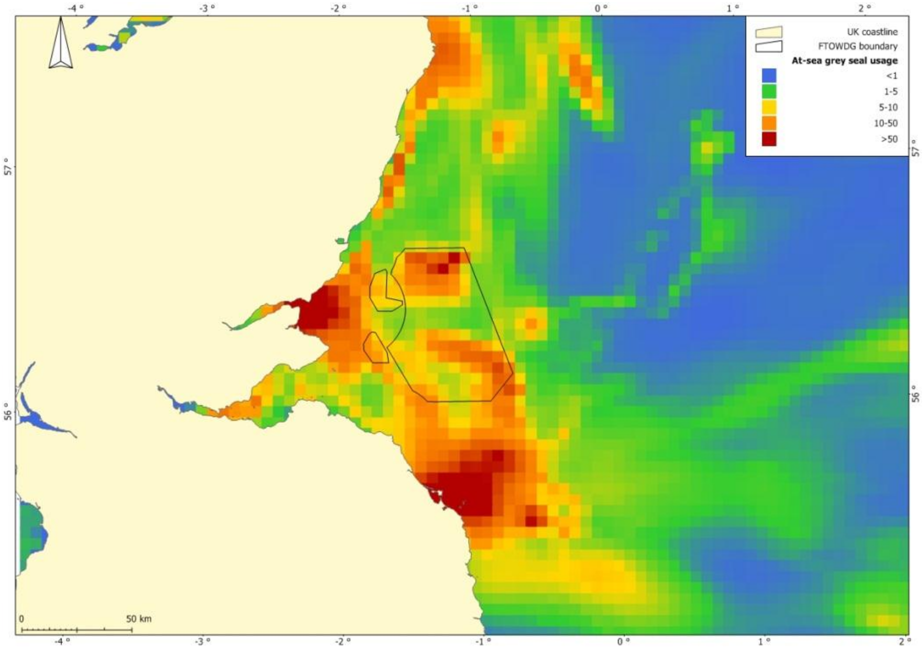

Figure 2. Grey seal density surface used in the simulations (from Sparling et al. 2011)

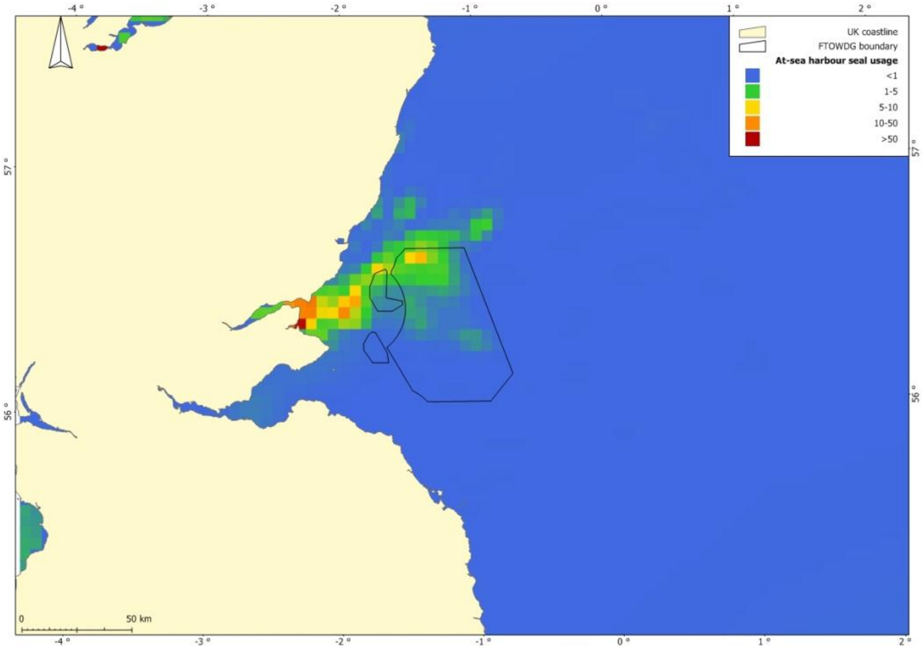

Figure 3. Harbour seal density surface used in the simulations (from Sparling et al. 2011)

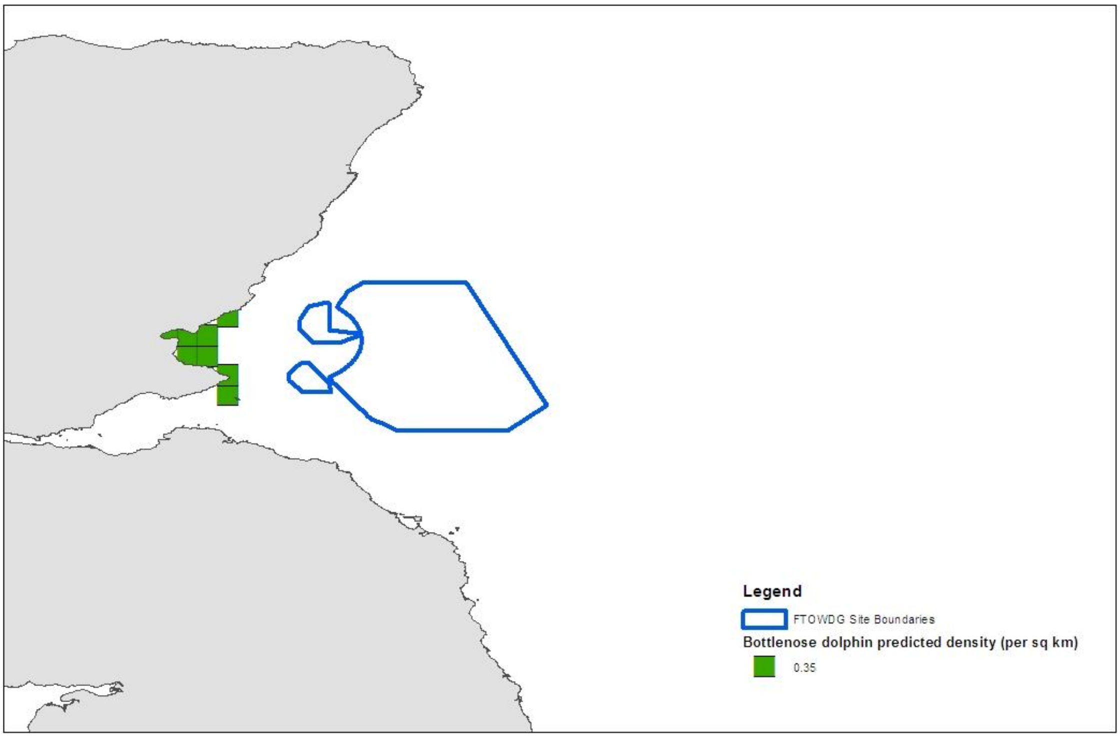

Figure 4. Bottlenose dolphin density surface used in the simulations (derived from Quick and Cheney, 2011).

1.2 Behavioural Effects:

SAFESIMM has the capability to simulate known behavioural responses of marine mammals to sound exposure. Incorporating behavioural responses where animals move away or towards the sound source provides not only another metric for assessment, but may also have an important bearing on the number of individuals predicted to experience physical injury. Unless otherwise specified, animals are predicted to follow a correlated random walk. However, they can be programmed to move towards or away from the sound source, both horizontally and/or vertically, if the received level of sound is above a given threshold. For the purposes of this assessment, an individual's movement in response to sound was determined probabilistically using a dose-response curve derived from data presented in work carried out by Paul Thompson and colleagues in the Moray Firth (Thompson et al.2011, Figure **1**) which predicts the proportional change in the occurrence of harbour porpoises with distance from a piling event and is based on data from changes in the detection rates during piling at the Horns Rev 2 wind farm from Brandt et al (2011). In the absence of empirical data for seals and bottlenose dolphins, this curve has been adopted in this assessment.

At each time step, the probability that each simulated individual will respond to the instantaneous M-weighted SEL experienced at its location is determined by this dose-response curve. The response simulated for both pinniped species is a movement away from the sound source in a directed manner (i.e. a flight response). The response simulated for both seal species and harbour bottlenose dolphins is a movement directly away from the sound source manner (i.e. a flight response). The speed at which grey seals and harbour seals move was determined from unpublished telemetry data collected in the FTOWDG region by SMRU. This gave a minimum speed of 0.01m.s^{-1} for both species and maximum speeds of 2.6m.s^{-1} for grey seals and 2.3m.s^{-1} for harbour seals. The minimum and maximum values of 0.01m.s^{-1} and 5.6m.s^{-1} for bottlenose dolphins were obtained from an extensive literature search.

The total numbers of individuals that respond in this way over the course of the scenario is documented by SAFESIMM and provided as an output. This metric doesn't tell us anything about how many times each individual responds throughout the simulation, or how far they move away, or how long they stay away for - this metric simply counts the number of animals that at least once throughout the simulation received a sound dose high enough to swim away from the sound. Any predicted behavioural responses need to be carefully interpreted in light of the likely spatial and temporal variation in abundance and likely motivation for being in a given area.

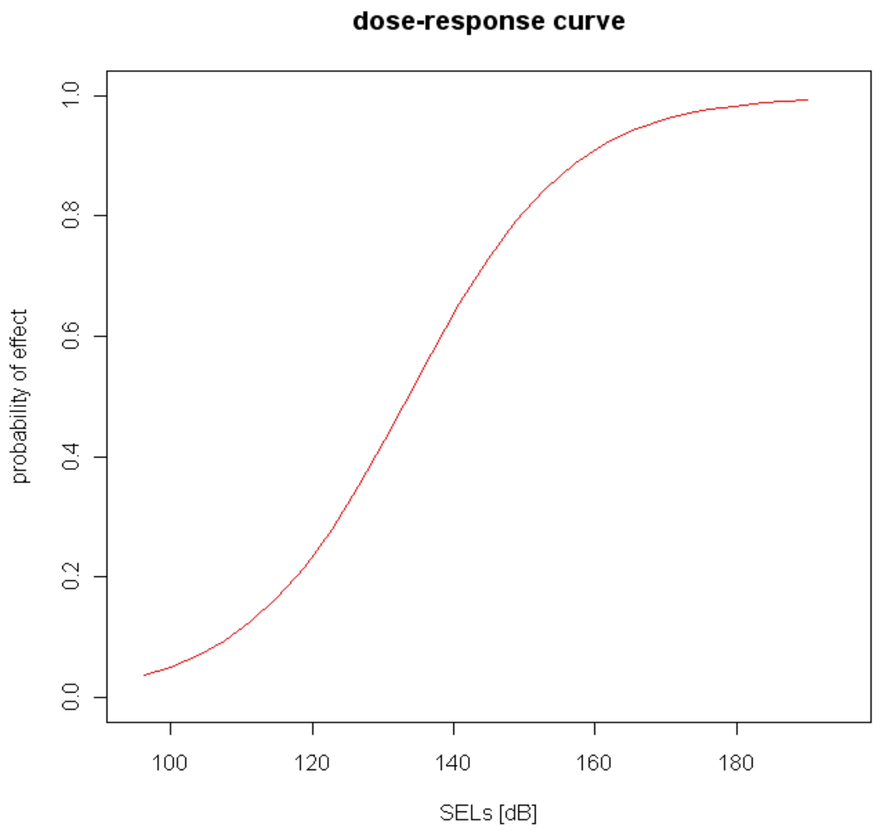

Figure 5. Dose-response curves used within SAFESIMM to relate the probability of behavioural displacement to M-weighted Sound Exposure Level (SEL) for cetaceans and pinnipeds exposed to pile driving noise.

1.3 Parameters modelled

Subacoustech provided SMRU Ltd with the outputs of sound propagation models for each pile driving scenario in the format of a calculated SEL for a single hammer blow (of 0.5 sec duration) for each blow energy used during the piling event on 96 transects radiating from the source location (3.75° apart). The predicted SEL was provided at steps of 100m along each transect. SAFESIMM then carried out a simulation of animal exposure over the whole piling duration using parameters for duration and strike rate provided by individual developers (Appendix Two). Where ramp ups were included in the engineering scenarios, Subacoustech provided a separate sound field for each different blow force – SAFESIMM cycled through these in accordance with the duration of each step in the ramp up. The details of the engineering scenarios and piling locations can be found in Appendix Two and summarised in Table **1**. There are uncertainties regarding the behaviour of animals during breaks in piling, therefore in order to explore the impact of including a long drilling period between two periods of piling, we ran two versions of Scenario 1, one with the drilling included (Scenario 1) and one where the simulation consisted of both driving periods running consecutively with no break (Scenario 1a). The predicted sound from the drilling operation was calculated from the following equations provided by Subacoustech. Their SPEAR model estimates the approximate levels of drilling noise at different ranges using simple SL – N log r equations that have been derived from measured data.

These levels were calculated for typical drilling operations at any range using the following equations (where r is the range):

Mid Frequency Cetaceans (Bottlenose dolphin)	$167.8 - 15 \log_{10} r$
High Frequency Cetaceans (harbour porpoise)	$165.8 - 15 \log_{10} r$
Pinnipeds (in water)	$167.8 - 15 \log_{10} r$

Table 1. Summary of scenarios assessed

Scenario	Site(s) and Location	Description
Scenario 1	NNG Loc 5	Drive-drill-drive
Scenario 1a	NNG Loc 5	Drive only
Scenario 2	NNG Loc 5 & 6	Drive-drill-drive
Scenario 3	NNG Loc 5	Drive-drill-drive
	IC Loc 4	Drive only
	FoF Loc 1	Drive only

2 Results and discussion

2.1 Neart na Gaoithe site only:

2.1.1 Scenario 1 – Single piling event at one location

Under Scenario 1 the absolute number of grey seals predicted to experience injury (PTS) and behavioural disturbance was greater than the number of harbour seals predicted to experience the same level of injury and disturbance (Table 2**Error! Reference source not found.**). This was a consequence of the much larger numbers of grey seals predicted to be present in the area. This is the case for all scenarios.

If we consider the numbers as a proportion of the at-sea population in the area of calculation (AOC) then the proportion of the harbour seal population that was affected was much larger than that of the grey seal (e.g. proportion of grey seal AOC population experiencing PTS under scenario 1 = 0.0054, proportion of harbour seal AOC population experiencing PTS under scenario 1 = 0.012). Similarly, the proportion of harbour seals responding behaviourally throughout the simulation was higher than grey seals, although the absolute numbers of animals affected were lower. This applies to all metrics and across all scenarios. No bottlenose dolphins were predicted to experience PTS; however, 6 individuals predicted to experience TTS. A total of 124 bottlenose dolphins were predicted to exhibit behavioural responses by moving away from the noise at least once during the simulated exposure.

Spatially, the highest numbers of affected seals (PTS) were in areas close to the coast, at the mouth of the Tay and Eden Estuary (Figure 6). This is likely to be a result of a combination of factors; particularly high usage in these areas (Figure 2 and Figure 3) and fleeing animals being constrained by the coast. Seals do have the option of hauling out here and thus preventing any further exposure to underwater noise (although this is mainly restricted to periods of low tide when the sandbanks are visible), however haul out cannot currently be incorporated into the simulations so these predictions may be slightly precautionary as a result.

Table 2. The number of grey seals, harbour seals and bottlenose dolphins predicted to experience physical (PTS and TTS) and behavioural effects as a result of two consecutive piling events with 19.5 hours of drilling between them at a single location at Neart na Gaoithe (Scenario 1). The abundance of animals predicted to be at-sea within the area of calculation (see Figure 6) is 9,196 grey seals and 335 harbour seals

Species	TTS	PTS	Behaviour
Grey seal	635	50	5,483
Harbour seal	57	4	314
Bottlenose dolphin	6	0	124

2.1.2 Scenario 1 vs 1a: drive-drill-drive vs drive only

Simulation of the drive–only scenario resulted in much fewer animals experiencing TTS and PTS compared to the drive-drill-drive scenario (Table 3). Approximately half the number of seals experienced TTS and PTS compared to the drive-drill-drive scenario and the number of seals responding behaviourally was between 10 and 20% lower. The reduction in numbers of seals responding behaviourally was smaller and was less than 10% lower under Scenario 1a than under Scenario 1. Only 1 bottlenose dolphin was predicted to experience TTS under the drive only scenario, compared to 6 under the drive-drill-drive scenario. 116 dolphins were predicted to respond under the drive only scenario compared to 124 under the drive-drill-drive scenario.

The difference in predicted impact between the two scenarios is most likely a result of animals no longer responding behaviourally once the drilling has commenced after the first driving period. Drilling is much quieter than piling, and noise levels drop below those predicted to elicit behavioural responses. Therefore during the extensive drilling period, simulated animals receive a sound dose below the threshold for a behavioural response and so start to come back into the area in order to be re-exposed to the 2nd piling period. We have to assume no recovery in sound exposure in the interim between driving periods; therefore individuals are predicted to receive a much higher dose of sound overall and are therefore more likely to develop PTS. We have very little information with which to assess how realistic this is. There are few studies which describe how quickly animals return to an area that they have been displaced from as a result of noise, although there is some evidence from sonar behavioural studies on beaked whales to suggest animals move into an area relatively quickly once sonar operations stop. Brandt et al (2011) found that porpoise activity was absent for the first hour after pile driving, thereafter increasing, although activity remained lower than normal for 24-72 hours after pile driving. It is likely that a proportion of animals return but overall density may remain lower than the starting density. Therefore it is inappropriate to assume that all animals keep fleeing during the drilling period, but it is similarly inappropriate to assume that all animals will start moving back in immediately after pile driving, during the drilling.

Furthermore, there is little data to assess how breaks in sound exposure over this timescale affect the relationship between cumulative sound dose and onset of injury – therefore this assessment is likely to be somewhat precautionary and true impact may be intermediate between the two sets of predictions. We have not carried out this comparison for the other scenarios as this was outside the original scope for this work. However it is reasonable to assume that the magnitude of the difference may be similar between drive-drill-drive and drive only scenarios when these operations are being carried out at more than one location sites.

Table 3. Number of grey seals, harbour seals and bottlenose dolphins predicted to experience physical (PTS and TTS) and behavioural effects as a result of two consecutive piling events with no drilling at a single location at Neart na Gaoithe. The abundance of animals predicted to be at-sea within the area of calculation (see map) is 9,196 grey seals and 335 harbour seals.

Species	TTS	PTS	Behaviour
Grey seal	347	22	4,404
Harbour seal	26	2	283
Bottlenose dolphin	1	0	126

2.1.3 Piling simultaneously at two locations at NNG (Scenario 2)

For both species of seal, the number of animals predicted to experience PTS under Scenario 2 was approximately 10-20% greater than the numbers predicted under Scenario 1 (Table 4). The difference between the two scenarios in terms of the numbers of animals predicted to experience behavioural disturbance was substantially less, with a high proportion of animals being disturbed even under the single location scenario. For harbour seals the percentage of the AOC population predicted to be behaviourally disturbed was 94% under both scenarios. Proportionally there was less disturbance of the grey seal AOC population, with 60% being disturbed under the single location scenario, and 65% under the 2 location scenario. For both grey seals and harbour seals the spatial extent where animals were predicted to experience PTS was greater under the 2 concurrent piling events at NNG than the single piling event at NNG, with higher absolute numbers in each grid cell under the 2 piling event scenario (Figure 6). For bottlenose dolphins, the results were identical regardless of whether piling was occurring at one location or at two locations simultaneously. This is likely to be because although higher numbers occurred in each grid cell under the two-piling event scenario, the numbers were still generally below 1 in each cell (Figure 6).

Table 4. Number of grey seals, harbour seals and bottlenose dolphins predicted to experience physical (PTS and TTS) and behavioural effects as a result of two simultaneous pile-drill-drive events at two locations at Neart na Gaoithe (**Scenario 2**). The abundance of animals predicted to be at-sea within the area of calculation is 9196 grey seals and 335 harbour seals.

Species	TTS	PTS	Behaviour
Grey seal	786	62	5939
Harbour seal	62	5	313
Bottlenose dolphin	6	0	124

Figure 6. The number of animals predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for Scenario 1, single location (left hand panels) and Scenario 2, piling at two locations simultaneously (right hand panels), for both harbour seals (top panels) and grey seals (middle panels) and bottlenose dolphins (bottom panels). Note that the scale differs between species.

The differences in behavioural responses between the various scenarios was much less pronounced than those for injury metrics, this is because behaviour (the probability of response) is much more closely linked to the absolute loudness than the cumulative nature of exposure over time, and absolute loudness was more similar between the different scenarios. Therefore an increase in the number of piling events will increase cumulative noise dose (and therefore the probability of injury) more than it will increase the number of animals responding behaviourally. Furthermore the spatial range of bottlenose dolphins in the simulations is small relative to the area affected by noise and an increase in the number of piling events does not appreciably increase the degree of overlap. The predicted noise levels in the coastal zone are above behavioural thresholds over much of the predicted range of bottlenose dolphin occurrence regardless of the scenario so the number of animals responding at least once does not differ much between scenarios. However it must be noted that the number of animals responding at least once does not reflect the exact nature of the behavioural response, and cannot be used to say anything about how far animals may be displaced, how long for, or what the consequences of this response may be for the population in the long term. The metric is presented here to provide a basic assessment of the scale of the response and how it might differ under different scenarios. Assessment of the long term population response nature will require much more detailed information on the spatial and temporal variability in behavioural response and a number of assumptions regarding how individual impacts may manifest on population dynamics. Such an assessment is outwith the scope of this current work although progress is currently being made on these issues on a number of current projects.

Overall the difference between a single piling event and two simultaneous piling events at the same site are relatively small compared to the differences between scenario 1 and 1a. This is because the spatial overlap between scenario 1 and 2 is high and very little ‘additional’ exposure results and temporally they are identical.

2.2 Cumulative Scenario - Single piling event at Neart na Gaoithe, concurrent piling at one location at Inch Cape and one location at Firth of Forth (Scenario 3).

Unsurprisingly, for both species of seal the extent of the spatial footprint of the cumulative scenario was greater than all individual site scenarios (**Error! Reference source not found.**). This was not the ase for bottlenose dolphins, because the entire range of the bottlenose dolphin was affected in all scenarios. It is probable that bottlenose dolphins are found outside of this mapped range but we currently have no data with which to quantify this, thus the simulations are restricted to this density estimate over this spatial scale.

For both species of seal, the numbers predicted to experience PTS under the cumulative scenario (Scenario 3) are approximately 50-60% greater than the numbers predicted under the NNG only scenario (Scenario 1) (Table 5). As was the case with the comparison between Scenario 1 and Scenario 2, the difference between the two scenarios in terms of the numbers of animals predicted to experience behavioural disturbance is substantially less than the difference in injury metrics, with a high proportion of animals responding under all scenarios. The reasons for this are similar to the reasons explained above, that the behavioural response is more closely linked to the absolute loudness of the noise rather than the temporal component, although numbers are larger due to the increase in the spatial overlap. In fact because the cumulative simulations cover a larger area, the abundance of seals within the area of calculation is higher, resulting in a lower proportion of the population responding. This is a result of how the simulations are set up with the spatial limits of each simulation set by the spatial area of the sound field supplied by Subacoustech. While these are appropriate for calculating the numbers of animals affected by each piling event (because impacts are not expected out with the spatial extent of the sound field used) the abundance in the area of calculation for each single simulation may not be the most appropriate reference value for comparing impacts proportionally. It may be more appropriate to use the largest AOC i.e. that of the cumulative scenario – this will give a more realistic indication of the number of animals 'available' to be impacted during each event (Table **6**. Summary of predicted impacts on all species, expressed as a percentage of the at-sea abundance in the maximum area of calculation from the cumulative assessment (AOC$_{max}$).).

Table 5. Number of grey seals, harbour seals and bottlenose dolphins predicted to experience physical (PTS and TTS) and behavioural effects as a result of two simultaneous pile-drill-drive events at two locations at Neart na Gaoithe (**Scenario 2**). The abundance of animals predicted to be at-sea within the area of calculation (see map) is 11,263 grey seals and 403 harbour seals.

Species	TTS	PTS	Behaviour
Grey seal	993	83	6,163
Harbour seal	96	9	305
Bottlenose dolphin	6	0	124

Table 6. Summary of predicted impacts on all species, expressed as a percentage of the at-sea abundance in the maximum area of calculation from the cumulative assessment (AOC$_{max}$). Unless otherwise specified, the NNG paramaters were drive-drill-drive

Scenario No.	site/parameters	sp	TTS	%AOC$_{max}$	PTS	%AOC$_{max}$	behav	%AOC$_{max}$
1	NNG loc5	grey	635	6%	50	0%	5483	49%
1	NNG loc5	harbour	57	14%	4	1%	314	78%
1a	NNG loc5 drive only	grey	347	3%	22	0%	4404	39%
1a	NNG loc5 drive only	harbour	26	7%	2	0%	283	70%
2	NNG loc5&loc6	grey	786	7%	62	1%	5939	53%
2	NNG loc5&loc6	harbour	62	15%	5	1%	313	78%
3	NNG loc5, IC&FoF	grey	993	9%	83	1%	6163	55%
3	NNG loc5, IC&FoF	harbour	96	24%	9	2%	305	76%
1	NNG loc5	BND	6	5%	0	0%	124	98%
1a	NNG loc5 drive only	BND	1	1%	0	0%	116	92%
2	NNG loc5&loc6	BND	6	5%	0	0%	124	98%
3	NNG loc5, IC&FoF	BND	6	5%	0	0%	124	98%

3 Summary and conclusions

Low numbers of marine mammals were predicted to develop PTS, as a result of the scenarios simulated. No bottlenose dolphins were predicted to develop PTS under any of the simulations. Relatively high numbers of animals were predicted to exhibit behavioural responses and it is likely that this may be a key concern and a focus for the design of appropriate mitigation.

Inclusion of a period of drilling in between two pile driving periods results in higher predicted impacts because animals are predicted to move back in between the two driving periods, thereby increasing overall exposure.

Increasing the number of locations of simultaneous piling events results in higher predicted impacts, although the spatial scale at which concurrent operations occur is important; there was a relatively small increase in impact with two locations at the one site (scenario 1 compared to 2). Although we do not have a scenario with two piling events at different sites for comparison, this suggests that the temporal nature of the piling may be more important than the number of individual events as long as the degree of spatial overlap can be minimised. This has implications for the consideration of cumulative impact and simultaneous piling within and between different sites, simulations should be carried out to explore the optimal balance of temporal and spatial overlap in piling to minimise overall impact.

In absolute terms, more grey seals were predicted to be affected than harbour seals. This is as a result of an overall higher abundance of grey seals in the region and when expressed as a proportion of total abundance, the impacts on harbour seals were much higher.

Injury metrics were more sensitive than behavioural responses to changes in scenario parameters such as the number of locations, different engineering parameters. Although both scale in the directions one would expect although there is a degree of variability due to stochasticity in animal responses and the probabilistic nature of the responses.

These predictions rely on a number of assumptions about the response of animals to noise, some of which have limited empirical basis, particularly for the species being assessed here. A full examination of the sensitivity of the results of these simulations to variations in the assumptions adopted is beyond the scope of this work but the biggest uncertainties probably relate to the nature and extent of species-specific behavioural responses to piling noise and the onset of auditory injury in marine mammals in relation to the specific temporal nature of exposure to piling.

Nevertheless these results represent the application of the best available information on these factors, along with the best available estimates of spatial variation in animal distribution in the region to produce the most robust estimates possible of the impact of pile driving in the FTOWDG region.

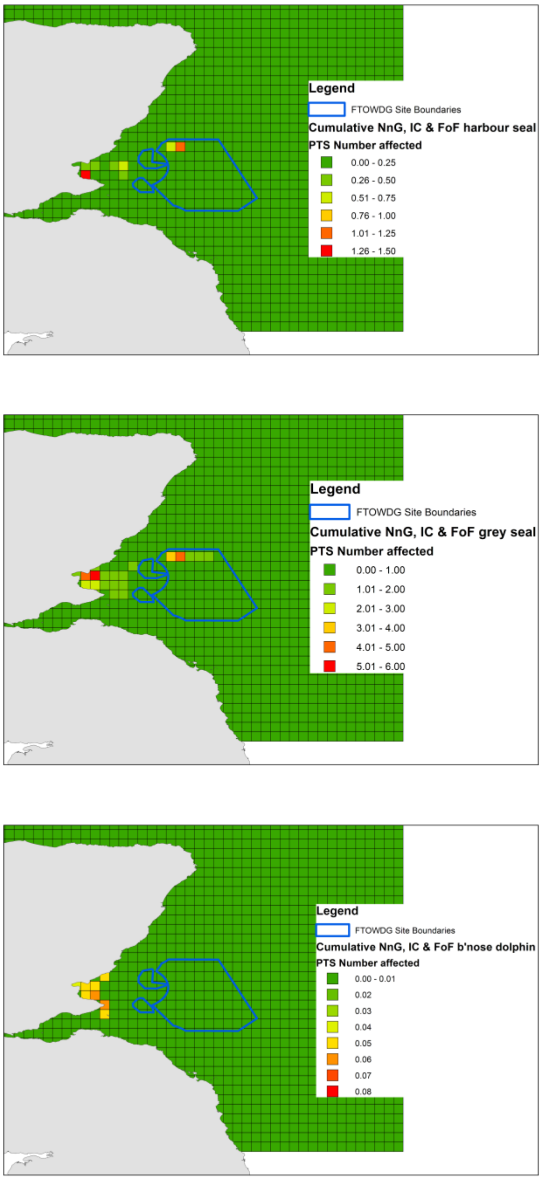

Figure 7. The number of animals predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for Scenario 3, piling at NNG, IC and FoF simultaneously, for harbour seals (top panels) and grey seals (middle panels) and bottlenose dolphins (bottom panels). Note that the scale differs between species.

4 References

Brandt, M.J., A. Diederichs, K. Betke, and G. Nehls. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series 421:205-216.

Finneran, J.J., Carder, D.A., Schlundt, C.E. & Ridgeway, S.H. (2005). Temporary threshold shift in bottlenose dolphin (*Tursiops truncatus*) exposed to mid-frequency tones. Journal of the Acoustical Society of America. 118: 2696-2705.

Thompson, P.M., Hastie, G.D., Nedwell, J., Barham, R., Brooker, A. Brookes, K., Cordes, L., Bailey, H. and McLean, N. (2011). Proposed framework for assessing the impacts of offshore windfarms on protected harbour seal populations. A report commissioned by the Moray Firth Offshore Windfarm Developers.

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C.J., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W., Thomas, J., & Tyack, P. (2007a) Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals 33: 411-521.

I. Appendix One

Donovan et al. Quantifying the effects of anthropogenic sound on marine mammals.
Draft: Please do not cite or quote without prior reference to the authors

A simulation-based method for quantifying and mitigating the effects of anthropogenic sound on marine mammals

Donovan, C. R., Harris, C.M., & Harwood, J.

Centre for Research into Ecological and Environmental Modelling

and Sea Mammal Research Unit, University of St Andrews.

Abstract

The SAFESIMM (Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna) algorithm is a software tool for estimating the potential effects of anthropogenic noise on marine animals. SAFESIMM can also be used to compare the effectiveness of different strategies for mitigating the effects of anthropogenic sound by determining the risk associated with these strategies under a range of scenarios. For example, a proposed sound producing activity can be analysed with SAFESIMM to determine the likely effects of changes in operational parameters (such

as the activity location and time of year, or the source level, frequency and duty cycle of the sound production) on the risk to marine mammals.

Introduction

SAFESIMM is a simulation-based framework for calculating the probable numbers of animals affected by underwater sound; for example active sonar, which has been implicated in recent marine mammal fatalities (Parsons et. al. 2008). SAFESIMM is the culmination of a large, multi-year collaborative project between BAE Systems and the University of St Andrews, specifically the Centre for Research into Ecological and Environmental Modelling (CREEM) and the Sea Mammal Research Unit (SMRU).

The project draws together, into a software tool, results from the latest research on the effects of sound on marine mammals, and data on the distribution, abundance and hearing characteristics of these species. The end result is a simulation-based statistical model that quantifies the probability of physical effects and behavioural responses, along with the expected numbers of occurrences and associated uncertainty in the predictions. The parameters used in each simulation are easily altered, allowing rapid comparison of alternative scenarios.

SAFESIMM is modularized and designed to allow easy modification, in anticipation of the rapid progress being made in this research area. In most situations, new research can be incorporated simply by modifying parameter values or information held in internal databases. More fundamental shifts in our understanding can be incorporated by replacing existing modules with improved versions.

This paper describes:

1. The problem in general terms;
2. The logical high-level solution;
3. The principal questions that must be addressed,
4. The solutions to these based on current knowledge;
5. The framework (SAFESIMM) that combines these.

The problem

The over-arching question is simple: what is the likely effect on marine animals of any activity that involves the generation of relatively large amounts of underwater noise? It is clear from the outset that the answer must be probabilistic due to the inherent uncertainties. For example, the location of all animals relative to the source will never be known with certainty.

The problem is more approachable if it is divided into a series of smaller questions that can be addressed in turn:

1. What is the distribution of the sound source's energy through space and time?
2. What sound exposure histories are likely to be experienced by the different components of the marine fauna?
3. What is the likely effect on this fauna of a given history of sound exposure?

So far, most of the research in this area has focussed on one component of the marine fauna (marine mammals, and particularly cetaceans), because they are perceived (at least by the public) to be the most vulnerable to anthropogenic sound. We have followed this example in SAFESIMM, and the rest of this paper deals primarily with evaluating the potential impacts of such sounds on marine mammals.

The distribution of sound from the anthropogenic source

The underwater propagation characteristics for many anthropogenic sound sources are well known. Indeed, the effectiveness of active sonar depends on knowing how the emissions travel through the aquatic environment. More generally, there are established physics principles governing the transmission of sound waves through water that can be used to model propagation-loss under a particular set of physical conditions (e.g. source spectra, bathymetry, water column temperature profiles, sediment types etc.).

The output from such a two or three-dimensional propagation-loss model can be used to predict the received sound-level, and history of sound exposure, at any point in space and time in the ocean, provided the important oceanographic features and source characteristics are known.

The distribution of animals within the sound field

Although it may be possible to determine the precise locations of individual animals that are detected and tracked, the specific locations of the vast majority of animals within the sound field will never be known. This is, to a large extent because of the limited availability of animals for detection (e.g. at the surface for a visual observer, or vocalising if passive acoustic detection is being used) and the relatively low probability that animals will be detected even if they are available (e.g. animals far from the observer/detector are likely to be overlooked).

However, extensive information is available about the distribution of marine animals, both horizontally and vertically, from surveys and statistical models. Published survey results can be used to identify regions of high or low densities for many species. Similarly, species distribution maps can be constructed using information such as presence/absence, density and habitat preference (Kaschner et. al. 2006, Costello et. al. 2007). Detailed studies of the diving behaviour of marine mammals also provide information about their depth distributions. This can be at a coarse level (such as maximum dive depth and preferred depths) or fine scale (distribution at depth from models of dive patterns or animal tag data). Collectively, this information can be used to predict the distribution of most marine mammals species in three-dimensions, and these models can be used to provide probabilistic predictions for a given area and time.

The likely sound exposure of these animals can be derived from the history of sound exposure for a hypothetical animal as it moves through the sound field. The distribution model described above can be used to provide probable starting points for these hypothetical animals. Then a suitable movement model can be used to provide species-specific sound-exposure histories. These movement models can be parameterised from detailed studies of the behaviour of individual animals fitted with various kinds of telemetry devices. For example, we can use the distribution of swim speeds and dive depths of these animals, with constrained random components to reflect the uncertainties in actual movement.

The range of probable sound-exposure histories for all of the individuals likely to be exposed to the predicted sound field can therefore be found by repeated computer simulations using the species distribution information and movement model. Each simulated animal represents a possible reality of sound exposures. Hence it is possible to calculate probable exposures for all animals, even though their precise locations are unknown.

The effect of sound exposure history

Sound exposure histories form the basis of Health and Safety regulation for humans and elements of this approach can be used to answer similar questions for marine mammals. In terms of physical effects, the most important factor is the accumulated amount of sound energy the subject has been, or is likely to be, exposed to.

For humans, accumulated sound energy is calculated as a function of the received levels through time. These are typically weighted, to give a single numeric measure called the personal exposure level for the period exposed. The weighting assigns less importance to sounds at frequencies to which the human ear is least sensitive. Similar calculations can be performed for marine mammal sound exposure histories, with the weighting provided by a measured or assumed profile of hearing sensitivity. Southall et al (2007b) provide a set of such weightings for different groups of marine mammals.

In the human case, the accumulated sound exposure can be compared to threshold levels which delineate safe and unsafe histories of sound exposure. In general this is based on dose-response curves that predict the probability of a particular response given a particular sound exposure history.

For human hearing, the most commonly used responses are temporary and permanent deafness (defined as an unacceptably large upward shift in the threshold for hearing) at particular frequencies.

Dose-response curves, relating sound exposure to the probability of physical effects, have been estimated for some marine mammals through captive studies (e.g. Finneran et. al. 2005, Kastak et. al. 2005).

A general framework for estimating the probable effects of anthropogenic sound

The information discussed above can be combined to estimate the probabilities of any individual marine mammal exhibiting physical effects from sound exposure, and hence the actual numbers that might be affected. The uncertainties associated with these calculations can also be quantified to provide information on the confidence associated with the individual estimates.

Put simply, the sound field produced by the source is simulated, as are the animals that might potentially be affected by it. These simulated animals sample the sound field through time in a realistic way and their sound exposure histories can be used to estimate the probability that they will suffer hearing problems. The simulation process is repeated a large number of times to reflect the uncertainty in the modelled system.

SAFESIMM

SAFESIMM implements the approach described above in such a way that it can be used to simulate the effects of anthropogenic sound in the marine environment anywhere in the world’s oceans. It includes a collection of global distribution maps for 115 marine mammal species; a database of information on hearing capabilities, diving and swimming behaviour, reactions to sound and conservation status for each species; parameter sets that define hearing sensitivities and dose response curves; and simulation routines. SAFESIMM can be used with any model providing propagation loss information.

The core code for SAFESIMM is written in the statistical programming environment R (R Core Development Team, 2008). The broad functioning is shown in Figure 8, the module descriptions that follow relate to this flow diagram.

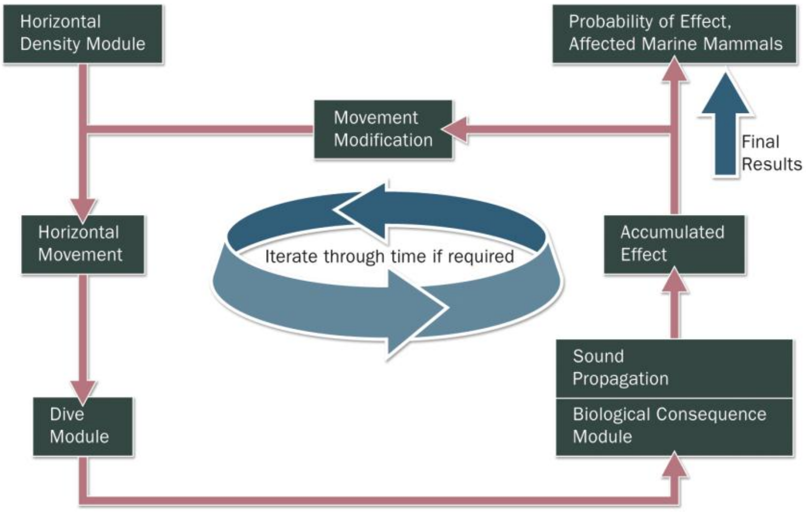

Figure 8: Broad overview of the modular nature of SAFESIMM

The *Horizontal Density Module* determines the horizontal distribution of animals that initializes the simulation process. Currently the data underlying this are species density maps provided as part of the UK Hydrographic Office's Integrated Water Column product but these data can readily be replaced with other density data where available. These are derived from the Relative Environmental Suitability models of Kaschner et. al. (2006), calibrated using published survey data for each species. The data is stored at 0.5°-grid cell resolution and gives both a density estimate and uncertainty measure for all 115 marine mammal species. In the case of 46 species, separate estimates are available for different quarters of the year.   Fig. 2 shows the predicted mean densities for Sperm Whales (*Physeter macrocephalus*) about the Hawaiian Islands.

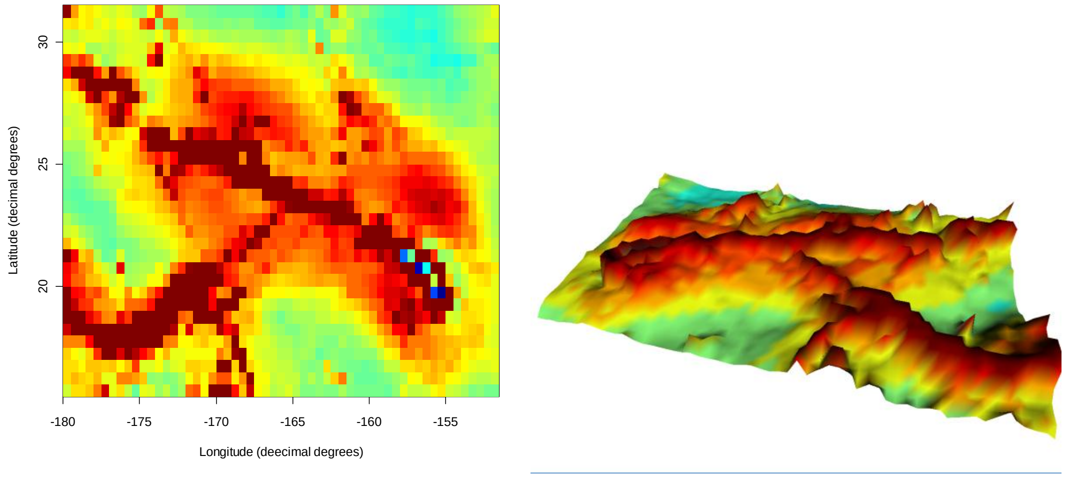

Figure 9: Density maps for sperm whales around the Hawaiian Islands, based on the RES models of Kaschner et. al. (2006) and calibrated against survey data.

The *Horizontal Movement, Dive* and *Movement Modification Modules* determine the movement of the simulated animals. The horizontal and dive movements are based on parameters from an internal database, which was populated from an extensive literature review. For example, specific parameters determine the depth of dives and speed of movement of each species.

The *Movement Modification Module* controls how the animals respond to the received sounds. Although such behaviour may be quite complex, current information on responses is limited, and so the modelled responses are limited to: movement away from the sound source, movement towards the sound source, a cessation of diving, and no response.

The movement of thousands of simulated animals and dozens of species are tracked at 1-minute intervals within the simulation, with received sound levels recorded at each step by reference to the sound field provided by the *Sound Propagation Module*.

At the end of the simulation process, the sound histories for the simulated animals are summarized by their Sound Exposure Levels (SELs). The *Biological Consequence Module* then uses information from the internal databases to determine the probability that this SEL will result in a Temporary Threshold Shift (TTS) in hearing or a Permanent Threshold Shift (PTS) based on the thresholds recommended by Southall et al. (2007). The current summary outputs are the probability, by species, that any animal will suffer PTS and the expected number of animals, also by species, that may are expected to suffer TTS. These values can also be displayed across all species. This information can be summarised for an entire area or displayed at the level of 0.5°grid-cell (or finer depending on resolution of input density data), allowing areas of high and low risk to be identified.

All density estimates have an estimate of uncertainty associated with them. These uncertainties, together with the uncertainty associated with the other parameters used in the simulation process, allow confidence intervals to be provided for any outputs.

Mitigations can be explored by comparing results under different scenarios. For example, deploying the sound source in a slightly different location or at a different time of year. Similarly, a small change in the characteristics of the sound source may have a substantial effect on risk, depending on the hearing sensitivities of the marine mammal species that occur in the region.

Behavioural responses to sound exposure are still poorly understood (Southall et al. 2007c) but, as understanding increases, they can be accommodated within SAFESIMM in two ways. Additional dose-response curves for particular behavioural responses can be included without system modification. The sound exposure and location of simulated animals are monitored at a fine spatial scale. It is therefore possible to record and flag particular high risk events, such as if simulated beaked whales are driven from deep to shallow waters during a simulation, or if a large proportion of a local population is driven out of a particular area.

Summary

SAFESIMM is a flexible algorithm for the calculation of risk to marine fauna from anthropogenic sound. It is currently populated with a large and comprehensive set of data that reflects the current state of knowledge for marine mammals.

The algorithm has been created in an easily modifiable form, so the latest research developments in this rapidly changing field can easily be incorporated.

References

Costello M.J., Stocks K., Zhang Y., Grassle J.F., Fautin D.G. (March 2007). About the Ocean Biogeographic Information System (OBIS).

Finneran, J.J., Carder, D.A., Schlundt, C.E. & Ridgeway, S.H. (2005). Temporary threshold shift in bottlenose dolphin (*Tursiops truncatus*) exposed to mid-frequency tones. Journal of the Acoustical Society of America. 118: 2696-2705.

Kaschner, K., Watson, R., Trites, A.W. & Pauly, D. (2006). Mapping world-wide distributions of marine mammal species using a Relative Environmental Suitability (RES) model. Marine Ecology Progress Series 316: 285-310.

Kastak, D., Southall, B. L., Schusterman, R. J., and Kastak, C. R. (2005). Underwater temporary threshold shift in pinnipeds: Effects of noise level and duration. . Journal of the Acoustical Society of America. 118 (5): 3154-3163

Parsons, E.C.M., Dolman, Sarah J., Wright, Andrew J., Rose, Naomi A., and W.C.G. Burns. (2008) Navy sonar and cetaceans: Just how much does the gun need to smoke before we act? Marine Pollution Bulletin 56 (7): 1248-1257

R Development Core Team. (2008) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. http://www.R-project.org

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C.J., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W., Thomas, J., & Tyack, P. (2007a) Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals 33: 411-521.

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C.J., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W., Thomas, J., & Tyack, P. (2007b) Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations - Structure of the Noise Exposure Criteria. Aquatic Mammals 33: 427-436.

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C.J., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W., Thomas, J., & Tyack, P. (2007c) Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations - Criteria for Behavioral Disturbance. Aquatic Mammals, 33, 446-473.

II. Appendix Two

Table 7 Engineering parameters modelled for each site.

Estimated Engineering Parameters	Inch Cape (Most Likely)		FOF (most likely Worst Case)		NNG (Most Likely)	
Pile Diameter (mm)	2438		2000		2500	
Total Penetration (m driven below seabed)	50		34		27.5	
Hammer Capacity (max blow energy, kJ)	1200		1800		1200	
Soft-start duration (mins)	20		20		20	
Total Piling Duration (hours per pile)	3 hours		2 hours per pile (for installation of full substructure 4 piles, 3hours break between between each driving operation		200 Mins (3 Hours 20 mins)	
Ramp-up Details	**Time (minutes at % efficiency)**	**Efficiency (% of max blow energy)**	**Time (minutes at % efficiency)**	**Efficiency (% of max blow energy)**	**Time (minutes at % efficiency)**	**Efficiency (% of max blow energy)**
	Use Soft Start + Standard Ramp up		15	20	20	20
			15	40	180	83
			15	60		
			25	80		
			50	95		
Strike rate (per s)	1		1		0.5	

NNG Most Likely Drill & Drive

Action	Hours	Action
Hammer 1 Pile 1	2	Virgin pile drive
Remove hammer and install drill	4	
Perform drilling operations	19.5	Drilling
Trip out drill string	3	
Hammer 2 Pile 1	1.333	Drive after drill

Figure 10. Locations used in the SAFESIMM simulations.