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1pAB8. Noise Dose for Aquatic Animals: Preliminary Estimates for Two Seismic Surveys

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Two major air-gun exposure experiments have been conducted in Norwegian waters: The Nordkappbank experiment in 1992 [Can. J. Fish. Res. Aq. Sci., 1996, Vol. 53, pp. 2238-2249] and the Vesterålen experiment in 2009 [Fisken og Havet, 2010, Nr. 2, 76 pp. Inst. of Mar. Res.]. Although changes in catch rates and distribution of fish were observed in both cases, the responses were higher in the first experiment. Simple metrics such as number of exposures by time and area reveal large differences between the experiments. This is further detailed in looking at the distribution of distances to air-gun emission positions throughout the experiments. The exposures were in general closer in the Nordkappbank experiment. Analyzing the noise level data for the Vesterålen experiment showed on average cylindrical spreading, which is used in a simple acoustic spreading model estimating the integrated sound exposure levels at a central point in both areas. The analysis shows that the total noise energy exposed to an imaginary fish in these central locations are similar, but that the daily maximum total energy is higher for the Nordkappbank experiment. This gives some indication that the initial simple metrics gave a fair assessment of the exposures between the two cases.

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Introduction

Two large experiments have been conducted in Norwegian waters on the impact on seismic air-gun exposures on fish, more specifically the changes in catch rates from fishing vessels in and near the areas subject to seismic air gun exposure. The experiment areas are shown in Figure 1.

Engås et al. (1996) showed a dramatic decline in catch rates of cod (*Gadus Morhua*) and haddock (*Melanogrammus aeglefinus*) over a 5 day air gun exposure. The exposed area was 5.5 km x 18.5 km [3 nautical miles (nmi) x 10 nmi], and trawl catch rates and long-line catch-rates declined in average about 50% and 40 %, respectively, within a larger area of 74 km x 74 km (40 nmi x 40 nmi). Within the smaller exposure area (5.5 km x 18.5 km) trawl catches were reduced by 70%.

More recently an experiment was conducted along with a seismic survey off the coast of Vesterålen (Løkkeborg et al., 2010). The area of exposure was much larger spanning 14 km x 85 km (8 nmi x 46 nmi). Increases in gill net catches were observed and reductions in long-line catches were observed. However, the levels of these effects were not in the same order of magnitude as the first experiment.

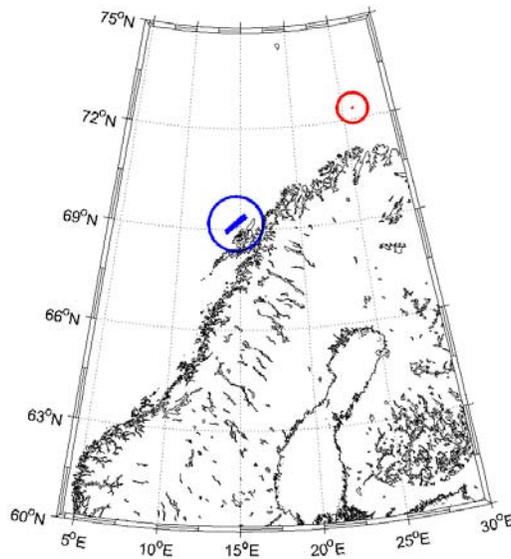


Figure 1: The area of the two major experiments in Norwegian waters. The blue area is the are of the Vesterålen experiment (Løkkeborg et al., 2010) and the red area is the are of the Nordkappbank experiment (Engås et al., 1996).

The objective of this paper is to present metrics of the air-gun exposures between the two experiments, which may be a candidate for explaining the observed differences. This will be achieved by comparing metrics as number of air gun exposures, gun exposures pr unit time and area, and further by defining, calculating and comparing coarse estimates of the total air-gun noise-energy exposure between the experiments.

Comparing the exposure from the two experiments

The simple picture - exposures pr area and time

Key properties are different between the experiments, and are summarized in Table 1. The duration of the Vesterålen experiment was approximately 10 times longer than for the Nordkappbank experiment. The exposure pr duration was approximately 50% higher for the Nordkappbank experiment. Further, for the Vesterålen experiment the energy was distributed over an area one order of magnitude larger. The exposures pr area and duration was 20 times higher for the Nordkappbank experiment. In summary, this indicates a much larger stress on the smaller area.

Table 1: The the key differences between the two experiments including the different air gun configuration (note that 13 784 kPa = 2000 psi).

		Vesterålen	Norkappbanken
Duration	days	38	4
Exposures	Count	164k	27k
Area	nmi ²	368	30
Exposures pr duration	days ⁻¹	4349	6739
Exposures pr area	nmi ⁻²	446	901
Exposures pr duration and area	nmi ⁻² days ⁻¹	12	225
Active guns	Count	34	18
Air gun pressure	kPa	13 784	13 784
Total active volume	cm ³	57 000	82 132

The distance distributions to the air-gun emissions

Comparing the simple statistics is useful for a gross overview of the differences, but to look into this in more detail, a central position of interest are chosen within in both areas, denoted \mathbf{x}_j . Other positions, e.g. the position of the gillnets and the longlines sets could also be chosen, and the method could be used to calculate explanatory variables for the catch changes in each gillnet position.

The position of each individual air-gun emission is denoted $\mathbf{x}'_i = (x', y')$. For the Vesterålen experiment, this is taken from the seismic vessels' log

files, whereas for the Nordkappbank experiments, the positions are estimated based on the description of the experiment. In both cases, the positions of the air gun shots and the point of interest is obtained, see Figure 2.

The distribution of distances between the point of interest and the air-gun shot positions $r_{ij} = |\mathbf{x}'_i - \mathbf{x}_j|$ gives an indication of how close to the seismic vessel the fish in the position of interest have been during the experiment, and gives an indirect indication of the noise energy exposure. Let h_r be the count of exposures in 250 m bins, from 0 km to 45 km, see Figure 3. It is quite evident that there is a higher number of exposures from short range for the Nordkappbank experiment, again indicating that the area was under a higher stress than during the Vesterålen experiment.

Sound exposure levels

The distance to the noise exposure does not take into account air-gun configuration or sound scattering. The next step is to include this in a simple sound exposure metric. An established standard for sound exposure is the sound exposure level (SEL), which is based on the acoustic energy flux (Carey, 2006). This is similar to the noise dose used for humans for noise regulations in the industry (Heathershaw et al., 2001), except that it is not scaled by the 8 h exposure time convention.

Assuming a plane sound wave, the acoustic energy flux of a transient or impulse signal is given by

$$E[J/m^2] = \frac{1}{\rho c} \int_{t_0}^{t_0+T} p(r, t)^2 dt = \frac{E_x}{\rho c}, [(\mu Pa)^2 (kg/m^3)^{-1} (m/s)^{-1}] \quad (1)$$

where ρ is the media density, c is the sound speed, T is the duration of the signal and $p(r, t)$ is the instantaneous (filtered) sound pressure. Given a reference energy flux of a 1-s gated sine wave with pressure amplitude of $1\mu Pa$, the energy flux can be presented as a power ratio proportional to the energy flux. The sound speed and density cancels yielding

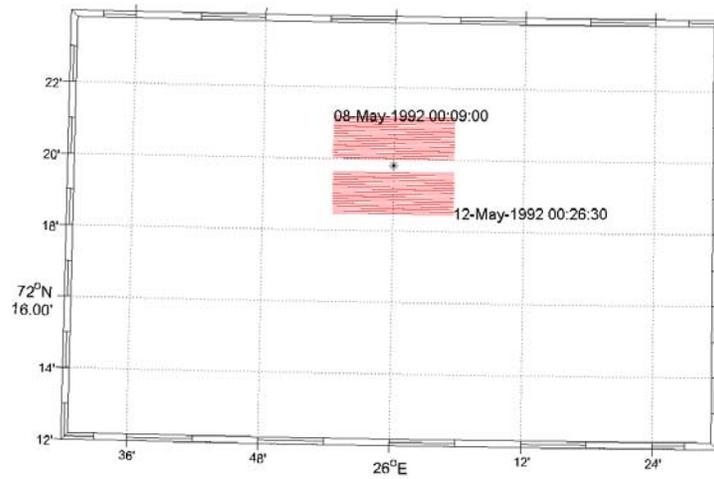
$$D_i = \frac{E_x}{E_{xref}} = \int_{t_0}^{t_0+T} \frac{p(r, t)^2}{t_{ref} p_{ref}^2} dt, \quad (2)$$

where $p_{ref} = 1\mu Pa$ is the reference pressure amplitude of the sine wave and $t_{ref} = 1s$ is the reference time gate. The sound exposure level (SEL) is defined as

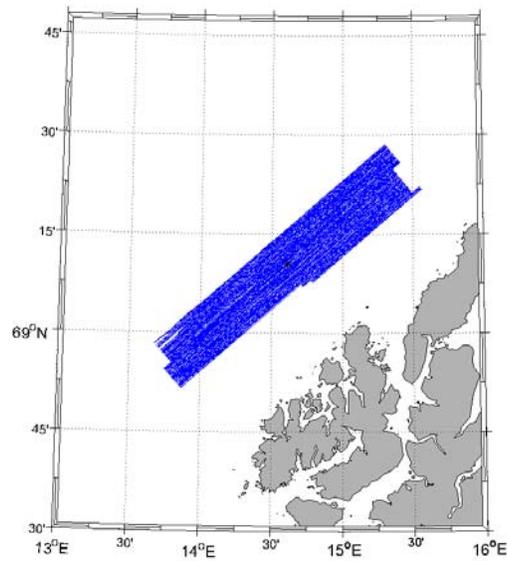
$$SEL = 10 \log_{10}(D_i) \text{ dB re } [(1\mu Pa^2)(1s)]. \quad (3)$$

The sound exposure ratio for one pulse extrapolated to a 1 m distance to the source is denoted the energy flux density source level

$$EFSL = 10 \log_{10} \left(\frac{E_x}{E_{xref}} \right) \text{ dB re } [(1\mu Pa^2)(1s) @ 1m]. \quad (4)$$



(a) Nordkappbanken



(b) Vesterålen

Figure 2: The positions of the seismic air-gun shots (red and blue areas are the Nordkappbanken and Vesterålen experiments, respectively.) and the central position (black asterisk), for both experiments.

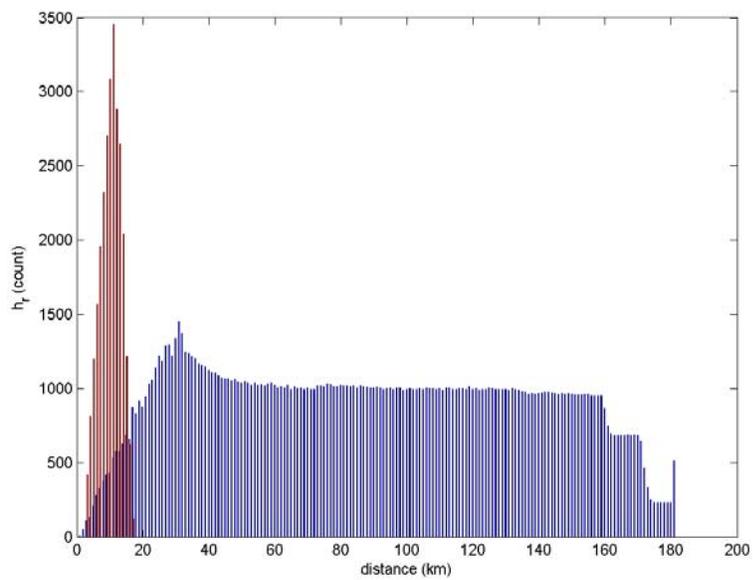


Figure 3: The h_r (distribution of r_{ij} as a function of r) for the two cases. The red and blue lines are Nordkappbanken and Vesterålen experiments, respectively.

This is different from the actual exposure level close to the air-gun (Caldwell and Dragoset, 2000), but serve as a reference level when estimating the received levels in the far field when assuming a noise spreading model and a far field air-gun beam-pattern.

For the purpose of comparing the energy flux from the two experiments, a relative level is required. A simple spreading model is used to get the gross differences in exposure. The spreading model and EFSL is estimated by analyzing the hydrophone data presented in (Løkkeborg et al., 2010), see Figure 4. The data supports a cylindrical spreading model and an EFSL of 160 dB re $(1\mu Pa^2)(1s)$. Note that this is probably too coarse on short range, but seem to be fair on longer ranges.

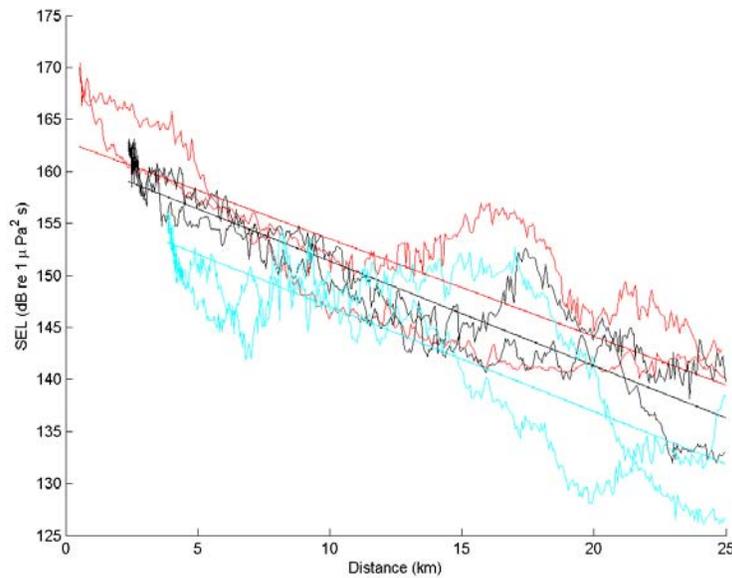


Figure 4: The noise observations on three different seismic air-gun vessel listening buoy passing, taken from (Løkkeborg et al., 2010). The slope of the linear fitted line is -0.93 , -1.01 and -1.01 , for the red, black and cyan curve, respectively, supports a cylindrical spreading model at distances more than a couple of km. The extrapolated EFSL is 163, 161 and 157 dB re $(1\mu Pa^2)(1s)$, for the red, black and cyan curve, respectively.

The air gun configuration was slightly different in the two cases (Table 1). The source level of an air-gun array is proportional to the firing pressure and the number of guns, but increases only by the cube root of the gun volume (Caldwell and Dragoset, 2000). A coarse approximation of the difference between the guns, assuming similar beam patterns and equal sized air-guns,

are given as a ratio between the expected source levels

$$r = \frac{n_v \left(\frac{V_v}{n_v}\right)^{\frac{1}{3}}}{n_n \left(\frac{V_n}{n_n}\right)^{\frac{1}{3}}} = \frac{34 \left(\frac{57}{34}\right)^{\frac{1}{3}}}{18 \left(\frac{82}{18}\right)^{\frac{1}{3}}} = 1.354, \quad (5)$$

where the parameters are taken from Table 1 and the subscripts v and n denotes the Vesterålen and Nordkappbanken experiments, respectively. This is of course a simplification, but the EFSL power ratio between the sources is $10 \log(1.354) = 1.3 \text{ dB} [(1 \mu \text{Pa}^2)(1 \text{ s}) @ 1 \text{ m}]$, which is low compared to the error in the spreading model and EFSL extrapolation in Figure 4.

Assuming that the EFSL for the Vesterålen experiment is $160 \text{ dB re } 1 \mu \text{Pa}^2 \text{ s}$ we get

$$E_x = 10^{160/10} (\mu \text{Pa}^2 \text{ s} @ 1 \text{ m}) \quad (6)$$

for the Nordkappbanken experiment, and

$$E_x = 1/1.354 \cdot 10^{160/10} (\mu \text{Pa}^2 \text{ s} @ 1 \text{ m}) \quad (7)$$

for the Vesterålen experiment.

The daily total energy exposure (dose) at a point of interest $\mathbf{x}_j = (x, y)$ for day k is calculated as

$$D_{jk} = 10 \log_{10} \left[\frac{\sum_{i \in \{A_k\}} \left(E_x \frac{r_0}{r_{ij}} \right)}{(1 \mu \text{Pa}^2)(1 \text{ s})} \right], \text{ dB re } [(1 \mu \text{Pa}^2)(1 \text{ s})] \quad (8)$$

where A_k is the set of air-gun shots i within each day k , $r_0 = 1 \text{ m}$ is the reference distance for the E_x , r_{ij} is the distance between \mathbf{x}_j and \mathbf{x}'_i . The daily dose for each experiment is given in Figure 5.

In addition to the maximum daily dose, the mean daily dose and the summed dose over the duration of the experiment are calculated, see Figure 6. The total dose is similar between the experiment, whereas the maximum daily dose is much higher for the Nordkappbank experiment.

To get a handle on which distances the energy contribution originates, the histogram of air gun shots divided by the distance $h'_r = h_r/r$ is calculated, see Figure 7. This simply assumes cylindrical spreading and scales the bars by the inverse of the distance. Recalling that the total energy exposure is the same, the energy contribution is more spread out in distance for the Vesterålen experiment. Note also that the cylindrical spreading model is probably less accurate at close range.

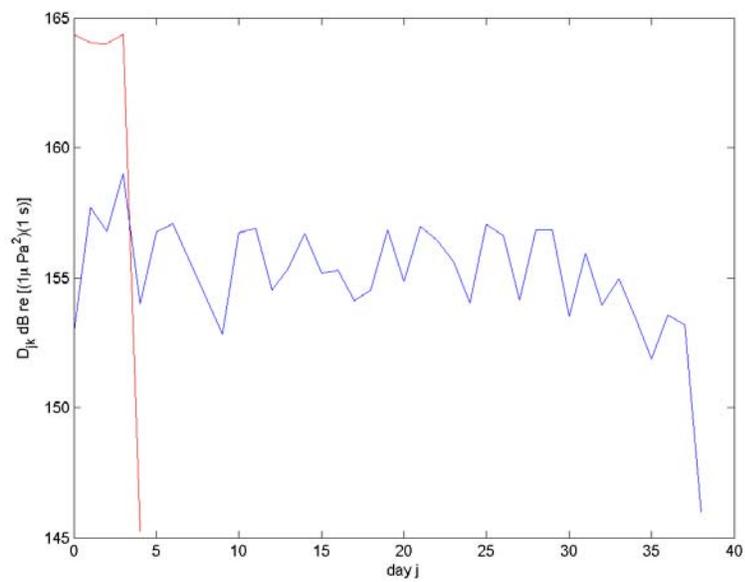


Figure 5: The daily dose for position \mathbf{x}_j for the two experiments as function day number j . The red and blue lines are Nordkappbanken and Vesterålen experiments, respectively. Note the duration of the experiments was different.

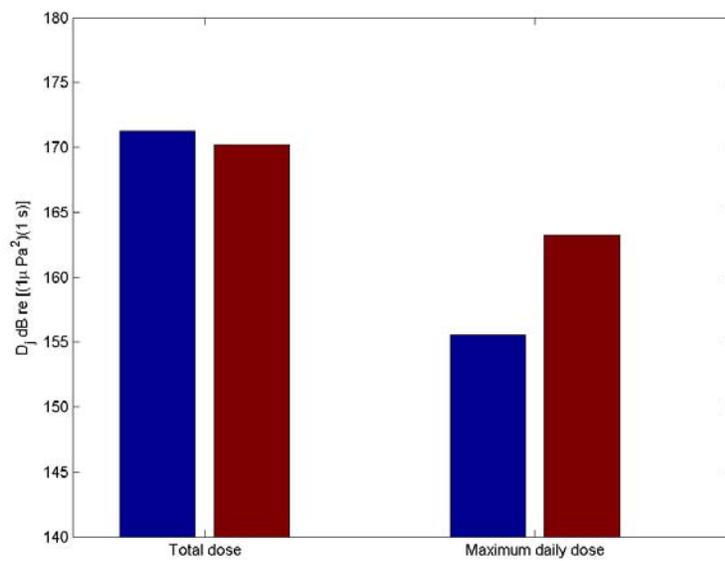


Figure 6: The total summed dose over the full duration of the experiments for the reference position \mathbf{x}_j in the two experiments. The red and blue bars are Nordkappbanken and Vesterålen experiments, respectively.

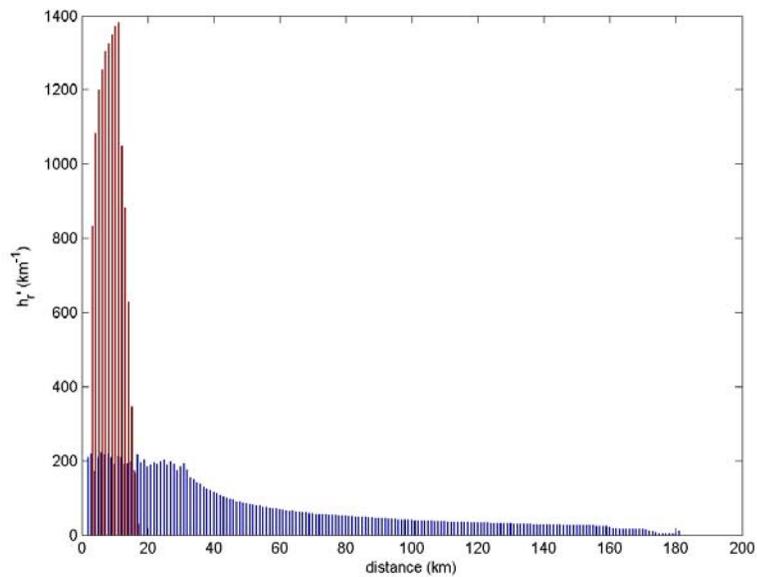


Figure 7: The h'_r (distribution of r_{ij} divided by r_{ij}) to mimic the energy contribution as a function of distance, assuming cylindrical spreading. Red and blue lines are Nordkappbanken and Vesterålen experiments, respectively. Note that the presentation is in linear values, not logarithmic as the dB scale.

Discussion

The path of the sound beams are affected by bottom topography, water stratification etc, leading to multiple paths reflected from surface and bottom before being exposed to the fish. Direct observations of exposure on animal shows that this is difficult to model (Madsen et al., 2006). This should especially affect the shorter range exposures from Nordkappbanken, where the cylindrical spreading model may be false. In any case, the levels should be regarded as nothing more than crude approximations, useful for investigating the *relative* contribution between the experiments.

It is worth noting that the "simple picture" simply analyzing the positions of each emission gave the same overall signal as the spreading model. Given the recent media focus on these issues a rather simplistic measure of impact may serve a better role than detailed modeling. Without concluding where this level of detail lies, it is certainly something that should be payed attention to. I propose that simple statistics, like the ones presented in the first part of this paper, should be presented along with more detailed observations and modeling of sound exposure levels for air-gun emissions. By doing so we may be able to establish a simpler and more transparent measure of impact than SEL for seismic surveys, that can easily be confused with sound pressure levels, spectral levels, and further by the air/water conversion of these metrics.

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