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ASSESSING THE IMPACT OF UNDERWATER NOISE ON MARINE FAUNA: A SOFTWARE TOOL

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Abstract

A software package is presented which models the effects of underwater noise on marine mammals. It consists of three main parts: an acoustic source model, a sound propagation model and a bioacoustic impact model. It has been corroborated in the field by measurements of the noise field, and visual and passive acoustic surveys of marine mammals. The software package was written for Environmental Impact Assessments (EIA), and has been used to aid research, to apply for permits of marine operations, to monitor marine mammals, to design mitigation protocols, and to guide environmental management and decision-making. This article gives an overview of our software and presents results of various EIAs.

1. INTRODUCTION

Since the beginning of the industrial revolution, the world's oceans have become increasingly noisy. Ship traffic, hydrocarbon and mineral exploration, offshore construction, naval activities, ocean acoustic research, all contribute to the noise pollution of the marine environment.

Noise effects on marine mammals in particular are of increasing interest and concern to the public, research organisations and environmental management. Underwater noise can have a variety of detrimental effects on marine mammals, on an individual and population level. Given that water conducts sound very well and light very poorly, marine mammals primarily use acoustics for communication and navigation. Underwater noise has the potential for interfering with odontocete (toothed whale) echolocation signals, impeding the animal's ability to navigate or find food. Noise can mask communication signals that play a role in social cohesion, group activities, mating, mother-calf contact, warning or individual identification. Noise can further interfere with environmental sounds or prey sounds that animals might listen to. For example, animals likely recognize the sound of surf, which guides them away from shallow water. Masking will be "biologically significant" if the animals' biological fitness is reduced (decreased rate of reproduction).

Noise has the potential of disrupting "normal" animal behaviour. The literature on observed behavioural changes due to human activities is steadily growing. Reported animal reactions include a cessation of feeding, resting, socializing and an onset of alertness or avoidance. If noise repeatedly impedes foraging, nursing or mating, or permanently displaces animals from critical habitat, the effect will likely be of biological significance.

Noise at extreme levels has the ability to induce physiological damage to tissues and organs, for example the ear. Hearing impairment can be either temporary (i.e. fully recoverable over time) or permanent depending on factors such as the spectral characteristics of the noise (frequency and amplitude), the amount of energy for impulsive noise, the hearing sensitivity (audiogram) of the species, the duration of noise exposure and the duty cycle or recovery time in between exposures. Data on temporary hearing impairment is scarce. There is no data on what noise characteristics cause a permanent hearing loss in marine mammals. Given the importance of hearing to marine mammals, hearing impairment (certainly in the permanent case) likely affects survival.

Based on our own research in marine bioacoustics and industrial noise, we have performed numerous EIAs for academia, government, military and industry. It became necessary to automate the process, because of a) the multitude of EIAs requested, b) a requirement for objectivity and reproducibility of results, c) the need to predict effects before activities began, and d) the need to model effects in the absence of direct data. The result was a software package, which is presented in this article.

2. ACOUSTIC SOURCE MODELS

For EIAs of airgun arrays used for seismic exploration, we apply an Airgun Array Source Model written by one of our team members [1]. This model is based on the physics of individual airguns, producing individual airgun signatures, which have been matched with experimental measurements. Individual signatures are superposed given the particular array configuration. In the near-field, the array is modelled as a set of individual airguns, accounting for travel time and phase differences, and surface ghosts. In the far-field, the array can be considered an equivalent point source. Modelled array outputs have been verified by measurements in the field.

Many of our EIAs have involved measuring acoustic signatures of ships ranging from small private boats to large vessels and icebreakers. We have accumulated a database of source signatures of over 30 vessel types including level modification functions for speed, operational power and directionality. This database can be used to model vessel noise emission.

In the absence of appropriate models and to verify modelled output, received noise time series are measured in the field at various azimuths, depths and ranges. Source signatures are computed using appropriate sound propagation software.

3. SOUND PROPAGATION MODELS

We use three different algorithms to model sound propagation under differing circumstances. All models support GIS data. For low frequencies and in a range-dependent environment, we use a modified Parabolic Equation Model [1]. The parabolic or one-way wave equation follows from the Helmholtz equation after a number of assumptions and ignoring negative ranges (backscattered waves). After integration and Padé series expansion, the pressure field can be computed recursively. Acoustic energy lost into shear waves in the bottom is important in shallow water and has been added to our model. The model outputs transmission loss values for a grid of receiver locations spaced in range and depth.

For very broadband or high-frequency sources, we developed a ray-propagation model [2]. This model traces rays by repeatedly applying Snell's law. It searches for eigenrays in a 2D environment (depth versus range), characterized by its bathymetry, sound speed profile (which can change with range), geoacoustic properties of the bottom (modelling absorption and reflection), and surface roughness. Frequency-dependent absorption by ocean water is also accounted for. Intensity is computed as an integral over all wavefronts of all eigenrays. Rays are superposed incoherently. The outputs of this model are 3D matrices of transmission loss as a function of range, depth and frequency.

The ray model has been modified for transient, broadband, impulsive sounds by adding the extra dimension of time. On a 2D grid in range and depth, received pulses are overlapped after accounting for travel time differences and phase changes.

All of these models compute sound propagation in 2 spacial dimensions: range and depth. To yield an image in 3D space, the models are run for a number of azimuth angles, ignoring the usually negligible scattering of energy from one 2D plane into the next. We employ a radial tessellation method (Fig. 1), seeding new fields with increasing range, to maintain a fine grid at large ranges.

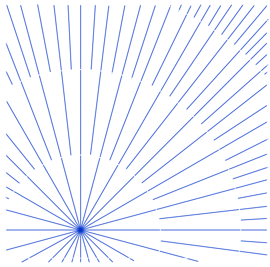


Fig. 1: Radial tessellation for 3D sound propagation modelling.

Simultaneous noise sources can be modelled. Fig. 2 shows how modelled outputs were verified by field measurements.

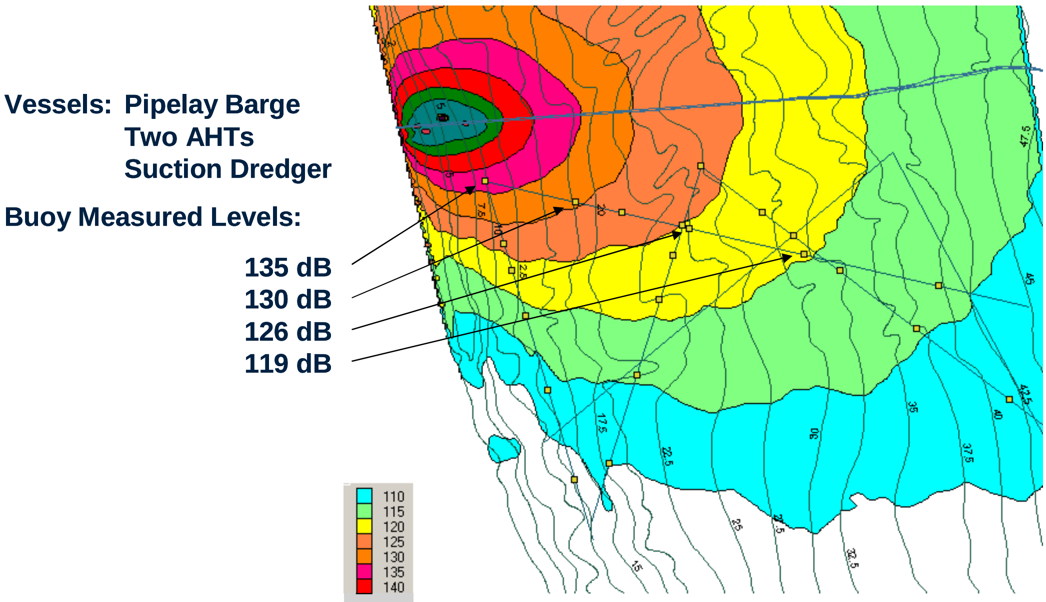


Fig. 2: Modelled noise field around 4 simultaneous sources, and level verification with deployed hydrophones.

4. BIOACOUSTIC IMPACT MODELS

4.1 Multiple-Taxa Harassment Zones

Most western countries have environmental protection acts and endangered species acts. Much of our work has fallen under US American legislation, where the Marine Mammal Protection Act generally prohibits "take" of marine mammals. "Take" is defined as "harass, capture or kill". Harassment is divided into Level A (the potential to injure a marine mammal) and Level B (the potential to disturb and disrupt current behaviour). Organisations planning to engage in marine activities have to consider the potential effects on marine mammals beforehand and may apply to the National Marine Fisheries Service (NMFS) for an Incidental Harassment Authorization (IHA), permitting an unintentional, but not unexpected, taking.

Our models have been applied to EIAs of seismic exploration in US waters, both for the application of IHAs and for marine mammal monitoring programs during actual operations in the field. The NMFS prescribes certain safety criteria. In the example of seismic surveys, received sound pressure levels (SPL) of >160 dB re 1 μPa_{rms} might cause a behavioural disturbance in cetaceans. SPLs >170 dB re 1 μPa_{rms} might cause a behavioural disturbance in pinnipeds. SPLs >180 and 190 dB re 1 μPa_{rms} might lead to temporary hearing loss in cetaceans and pinnipeds respectively, e.g. [3][1]. With the aid of our models, such impact thresholds were related to Multiple-Taxa Harassment Zones in the wild. Industrial operations, once approved, usually involve a marine mammal monitoring program (visual and/or passive acoustic). When observers detect marine mammals within the modelled zones, certain mitigation procedures (e.g. shutting down) are initiated.

The Noise Exposure Criteria Group [4] has derived so-called M-weighting functions (Fig. 3) that filter sounds corresponding to marine mammal audiology. These are best applicable to high-level noise exposure. Marine mammals were grouped into low-frequency, mid-frequency and high-frequency cetaceans, as well as pinnipeds in-air and underwater, according to their lower and upper limits of hearing. M-weighting functions model the bandwidth of the animals' auditory filter, ignoring absolute thresholds. It has been suggested that they be used as conservative criteria for behavioural disturbance and ultimately injury.

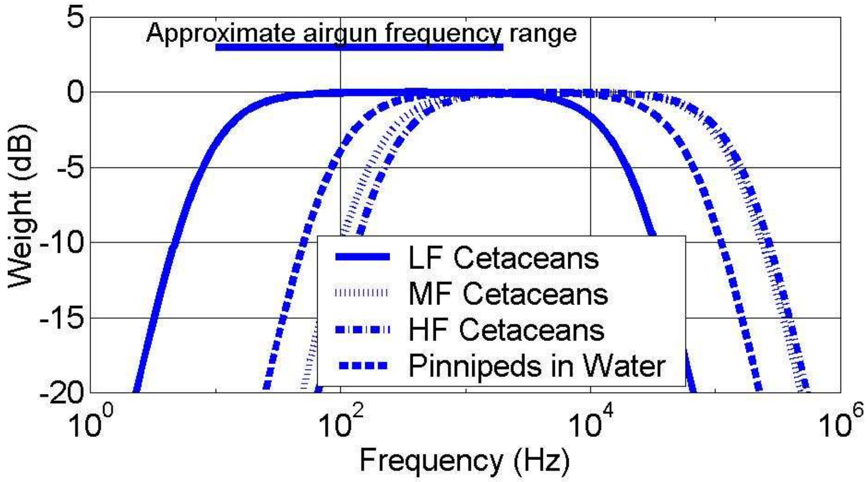


Fig. 3: M-weighting functions.

Applying these M-weighting filters to the noise of an airgun array shows how sound exposure levels (SEL, an energy metric) vary with taxon (Fig. 4). Given that the bandwidth of the airgun array falls into the LF-cetacean filter, the plots of SEL barely differ for the unweighted and the LF-cetacean-weighted cases. Broadband SELs are lower for pinnipeds, because of their reduced low-frequency hearing. SELs for MF-cetaceans are reduced even further. As a result, LF-cetaceans are likely most affected by airgun arrays. HF-cetaceans are of least concern.

[1] These rms pressure levels are computed over the duration of the signal. For seismic airgun pulses, the duration is taken to be the interval during which 90% of the energy is received. On a cumulative-energy-curve, the 5% and 95% points are used as start and end times of a pulse.

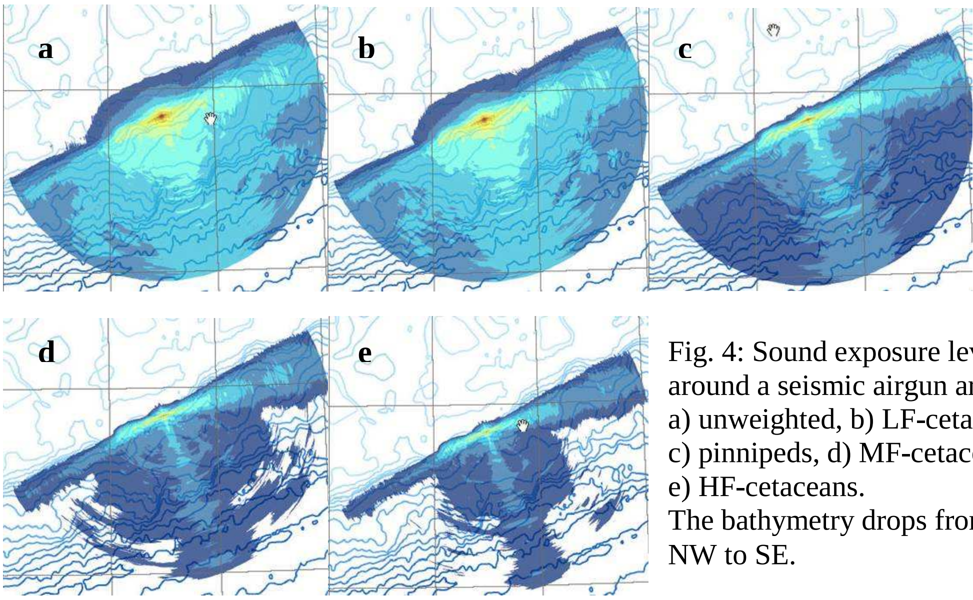


Fig. 4: Sound exposure levels around a seismic airgun array: a) unweighted, b) LF-cetaceans, c) pinnipeds, d) MF-cetaceans, e) HF-cetaceans. The bathymetry drops from NW to SE.

4.2 Species- and Impact-Specific Zones

Sometimes bioacoustic impact has to be and can be assessed in more detail and with regards to a specific target species, e.g. an endangered species or a species heavily watched by whale-watchers. For such cases the following models were derived. Since their initial publication [2], these models have continuously been expanded and updated as new scientific information has become available.

4.2.1 Zones of Audibility

Audibility of an anthropogenic noise source is limited by the target species' hearing sensitivity and ambient noise levels. An audiogram gives acoustic detection thresholds at a series of frequencies. About a dozen marine mammal species have been measured so far, e.g. [5]. The auditory system integrates energy in a series of filters, called critical bands. The model computing zones of audibility first computes critical bandlevels of the anthropogenic noise by integrating the source spectrum over the critical bands of the target species. It then subtracts the transmission loss values computed with the sound propagation model, yielding received noise levels in a series of critical bands. The model compares these noise band levels to the animal audiogram and to levels of ambient noise (also integrated into critical bands). If any of the received noise band levels are above the audiogram and ambient noise levels at the corresponding frequencies, then the anthropogenic noise is considered audible. This argument is based on an equal-power-assumption (At detection threshold, the power of the signal equals to the power of the noise in the corresponding auditory filters.), which we corroborated with beluga whales [6].

4.2.2 Zones of Masking

Here, the interference of anthropogenic noise with signals important to marine mammals is modelled. To assess the masking of communication sounds, typical animal vocalisations are required. Masking depends on the loudness of the received signal (which relates to the distance between two communicating animals) and directional hearing capabilities. The software takes a conservative or worst-case approach where signal and noise come from the same direction and two animals are maximally apart. Our previous research with trained beluga whales [7] led to the derivation of signal detection criteria (e.g., at detection threshold signal and noise exhibited equal energy in the critical bands encompassing the most energetic frequencies of the signal). Software (matched filters and neural networks) was developed to simulate signal detection in beluga whales [6], [8]. The current model is based on the criteria and algorithms developed earlier.

4.2.3 Zones of Behavioural Disturbance

Behavioural reaction thresholds may depend on a variety of factors, such as the received noise level, the bandwidth, the anthropogenic-to-ambient noise ratio, the behavioural state of the animal, age and sex, individual audiograms, past experience, habituation or sensitization. To model behavioural disturbance, information on what noise characteristics have been shown to alter behaviour is required. The literature is searched for behavioural studies with similar noise and the same species. Noise characteristics are published in a multitude of formats and units. Conversions are made and thresholds applied to the current scenario.

4.2.4 Zones of Hearing Impairment

A few studies have investigated a temporary threshold shift (TTS) in delphinids and pinnipeds after exposure to impulsive noise, octave-band noise and pure tones. Some of these studies have tried to derive a functional relationship between noise level, noise duration and TTS by comparing data amongst marine mammals and with terrestrial mammals. The paucity of data makes transfers to other species and other noise characteristics unreliable. For the current model, the most similar data in the literature are used to compute estimates of the zones of TTS.

5. APPLICATIONS

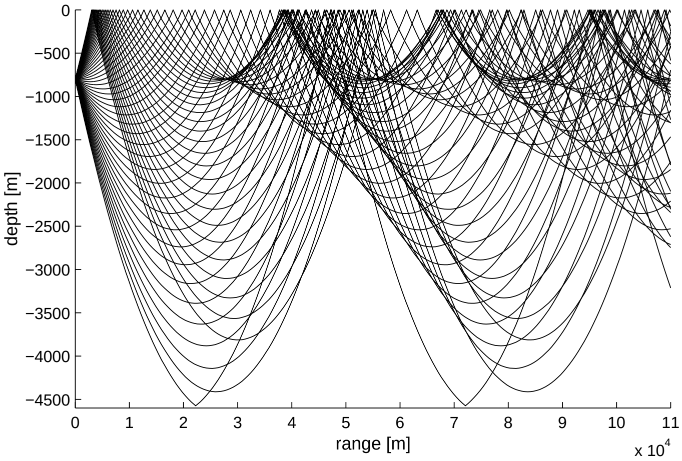
Our models for species- and impact specific zones have been applied to various EIAs, e.g. icebreakers affecting beluga whales in the Arctic [9], and whale-watching boats affecting killer whales in British Columbia and Washington State [10]. Results of an EIA of a RAFOS sound source in Antarctic waters are presented in the following.

RAFOS[2] sources are used for physical oceanographic research. In this study, one was deployed at 800m depth over a 4500m deep and flat ocean basin. The signal was an 80s long tone at 260 Hz with a source level of 183 dB re 1µPa @ 1m. The duty cycle was 1 transmission every 24h. The ray code was used for TL modelling. Effects on southern elephant seals (*Mirounga leonina*) were modelled. We used an audiogram of northern elephant seals [11], [12]. The widths of the filters of the seal's auditory system were estimated from critical ratio and critical bandwidth measurements [13], [14] and taken to be on average 1/12th of an octave wide. Thresholds for behavioural reactions were derived from reported responses of northern elephant seals to the ATOC sound source [15]. Diving behaviour changed when received levels exceeded 118 dB re 1µPa, i.e. about 20dB above audibility. Both sources emit narrow-band low-frequency sounds; the 20dB threshold was therefore also applied to the RAFOS source. Two studies have measured TTSs in northern elephant seals [16], [17] reporting an onset of TTS at sound exposure levels of 137.6 dB above sensation.

RAFOS was deemed audible to southern elephant seals near Antarctica over 220km range at depths to 1000m (Fig. 5). At 800m depth (the source depth) the sound would be audible even farther. An alteration of diving behaviour might be seen over 55km range. Given the low duty cycle of the RAFOS source, this is probably not biologically significant. Note that the full depth was modelled even though elephant seals have not been reported to dive

[2] http://www.po.gso.uri.edu/rafos/general/history/index.html, last accessed 14 May 2007

deeper than 1500m [18], [19]. Given the narrow-band, pure-tone quality of RAFOS, no masking of broadband signals (such as communication or environmental sounds) was predicted. No TTS was modelled using the 137.6 dB criterion.



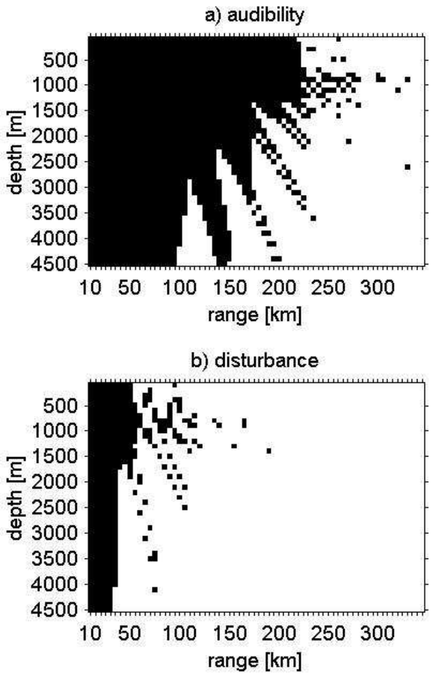


Fig. 5: Ray paths from the RAFOS sound source at 800m depth. A pattern of convergence and shadow zones is visible.
Modelled zones of audibility and disturbance for elephant seals.

6. CONCLUSION

We have presented a software package that can be used for Environmental Impact Assessments. It consists of noise source models, sound propagation models and bioacoustic impact models. Our software has been used to aid research, to apply for permits of marine operations, to monitor marine mammals, to design mitigation protocols, and to guide environmental management and decision-making. Results from various studies have been shown. The effects of underwater noise on marine mammals, in particular biologically-significant and long-term effects, are not fully understood. Basic research into the audiology of marine mammals, their hearing, their utilization of acoustics and their susceptibility to noise impact is needed. A major data gap exists for species that are not readily available in captivity. Our models are continuously being expanded and upgraded, as new scientific information becomes available.

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