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## **Using Modelled Far-field Signatures of Airgun Arrays to Estimate Impact on Marine Mammals**

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### **SUMMARY**

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We present a workflow to assess the risk of excessive sound exposure on marine mammals based on forward modelling of the far-field signatures from airgun arrays. The employed physical model takes into account the hydrodynamic effects around an airgun including the air bubble, directivity effects of realistic airgun arrays, and the interaction of the primary signals with the surface ghost reflection. Based on such signatures, we are calculating sound pressure and sound exposure levels as a function of distance and direction from the source, taking into account different geometrical spreading models. We also consider the frequency-dependent hearing threshold for different cetacean species. The workflow allows the estimation of a variety of different properties and scenarios in line with most recent regulatory requirements. Results can be used as a base for the planning of mitigation measures, such as exclusion radii around sensitive areas and soft-start procedures.

## Summary

We present a workflow to assess the risk of excessive sound exposure on marine mammals based on forward modelling of the far-field signatures from airgun arrays. The employed physical model takes into account the hydrodynamic effects around an airgun including the air bubble, directivity effects of realistic airgun arrays, and the interaction of the primary signals with the surface ghost reflection. Based on such signatures, we are calculating sound pressure and sound exposure levels as a function of distance and direction from the source, taking into account different geometrical spreading models. We also consider the frequency-dependent hearing threshold for different cetacean species. The workflow allows the estimation of a variety of different properties and scenarios in line with most recent regulatory requirements. Results can be used as a base for the planning of mitigation measures, such as exclusion radii around sensitive areas and soft-start procedures.

## Introduction

The first step in designing procedures for mitigating the impact of seismic signals on marine mammals is an accurate prediction of the expected amplitude of the source signature and its decay with distance. Forward-modelled far-field signatures can then be used to define operationally feasible exclusion radii while ensuring that predictions are conservative enough so that actual airgun output is not underestimated.

The far-field signature of an airgun array is the result of a complex interaction between the initial pressure pulse, the surface reflection (ghost), as well as the airgun bubble. A typical airgun array utilized for seismic surveys consists of 15-30 individual airguns of different volumes arranged in a fixed frame. The aim of the array is to produce a single pulse-like wavelet without excessive reverberations from bubble pulses and other effects. The tuning of the far-field signature is achieved by arranging airguns of different volumes with different bubble periods at a specified geometry. The above tuning and directivity effects can be forward-modelled and combined with propagation (e.g., geometrical spreading), and receiver effects, i.e., the mammal's hearing capability. The result is a three-dimensional distribution of the sound pressure level (SPL, measured in dB re  $1\mu\text{Pa}$ ) or sound exposure level (SEL, measured in dB re  $1\mu\text{Pa}^2 \text{ s}$ ) in the water around the source that can be used to derive exclusion radii for the source vessel from sensitive areas based on the agreed-upon threshold level. Cumulative effect of multiple exposures to the seismic source can also be computed. In addition, mitigation scenarios such as a soft-start procedure can be simulated and their effect on sound pressure effects evaluated. A soft-start procedure progressively switches on the individual airguns of an array to gradually increase the sound pressure level over a time period. It is meant to give marine mammals in the area time to adapt and temporarily migrate to quieter locations in the vicinity.

## Methodology

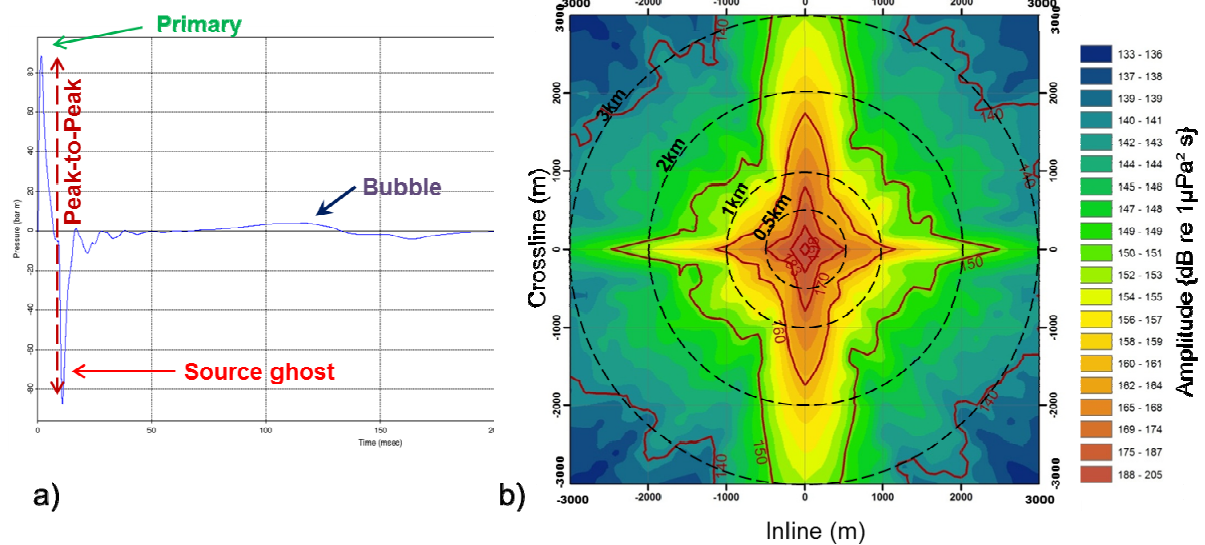
We model far-field source signatures and array directivity effects with the Nucleus package which is based on hydrodynamic equations given by Gilmore (1952) and Ziolkowski (1970), using an extensive signature library for calibration. A typical far-field signature is shown in Figure 1a, labelled with the main contributing effects. Assuming that intrinsic attenuation in the water column plays a negligible role at the dominant frequencies of marine seismic sources ( $< 150 \text{ Hz}$ ), we model the geometrical spreading of the wave front. In its simplest form, the geometrical spreading can be considered as a  $R^n$  decay function. Spherical spreading ( $n=2$ ) is a valid first-order assumption in deep water. In shallow water, which includes continental shelves where the majority of seismic work is being conducted, a cylindrical spreading function ( $n=1$ ) is a more appropriate first-order assumption. Consideration of more sophisticated hydro-acoustic propagation models implies knowledge of the seawater property variation with depth as well as detailed knowledge of the bathymetry in the investigated region.

The frequency-dependent hearing capability of different marine mammal species was described by Southall (2007) who categorized marine mammal species into different functional hearing groups and

gave specific response spectra for them. We implement these response spectra as bandpass filters on the far-field signature (so-called M-weighting filters) before measuring the amplitude and calculating the sound exposure level. Figure 1b shows the resulting map of the sound exposure level for the far-field signature in Figure 1a, using a cylindrical spreading function (shallow water) and a mid-frequency M-weighting filter. Such maps can be used to define exclusion radii around sensitive areas. In this case, the signal has decayed below 180 dB within 200-250 m around the source. Note the strong array directivity effects predicted by the modelling.

## Conclusions and Outlook

The presented forward-modelling workflow estimates the far-field signature and amplitude decay with distance of airgun arrays and considers the frequency-dependent hearing capabilities of marine mammals, particularly cetaceans. The methodology considers latest findings on the subject and is in compliance with the requirements from a number of regulatory agencies. The workflow allows to properly plan mitigation measures such as exclusion zones and soft-start procedures. Future extensions include hydro-acoustic modelling of the amplitude decay for given seawater profiles and bathymetric models.



**Figure 1** a) Far-field signature with source ghost for a typical airgun array consisting of 27 source elements with a total volume of 4135 cu. in. b) Map of sound exposure level (SEL) decay with distance for a medium mammal hearing threshold filter, assuming a cylindrical spreading function (shallow water case). The sound exposure has decayed below 183 dB within 200-250 m from the source.

## References

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