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Antecedents

The directivity diagrams that are used here were constructed for all used sources. We also took into account the water column and sediment characteristics to propagate the different sources into our model, including propagation loss.

Below is a review of the published data on the effects of noise on marine mammals and especially masking from anthropogenic sources.

The modeling performed in WP4 clearly assumes that masking from shipping noise affects a portion of communication signals from certain species, leaving aside possible physiological injuries that have not yet been demonstrated in any study.

However, there is indeed a growing consensus about the potential impact of man-made sound on marine fauna. The conscious awareness of this issue has been reinforced by a series of strandings coinciding with the exposure to man-made sound sources. Anthropogenic originated sound can affect cetaceans in different ways, and these effects can be on an individual or group level. The question of how and why man-made sound affects marine mammals is controversial and it is therefore essential to consider that the control and adjustment of marine noise is a question that could demand great financial cost, and yet it remains vital for research into this area to be continued in the future. For now, the following associations can be established:

Types of anthropogenic sound that can affect marine mammals[1]

Source	**Effects of greatest concern**
Ships	Masking Habitat displacement
Airguns (compressed air)	Masking Physical trauma Auditory loss Behavioral changes Habitat displacement Behavior conditioning effects
Intense low or mid frequency sonar activity	Physical trauma Auditory loss Behavioral change Behavior conditioning effects
Pile driving	Physical effects Auditory loss Behavioral change Behavior conditioning effects

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[1] Boyd *et al. 2008*

Other types of sonar (deepwater soundings, trawlers, fishing boats)	Masking Auditory loss Behavioral change Behavior conditioning effects
Dredgers	Behavioral change Habitat displacement Behavioral conditioning effects
Drilling	Auditory loss Behavioral change Behavior conditioning effects
Towed fishing materials	Behavioral change Behavior conditioning effects Habitat displacement
Explosions	Physical trauma Auditory loss Behavioral change Behavior conditioning effects
Recreational boats	Masking Behavioral change Behavior conditioning effects
Acoustic hardware	Behavior conditioning effects
Airplanes	Behavior conditioning effects

Signal masking

The process known as auditory signal masking happens when noise reduces, partially or completely, the capacity to hear sound or signals. The scope of interference depends on the spectrum and the temporal-spatial relationship between the signals and the masking noise, among other factors[2].

In addition to the acoustic effects of “overlapping” from auditory masking, if a mammal can hear a sound, this sound, at a determined level, may injure the ear causing a reduction in sensitivity. The minimum level at which a sound can be perceived is called the auditory ‘threshold’. If an individual needs a significantly greater sensitivity than is normal for its species to perceive a particular frequency, an auditory deficit marked by a change in the threshold level or *threshold shift* occurs. Any noise at a sufficient level may change the auditory threshold, whilst a different sound, produced at the same level, may not provoke equivalent changes If a change in auditory threshold is accompanied by lesions in the ear, this will be deemed acoustic trauma that may be temporary or permanent, depending on the duration of the exposure.

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[2] Southall *et al.* 2007

We can conclude that masking is the increase of the auditory threshold for a sound due to the presence of another sound[3]. It has been confirmed[4] that signal masking is particularly pronounced if the spectral frequency of the masking noise superimposes the critical band surrounding the frequency of the signal.

The majority of underwater activities produce low frequency sound. This noise can potentially mask the communication signals of all baleen whale species that use frequencies below 1 kHz and some odontocetes, such as sperm whales. The direct consequences of this masking of communication and related signals can be diverse: group dispersal, reducing a fundamental part of their interaction with the natural environment (echolocation)[5], impaired feeding ability and the separation of mothers from young with usually fatal consequences for the calf. It is believed that continuous noise is more detrimental than temporal signals[6] and that low frequency sounds possess a greater masking effect than higher frequencies[7]. There is still no data on the effect of low frequency masking, nor direct measurements with baleen whales.

The responses of different species to the presence of ambient noise have different results, some of which have been documented. For example, sperm and pilot whales have been observed to cease vocalizations during the exposition of intense noise sources[8]. The contrary has also be shown as in the case of Beluga whales[9] and dolphins[10] which increase the intensity and frequency of their vocalizations to compensate for the presence of ambient noise. Despite these strategies, it is likely that the level of efficient communication has been reduced and that this reduction has limited their ability to react to stressful or dangerous situations[11]. However, the directionality of the auditory reception could compensate for some of the negative effects of masking. The directionality index of the bottlenose dolphin has been measured up to 20 dB[12].

The capacity of an animal to hear directionally could indeed help it avoid masking, in that it is capable of differentiating between the signal's propagated direction and noise. The 20 dB directionality index measured in dolphins would mean that they could hear a signal coming from a certain direction as if this signal was ten times higher than ambient noise.

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[3] Erbe 1997

[4] Fletcher 1940, in Johnson *et al.* 1989

[5] André and Natchtigall, 2007

[6] Richardson *et al.* 1995b

[7] Erbe 1997

[8] André *et al.* 1997

[9] Au *et al.* 1985; Lesage *et al.* 1993

[10] Au 1993

[11] Lesage *et al.* 1993

[12] Au and Moore 1984

Grey whales also modify their vocalizations to optimize transmission and signal reception in response to growing noise levels[13]. It has been suggested that grey whales have evolved in function of an environment with a determined ambient noise, and will thus[14] be especially sensitive to changes in this environment. It has also been suggested[15] that the ability to detect low intensity sounds could be of great importance for the wellbeing of cetaceans. The following table summarizes these and other experiments related to the masking of signal on cetaceans.

Summary of relevant articles on the masking of acoustic signals of cetaceans

Species	**Experiment objectives**	**Results and conclusions**	**Source**
Beluga (captivity)	Analyze the noise effects of icebreakers and the elaboration of *maskograms* to illustrate masking zones around various noises.	Masking radius: - 15 km for "bubbler system" of icebreakers (SPL 194 dB re 1µPa) - 22 km from propeller noise (SPL 203 dB re 1 µPa ref 1m) Melting ice does not seem to contribute to the masking of beluga signals.	Erbe 1997; Johnson *et al.* 1989
	Analyze the effects of icebreakers in masking noise and the construction of a model to process the effect.	The noise from the bubbler system in icebreakers and the "ramming" of the ice produces a noise masking signal rate of 15-29 dB. The masking zone for beluga vocalizations extends for over 40 km.	Erbe and Farmer 1998; 2000, Erbe *et al.* 1999, 2000
	Study the vocalizations of belugas when there is an increase in ambient noise.	Belugas change their vocalizations when there is an increase in ambient noise. With low frequency noises an animal increases the level and frequency of its vocalizations in a possible attempt to avoid masking.	Au *et al.* 1985
Beluga	Study the vocalizations of belugas as a response to boat noise.	The belugas increased the frequency of their vocalizations and change to higher in response to	Lesage *et al.* 1999

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[13] Dahlheim 1993

[14] Crane and Lashkari 1996

[15] Gordon and Moscrop 1996

		boat noise.	
Sperm whale	Study the behavioral responses in sperm whales after the emission of different acoustic sources with the objective of diverting them from shipping lanes and avoiding collision.	The sperm whales that were studied did not react to the majority of the emitted signals despite the very high level of the first exposure. They did momentarily cease making their ‘clicking’ echolocation signals after having been exposed to a series of artificial codas.	André *et al.* 1997
Long fin pilot whale	Study pilot whales vocalizations as a response to the “Head Island Feasibility Test/HIFT” 1991.	Pilot whales ceased all vocalizations when exposed to HIFT.	Bowles *et al.* 1994
Dolphins	Study the effect of masking noises in dolphins while using echolocation.	The capacity of distinguishing and detecting targets can be seen to be severely reduced by the introduction of masking noise.	
	Study the effects of ambient and anthropogenic noise in dolphins.	The capacity to distinguish and detect objects diminished severely upon the introduction of making noise. On many occasions dolphins compensated for the presence of masking noise by emitting more “clicks” by sweep.	Au 1993
Bottlenose dolphins	Demonstrate that natural sounds (shrimp) can degrade the detection range of dolphin prey by means of echolocation.	In an ambient noise of 55 dB re 1 µPa^2/Hz there is a reduction of 46% in the detection range (going from detecting a 28 cm cod from a distance of 173 m to detecting it from 93m away).	Au *et al* 2007
	Model the noise masking zone from pile driving and wind farms.	The masking zone for strong vocalizations is from 10-15 km, and up to 40 km for those weaker vocalizations.	David 2006
Harbor porpoise	Study the 3 types of wind power generators in Denmark and Sweden	It’s unlikely that this noise reaches dangerous levels at any distance from the turbines, and this noise is not considered capable of masking	Tougaard *et al* 2009

	(Middelgrunden, Vindeby, and Bockstigen-Valar). The turbine noise was only measured above the ambient noise in frequencies below 500 Hz.	porpoise communication.	
	50% of the detection of a porpoise's auditory threshold for a narrow band modulated frequency signal of 4.0 kHz where studied using behavioral methods, in the bottom noise level of a swimming pool and with two levels of masking noise.	The masking consisted in a noise in a 1/6 octave band with a frequency of 4.25 kHz. Its amplitude was reduced to 24 dB/octave on both sides of the respective spectrum plane. The auditory system of the animal responded in a linear form with the increase of the masking noise. Given that the narrow band noise was centered outside of the test frequency, the critical ratio of the porpoise for tonal signals of 4 kHz in target noise, can only be estimated to be between 18 and 21 dB re 1µPa.	Kastelein and Wensveen 2008
Narwhal	Study the reaction of the narwhal to icebreaker noise.	The narwhal exhibited a totally silent behavior in contrast to the known state of alarm behavior of belugas when they were exposed to icebreaker noise.	JCNB/NAMMCO 2005
Killer whales	Study the vocalizations of killer whales as a response to its interaction with whale watching boats.	It was suggested that the Killer whales change frequency and prolong their vocalizations in response to the presence of whale watching boats.	Foote *et al* 2004
Humpback whale	Study humpback vocalizations as a response to low frequency active sonar transmissions.	Some humpbacks were observed to cease vocalizations, while the songs of others were 29% longer at a maximum received level of 150 dB. Miller *et al.* 2000 signaled that perhaps this was to compensate for interference. Fristrup *et al* (2003) showed that humpback's songs were up to 10% longer, two hours	Miller *et al.* 2000; Fristrup *et al*. 2003

		after the exposure to sonar.	

1. Modeling effort

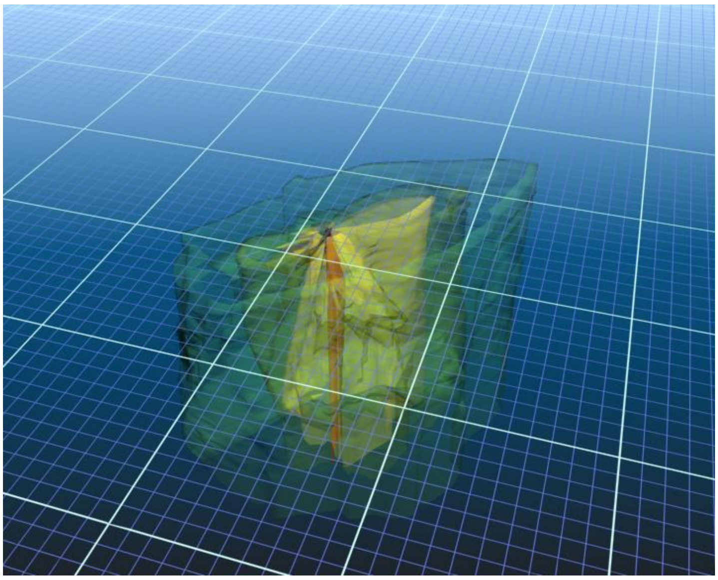
In order to model and manage the relationship between anthropogenic noise and marine mammals, the following process was followed:

First, measurements were taken from various sound sources, including ships and oil & gas prospection in different environments (e.g. literature, partners data and own data).

Second, to estimate the noise contribution to an area where an activity takes place or a ship passes through, the source levels had to be estimated for the measured ships. This was done through simulations using ORCA, computing the propagation loss and subsequently the source levels using the measured levels. The focus here was on the frequencies that are defined in the GES (Good Environmental Status, Marine Strategy Framework Directive) descriptors on noise. For these frequencies and ship speeds that were measured, the Doppler effect was considered to play an insignificant role and was therefore ignored.

Third, the sources of sound (oil prospecting ships) were placed in a different environment and using their estimated source the background noise levels in the environment were computed. For this different methods available in the ocean acoustic library were used.

Last, the data was entered into SONS-3D, the three-D simulator developed by the LAB to combine the noise produced by anthropogenic sources with cetacean presence and to assess the influence of these sources in the nearby area.

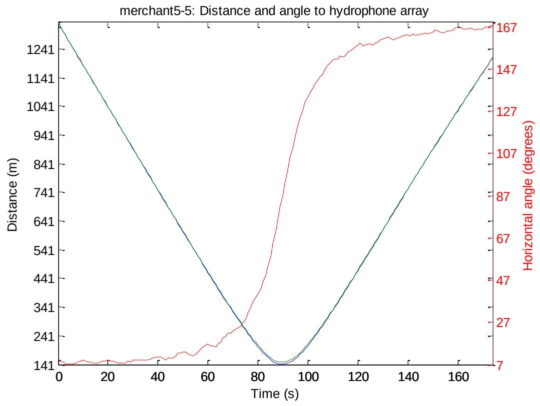


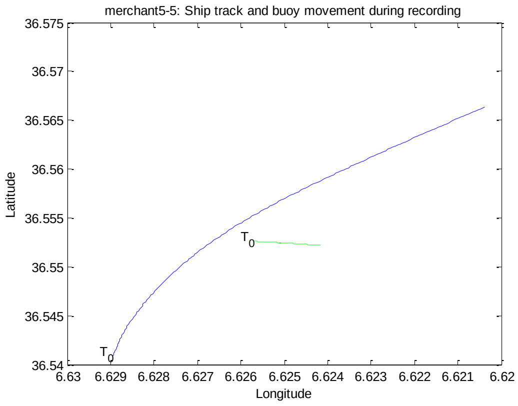
3D reconstruction of a merchant ship acoustic diagramme

Example of the processing : Merchant Ship

- Ship Track :

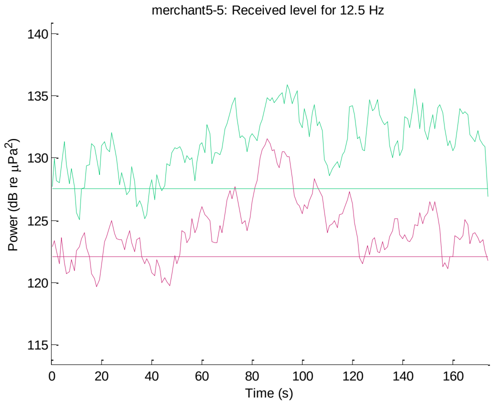
Ship distance and angle to hydrophone array. The time is in seconds from T_0 which was based on the start of the recording or GPS data.

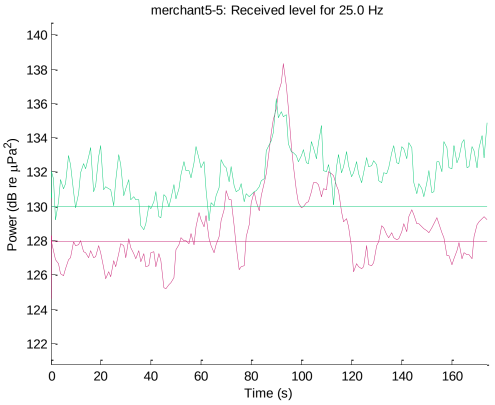




- Signal quality :

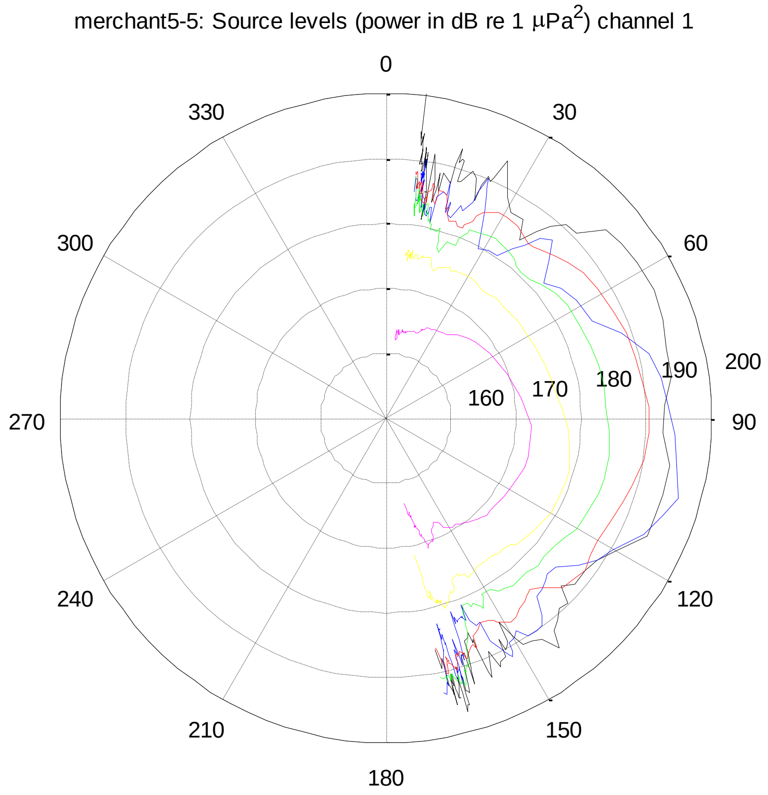
In the figures, the red line represents channel 1, the green line channel 2. The horizontal lines are the noise estimates based on the noise recordings. The two figures show the noise and signal in the 12.5 and 25 Hz third octave bands.

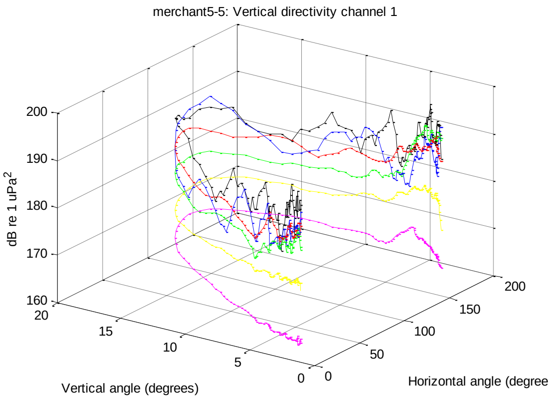




- Directivity :

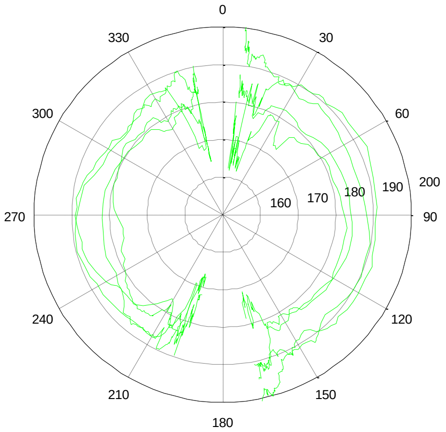
These directivity figures should be considered as estimates due to some uncertainty in the noise signatures. The small range in vertical angle did not allow the estimation of a good vertical profile.

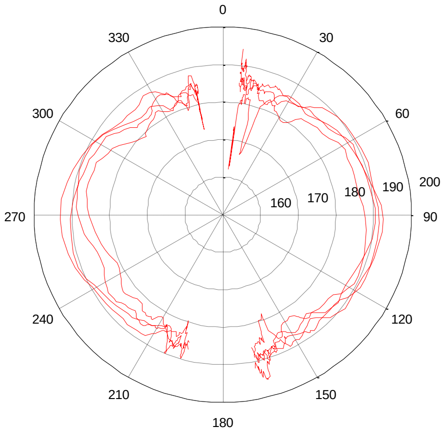


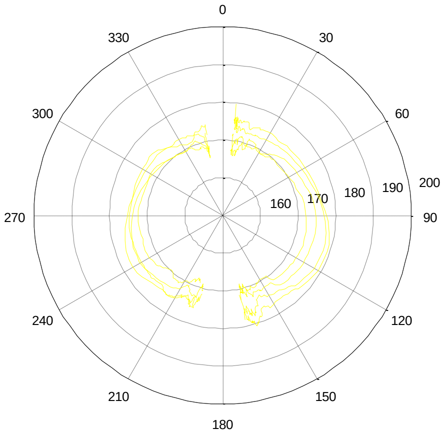


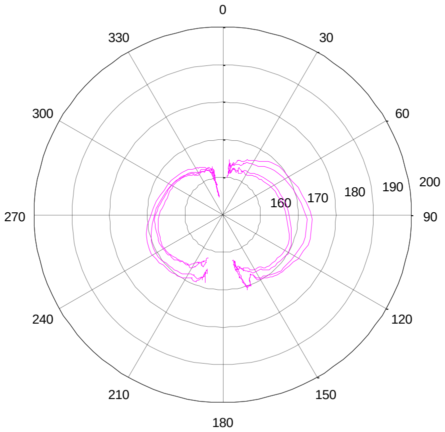
2. Summary Information

Below graphs show an overview of the estimated source levels for each frequency. The plots combine all runs and both hydrophones. Inconsistent source levels between runs may be caused by differences in ship speed and proximity to the hydrophone. Especially at the lower frequencies the poor signal to noise ratio adds to some inconsistency in source levels.


merchant5: Source levels for 63 Hz


merchant5: Source levels for 125 Hz

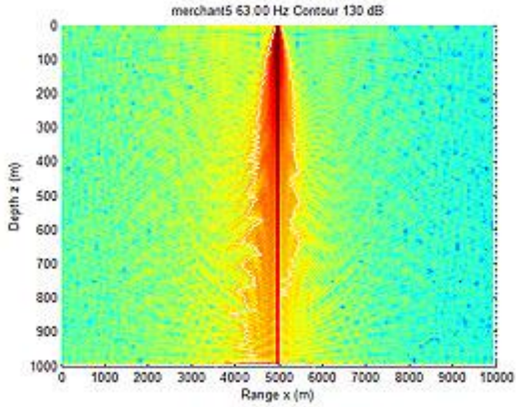

merchant5: Source levels for 1000 Hz

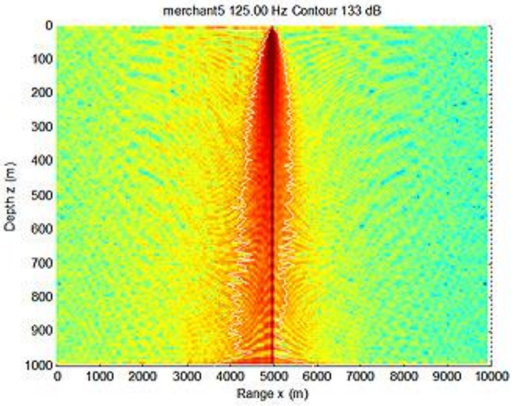

merchant5: Source levels for 5000 Hz

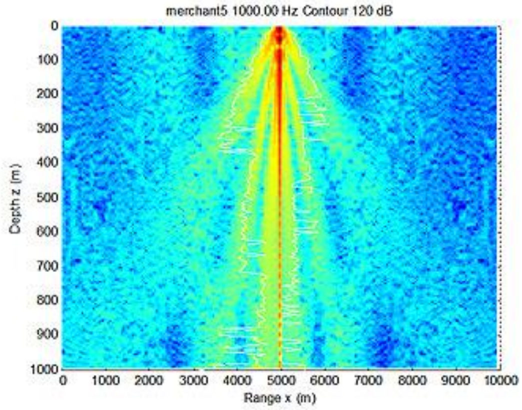
3. Propagation into the Environment

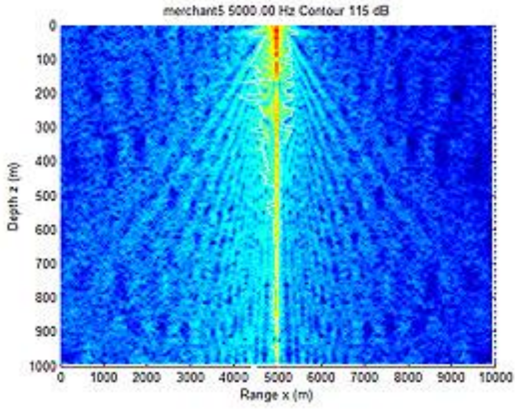
Vertical cross-sections

The four images below show the sound levels for a measured merchant. This ship was placed in the centre of a 10 km long range. The **vertical cross-sections** were taken along the length of the ship. To assist interpreting the graphs a white contour level is plotted at certain dB levels.



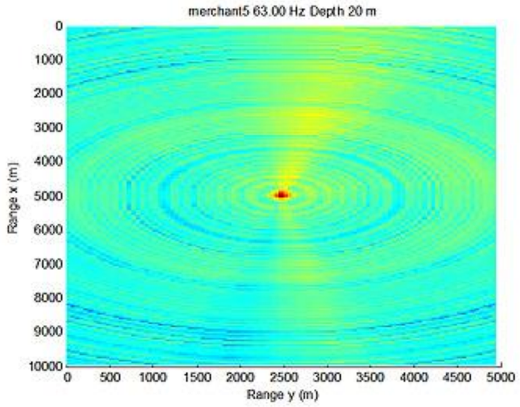


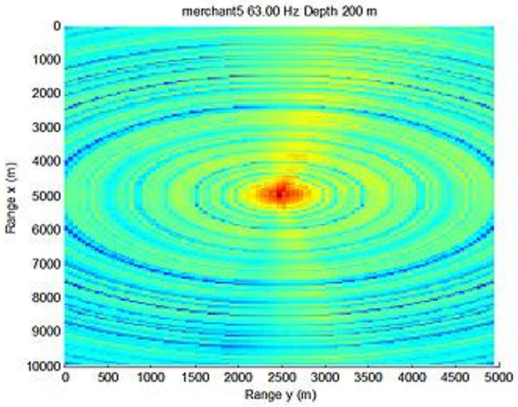


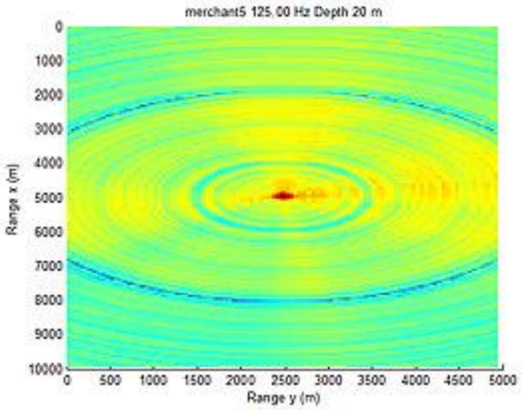


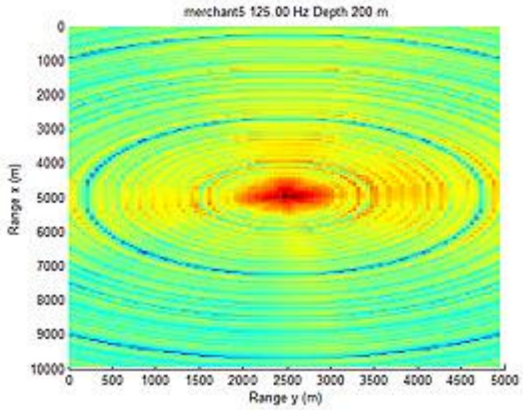
Horizontal cross-sections

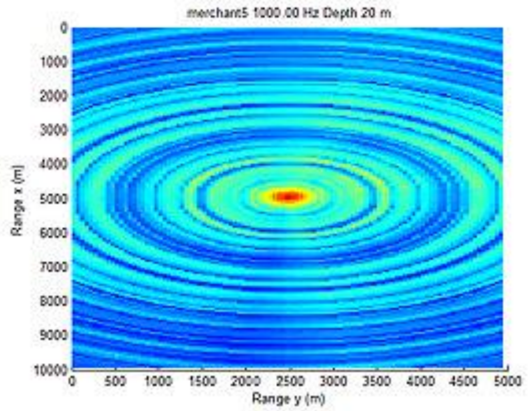
The following images show the sound level at 20 and 200 m depths in **horizontal cross-sections**. The ship was placed in an area of 10 by 5 km. The axis of the ship was along the x-axis in the positive direction. The directivity pattern that was measured in WP2 is clearly visible, especially at low frequencies. The patterns were smoothed to remove abrupt changes and to obtain a continuous transition especially between 0 and 360 degree angles.

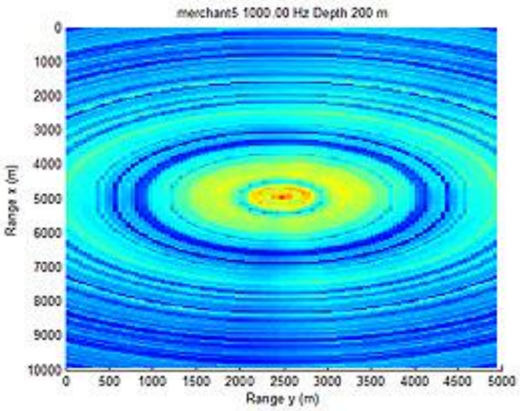










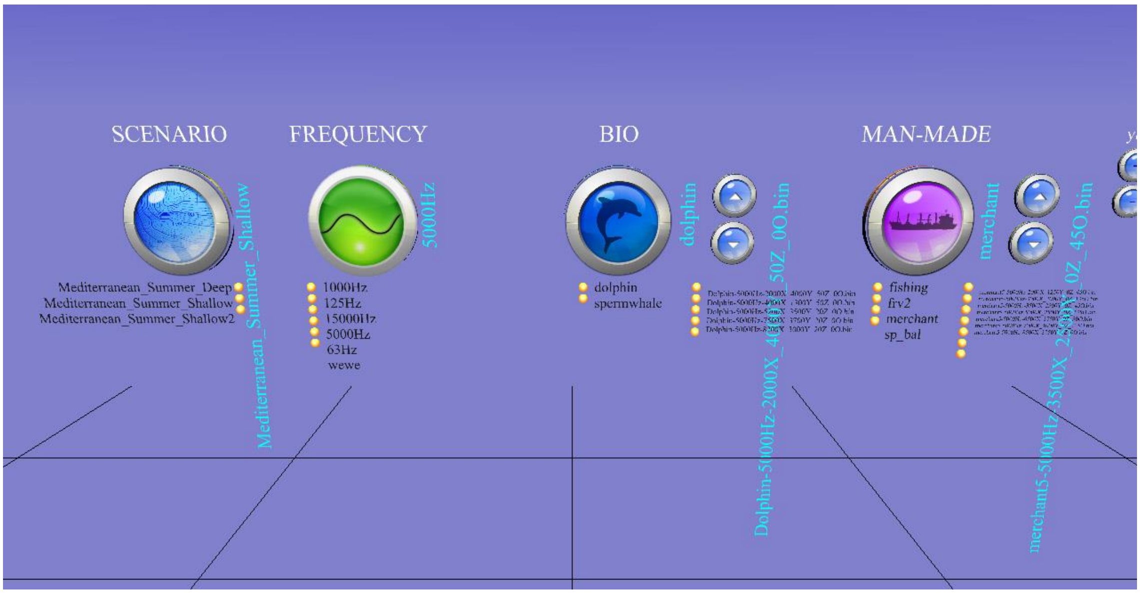


4. Assessment of shipping noise effect in the marine environment (SONS-3D):

Because, the effects of noise on the hearing capabilities of most species are still not yet understood and can change with behaviour (foraging, breeding, etc.), we chose here to concentrate the noise assessment on the physical parameters involved in the noise and biological sources interactions, and look at the masking effects due to shipping noise, without including possible physiological damages.

Although many species of cetaceans produce highly directional signals, in particular for foraging (e.g. echolocation signals), their orientation in the water column was ignored in the simulations, because these animals are considered to move around continuously. **These choices allow an objective interpretation of the simulation output, intentionally avoiding controversy on pain or injury levels after noise exposure.**

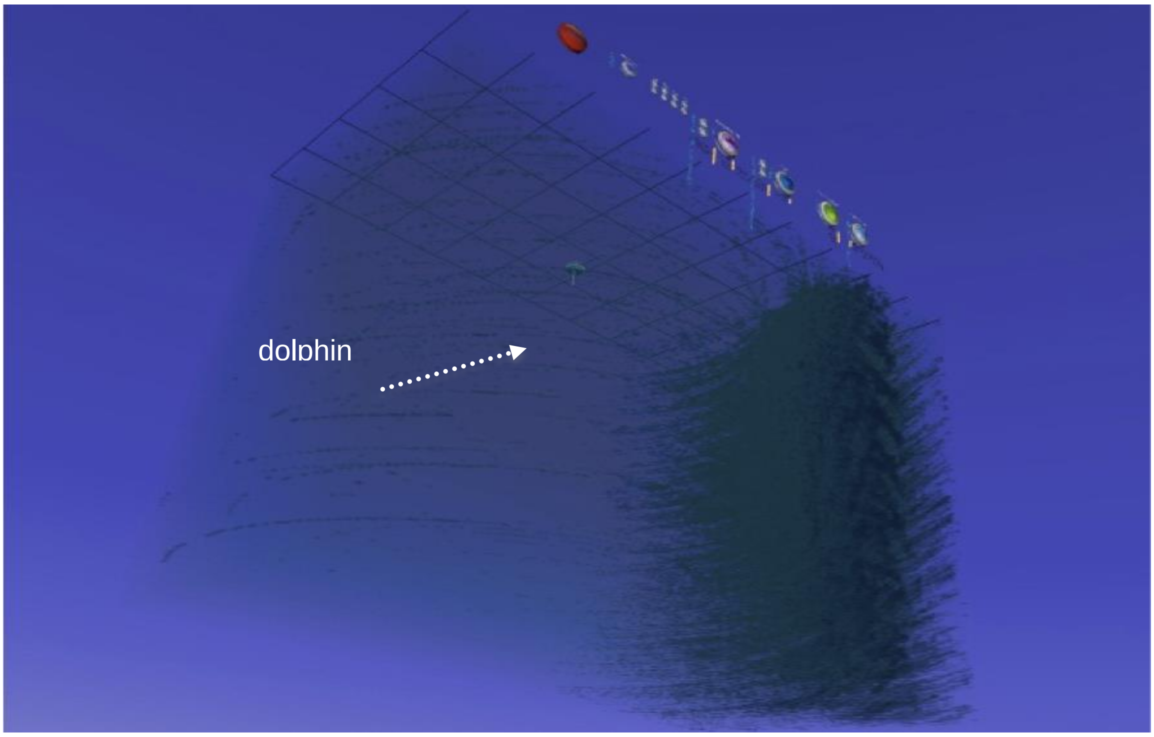
SONS-3D, the 3D simulator



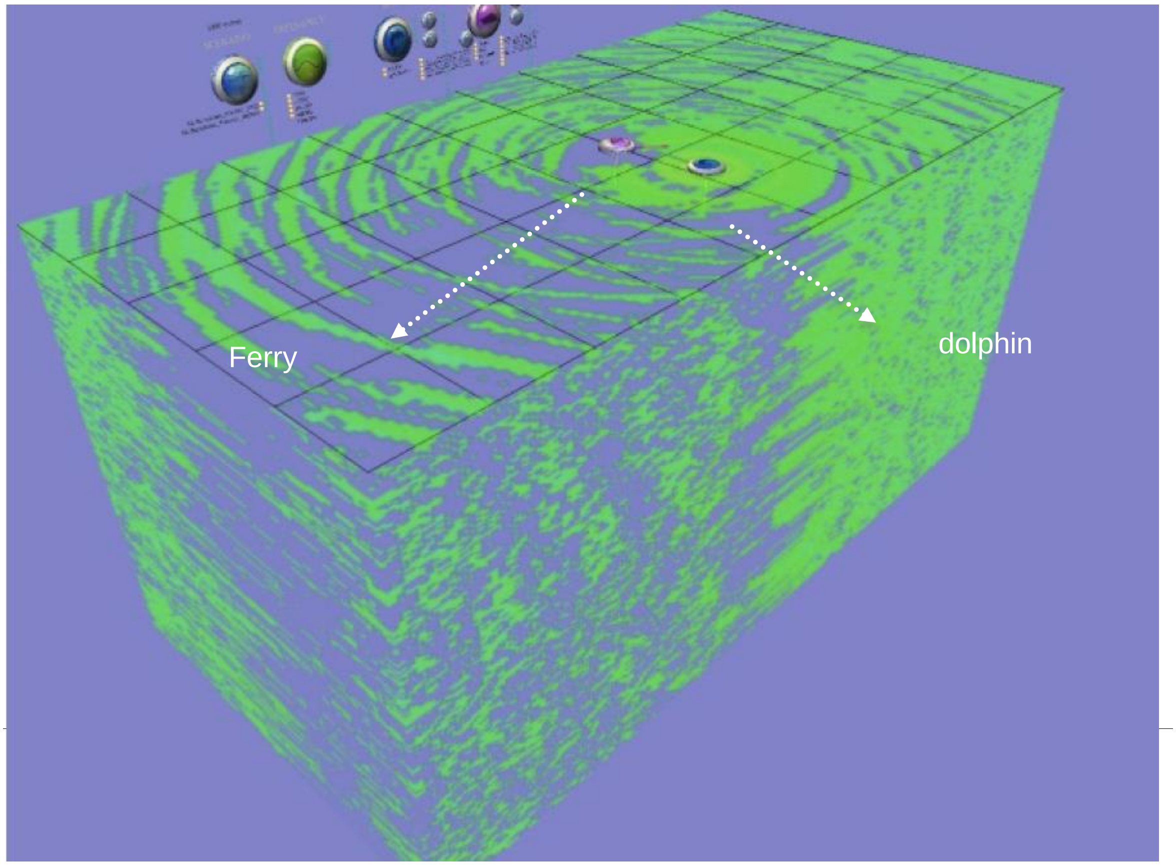
Clicking on the SCENARIO button and on FREQUENCY allows to choose the acoustic source which is modelled and its effects on biological sources. Different view modes and parameters are available, as well as the selection of axis and scales, background noise levels (set to 80dB by default), total layers to be drawn (set to 20 by default) and depth of the first and the last layer. 200 hundred layers with separation of 5m between each other, represent 1000 meters and require some minutes to be calculated. A single layer takes only a few seconds to appear on the screen. 3D moving around scenario model goes very smooth.

Scenario I: Simple Example of a Dolphin with a single ship

For the second scenario a dolphin was situated at 20 m depth next to a research vessel in a deep water environment at 5 kHz. The source level of the dolphin (whistle) was set to 165 dB. The first two images give the overview of the scenario. The discolorations indicate areas where the dolphin whistle would be masked by the ship or background noise.

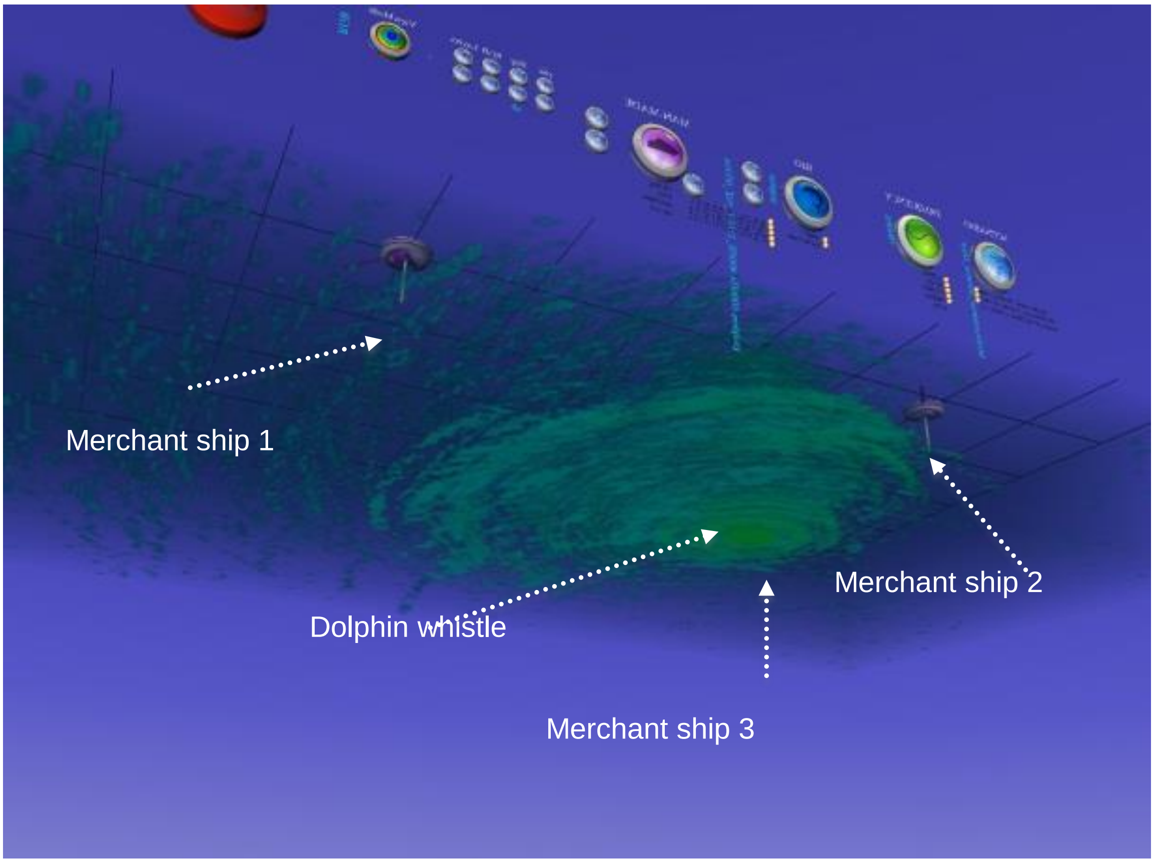


In the next image the dolphin was positioned next to a ferry. The translucent areas indicated zones where the signal could be masked by the background noise.



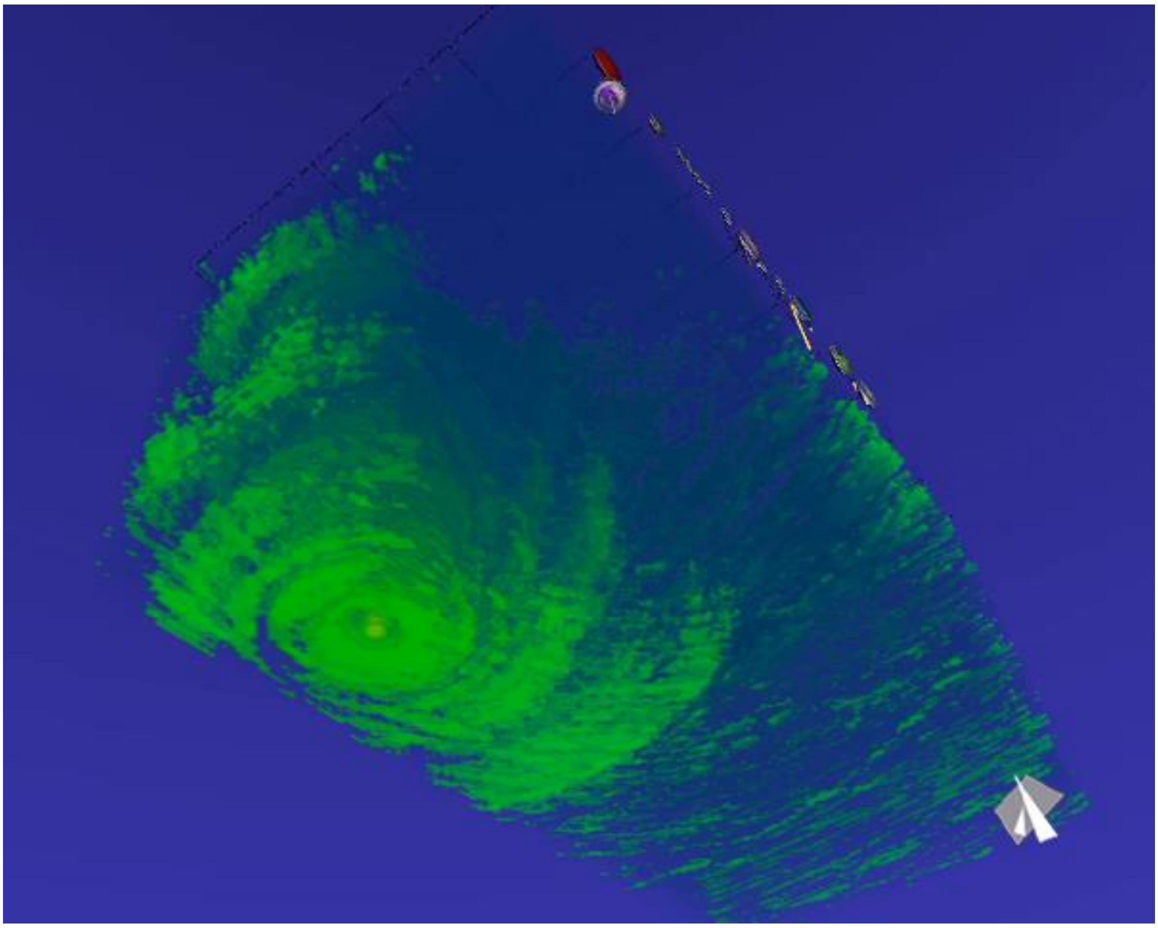
Scenario II: Example of a Dolphin with multiple ships

Elaborating on Scenario I with one dolphin and a ship, in this scenario one dolphin was placed at 50 m depth and was surrounded with three merchant ships. The coloured area now shows the unmasked zones where the dolphin whistle could be heard above background noise. While there is a small corridor between two ships, the area of communication for dolphins in this kind of environment would be very limited.



Scenario II: Example of a Fin Whale call and a Oil & Gas Streamer

Here, we placed a fin whale in the water column producing a typical impulsive call at 20Hz. The streamer was located 5km away (right corner, under the red flag), heading towards the whale. The green portion of the image below shows the whale call, while the translucent part represents the masking of the streamer noise that prevents not only the detection of the whale by passive acoustic monitoring (PAM) towed array – i.e. the sensors are typically towed at a distance of 500m behind the vessel where the ship noise totally masks the whale sound – but also prevents the whale to communicate with conspecifics.



5. Discussion

There are a number of steps that need to be taken to assess the anthropogenic acoustic impact on the environment. In deliverable 4.51 an overview was made of the presence of marine mammals in the Arctic environment and the human activities (shipping and fixed platforms) within the area of study. Especially the noise propagating from shipping traffic was studied in 2.4.3 since many measurements of ships have been available from literature, including measurements made by consortium partners. Unfortunately, much less is known from noise produced by exploration platforms and these were not yet considered to estimate noise levels in the area.

Noise produced by ships was modelled in two different ways: 1) In 2.4.3 the effort was put on estimating the sound exposure level (SEL) that animals would experience in the area. An increase in SEL may drive animals away or produce long term hearing insensitivities; 2) In this section (4.52) a more direct effect was modelled mostly concerning animals near shipping lanes based on the sound pressure level (SPL). High sound levels may lead to acute hearing problems and signal masking in the vicinity of the ship. When shipping increases, as in Scenario II, the communication and sonar range of animals can be considerably reduced for long periods of time. Both these results should be taken into account when an area is considered in need of protection. The SEL should stay low enough to avoid displacement, but also ships should pass with sufficient distance from the area and each other to avoid continuous masking.

Finally, once modelling results can be confirmed by sound measurements, the results of both 2.4.3 and 4.52 can be used with the output of 4.51 to demonstrate the acoustic impact on the environment.