The sperm whale sonar: monitoring and use in mitigation of anthropogenic noise effects in the marine environment

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Abstract

Noise pollution in the marine environment is an emerging but serious concern. Its implications are less well understood than other global threats and largely undetectable to everyone but the specialist. In addition, the assessment of the acoustic impact of artificial sounds in the sea is not a trivial task, certainly because there is a lack of information on how the marine organisms process and analyze sounds and how relevant these sounds are for the balance and development of the populations. Further, this possible acoustic impact not only concerns the hearing systems but may also affect other sensory or systemic levels and result equally lethal for the animal concerned. If we add that the negative consequences of a short or long term exposure to artificial sounds may not be immediately observed one can understood how challenging it is to obtain objective data allowing an efficient control of the introduction of anthropogenic sound in the sea. To answer some of these questions, the choice to investigate cetaceans and their adaptation to an aquatic environment is not fortuitous. Cetaceans, because of their optimum use of sound as an ad-hoc source of energy and their almost exclusive dependence on acoustic information, represent not only the best bio-indicator of the effects of noise pollution in the marine environment, but also a source of data to improve and develop human underwater acoustic technology. Here, we present how the characteristics and performance of the sperm whale mid-range biosonar can be used to develop a mitigation solution based on passive acoustics and ambient noise imaging to prevent negative interactions with human activities by monitoring cetacean movements in areas of interest, e.g. deep-sea observatories **.**

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1. Introduction

Ocean noise has always existed, both in natural and biological forms. Without any doubt, due to its recent and uncontrolled character, the massive introduction of artificial sound sources at a large scale has become a threat to its balance, more importantly than most of other pollution sources found in the marine environment.

Marine mammals depend heavily upon sound for their daily activities. The last hundred years have seen the introduction of man-made noise into the oceans on a scale never experienced during the ten million years of evolution of modern orders of cetaceans. Although the negative effects of loud sound sources such as industrial activities, seismic exploration, and vessel traffic have been demonstrated in terms of avoidance and other changes in behaviour [1], it has been very difficult to determine whether man-made sounds actually lead to mortality.

However, this situation has changed recently with the linkage of mass mortality of various cetacean species, particularly those of the beaked whale family Ziphiidae, with the use of active sonar. Anatomical evidence indicates that such high intensity sounds can cause lesions in acoustic organs, severe enough to be lethal [2, 3]. It is also suspected that the same sources may produce physically-induced or behaviourally-induced acute lesions eventually leading the animals to strand and die [3]. If confirmed, this would add yet another element of unpredictability in determining which sounds are to be considered dangerous for marine mammals. As yet, we do not fully understand under what circumstances exposure to loud sounds will cause harm. Very many factors potentially can be involved: the sound source-level, its transmission through the water, the dominant frequencies of the sound, its duration and amplitude, the position of the animal in the water column, its behavioural and physiological state, and synergistic effects including any chronic physical damage. All these may play a part but until more research is conducted, we are constrained in the mitigation measures that we can take. These measures go, amongst others, through a better understanding of the biological properties of cetacean sonar and the use of this understanding to develop passive technologies to monitor the presence of cetaceans in areas of interest. Particularly, around deep-sea observatories where real-time analysis can be performed

Here, we present both approaches, taking the sperm whale as an example and key species for this new level of understanding.

2. The sperm whale sonar

Sperm whales are known to spend most of their time foraging and feeding on squids at depths of several hundreds of meters where the light is scarce. While foraging, sperm whales produce a series of acoustic signals called usual clicks. The coincidence of the continuous production of usual clicks together with the associated feeding behaviour has lead authors to suppose that those specific signals could be involved in the process of detecting preys. Because of the usual click known acoustic signal features differing from most of the described echolocation signals of other species, it has been long speculated about the sperm whale sonar capabilities. While the usual clicks of this species were considered to support mid-range echolocation, no physical characteristics of the signal had, until very recently, clearly confirmed this assumption nor have explained how sperm whales forage on low sound reflective bodies like squids. The recent data on sperm whale on-axis recordings have shed some light on those questions and allowed us to perform simulations in controlled environments to verify the possible mid-range sonar function of usual clicks during foraging processes.

The sperm whale diet in most areas of the world, consists in cephalopods. Amongst them, sperm whales eat primarily squids and occasionally octopuses. The size of these preys varies from a few centimetres to several meters long, depending on the animal age-related diving capacity, although most of their diet consists of animals whose length are below 1 meter.

On-axis sperm whale clicks are broadband, highly directional, last for a few ms and present a very high SL. Clicks recorded off the axis of the beam pattern present a much lower directivity index and are several orders of magnitude weaker than the main on-axis pulse. The on-axis clicks have an average centroid frequency of 15 kHz. Möhl and colleagues [4, 5] and more recently Zimmer and colleagues [6] have constructed the beam pattern of the components of a sperm whale click, P0, P1, P2 and so on as well as a LF component, each of them having its own characteristics although generated by the same acoustics events. While P1 would serve an echolocation function, the LF and P0 components would be used for dive synchronisation between members as well as long range orientation.

Due to its high directionality, the forward-directed P1 pulse is well suited for echolocation. The high source level of the P1 pulse and the long ICI of usual clicks suggest a potential for long detection ranges.

Now, the question was: What is the scattering mechanism occurring off a squid when insonified by an on-axis sperm whale click and what would be the ranges at which prey targets are detected?

To answer these questions we conducted a theoretical and experimental approach aiming at determining the squid target strength and the propagation of both the incident and reflected sperm whale acoustic signal under different environmental conditions.

2.1. Scattering and Target Strength

The type of scattering that occurs off a reflective object is governed by the ratio of a representative length of the object and the wavelength. This is quantified by the product ka, where k is called the wave number and a represents the length of the object.

If $ka >> 1$, a geometric scattering applies where the frequency dependence of the target is weak: In that case, the target strength of fish, squid or crab can be approximated from the knowledge of the body length of the animal to within an error of 6dB.

If $ka << 1$, the Rayleigh scattering occurs. Here the target strength increases linearly with frequency and depends little on the particular scatterer.

At ka close to 1 there is a transition region where the TS can change dramatically with frequency. Here, the specific changes depend a lot on the particular scattering object. This transition region occurs at hundreds of Hz to a few kHz frequencies for squids of the sizes typically found in the sperm whale diet. Those frequency components constitute the lower end of the sperm whale click frequency spectrum and it could be speculated that using this lower frequency end the whale is able to detect the transition region and estimate the size of the insonified object. If this was the case, the sperm whale would adopt an opportunistic feeding strategy, detecting the size of the target before any other characteristic.

Now, although it is difficult to accurately assess the typical size of sperm whale preys, most caught squids have mantle lengths between 0.2-0.7m. Since the on-axis click occupies frequencies above 5kHz, *ka* is therefore >>1 and geometric scattering usually applies.

2.2. Squid TS measurement: experimental approach

In order to further investigate whether the target strength predictions of Love are valid for squid, and to see whether very weak target echoes could be accurately measured with a simple setup and means, we conducted measurements of the target strengths of a squid (*Loligo vulgaris*) and a cuttlefish (*Sepia officinalis*). Measurements were conducted in a 4-by-8 meter freshwater pool. The measurements were done at 15 kHz, described at the P1 pulse centroid frequency of the on-axis click. Here, geometric scattering applies (frequency independence of the target) and measurements of squid target strength could be therefore carried out at only one frequency. A schematic measurement setup is shown in Figure 1.

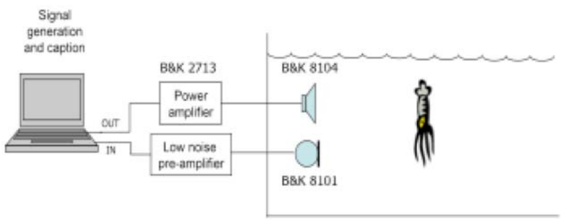


Figure 1

The same laptop handled both the signal generation and caption, avoiding this way timing problems. The target (squid or cuttlefish) was carefully emptied of air and cleaned of air bubbles. We estimated that during the measurements the dorsal side of the animal faced the transducer with an error of less than 15°.

The setup was designed to ensure that no other echo or reflection would arrive at the receiver at the same time as the target echo and that the source waveform was short enough so the direct path signal would not overlap with the target echo.

However, in light of the signal time arrivals, the last approximately 0.1 ms of the target echo might have overlaped with other reflections. To be sure of analysing only the target echo, we restricted the analysis to 0.7 to 1.0 ms after the pulse transmission.

A calibration measurement was conducted without any target present in the pool and with the hydrophone 1 m away from the transducer.

Then, the hydrophone was positioned next to the transducer which was set to send out a 0.5 ms burst of a 15 kHz sine wave every 100 ms. The transmitted burst is shown here, as well as its spectrum.

Measurements were taken without a target (Fig. 2a), with the squid target (Fig. 2b), and with the cuttlefish target (Fig. 2c).

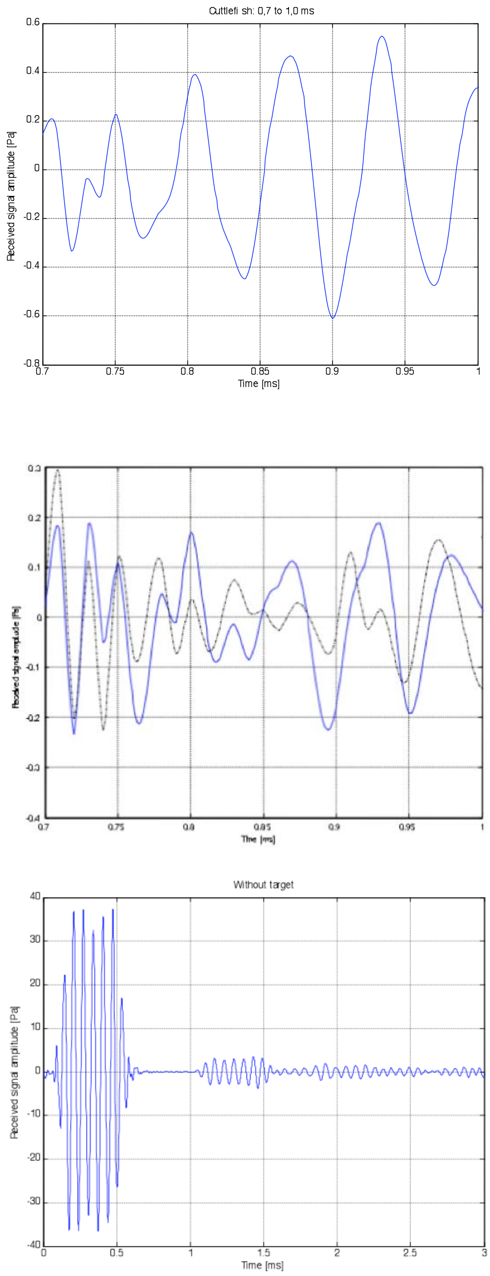


Figure 2. measurements a) without a target; b) with the squid target, solid line against dotted line without target; c) with the cuttlefish target

The received waveforms, converted into acoustic pressure, showed that there is a clear gap in the response between the direct pulse and the first reflection from the surface or bottom. The target echo occurs just in this gap. When looking at the squid signal between 0.7 and 1.0 ms the result, given in Figure 2b, showed that the signal clearly changes when introducing the squid target. (These waveforms were obtained by averaging 5000 returns.) The greatest peak-to-peak amplitude of the squid echo was 0.41 Pa. while for the cuttlefish echo it was 1.16 Pa.

2.3. Target strength estimation

The target strength of a scattering object is defined as TS = 10 log I_r/I_i = 20 log p_r/p_i

where I_r = the acoustic intensity of the scattered sound at a distance of 1 m and I_i = the incident acoustic energy.

With the previous calculated distances of the source and target and the pressure of the scattered sound field from the scatterer, we obtained the target strength of the squid as being -36.3 dB and that of the cuttlefish as -27.3 dB

2.4. Propagation

Different numerical techniques for estimating the propagation of acoustic energy in the ocean were considered. It was found that at frequencies above a few kHz, ray tracing was the best option.

The LAB has developed a ray tracing software called Songlines for use in the Whale Anti-Collision System Project. This software runs broadband propagation modelling in three dimensions with target reflections, and so is nearly ideal for the task at hand. A scenario with a vertically diving sperm whale at a depth of 300 m and a squid at 2000 m depth was developed in the model. All propagation was vertical and along straight rays.

The sperm whale click source level of 230 dB_{peak} and the diameter of the modelled circular piston radiator of 0.8 m, as given by Mohl et al (2003) were used. The *Loligo vulgaris* specimen with a target strength of -36.3 dB used for the measurements was also used as the imagined target in these simulations. The simulations were run for all frequencies in the geometric scattering region of the specimen, which was determined to lie above 10 kHz. The upper frequency of the simulations was the Nyquist frequency of 48 kHz.

The simulation results showed that in order for the spectrum level of the direct/direct path target echo to be the same as a typical deep sea noise level at sea state 1, the sperm whale would need a hearing directivity of between 21 and 24 dB between 13 and 18 kHz. Hearing directivities of 21 dB have been measured for dolphins, so such values do not appear unreasonable. This implies that a sperm whale could detect a single small squid of around 25cm long at a range of 1.7 km against a sea state 1 noise background. Higher sea states would require a more directional hearing or a better signal processing by the sperm whale auditory system. Directional hearing would also be helpful in attenuating the returns from surface and bottom reverberations. The effects of reverberation from non-specular scattering at the sea surface and seabed were not included in the simulations.

3. 3D Localization and Tracking of whales

The properties of the sperm whale sonar described in section 2 have allowed us to perform simulations in controlled environments to estimate the possibility of detecting and tracking whales by passive acoustics and ambient noise imaging from deep diving echolocating whales [7, 8, 9].

3.1. 3D Passive acoustic detection

The 3D localization is based on the acoustic signal arrival time-delays and the assumption that sound propagation can be modeled by straight rays, resolving both the azimuth and elevation on a short aperture triangular array of passive sensors and the source distance from the time arrival on a distant fourth hydrophone (wide aperture array). To predict the estimation error (Fig.3) a 3D error map is created considering and discarding when appropriate the following error-sources:

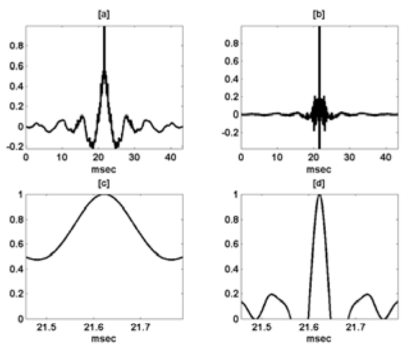
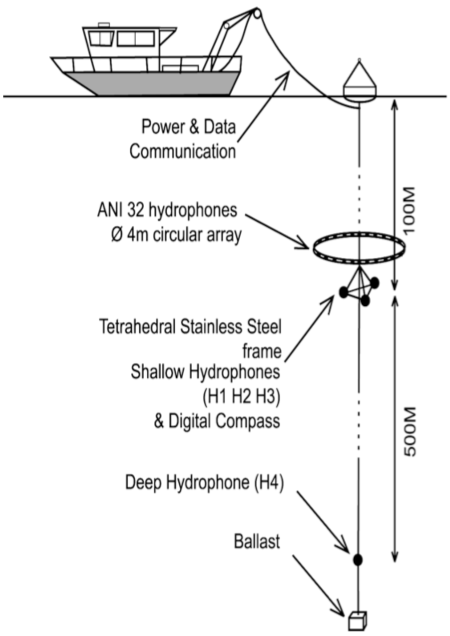


Figure 3. Auto-correlation function of a sperm whale click, sampled at 48kHz and interpolated by 10: [a] low-pass filtered at 5000Hz, [c] is [a] zoomed 35μsec around the peak, [b] full spectrum (100Hz-24kHz), [d] is [b] zoomed 35μsec around the peak. Cross-correlation allow more precise time-delay estimates when the full bandwidth is used.

• Sound speed error and the straight ray assumption
The speed of sound is highly depth-dependent and therefore the estimated average used will give a quantifiable error. We use an average such that this error is minimal at low depths, accepting that it will

give some error when the whale is at greater depth. A frequency dependent curved ray solution of click propagation showed a few microseconds differences in arrival times compared with straight rays when whales were 2km deep within the range of interest (~ 5km).

• Cross-correlation peak time
The top array has a relatively short aperture (a 3m side equilateral triangle), which will play a large role in the positioning error. (We need either a high sampling frequency or a fast interpolating filter and an accurate matching algorithm to precisely calculate the TDOA of a click at different hydrophones. Accordingly) We use a wide bandwidth (100Hz-24kHz) to take advantage of the click inherent broadband transient characteristic and interpolate 10 times to recreate the analog signal shape and avoid round-off errors due to Nyquist sampling. With this configuration, the 3D localization algorithm calculates the whale’s position from one click in the 3000m water column and at a 5km diameter range with a 50m maximum error distance.



3.2. Detecting silent whales from deep diving echolocation whales

The system further integrates the tracking of acoustically passive whales or silent objects by a sperm whale click-based ambient noise imaging sonar. As an alternative to conventional sonar, an innovative solution called Ambient Noise Imaging (ANI) fills the gap between active and passive solutions by using sound underwater in comparable ways as terrestrial life forms use daylight to visually sense their environment.

Instead of trying to reject the surrounding ocean background noise, ANI indirectly uses it as the illuminating source and searches the environment for a contrast created by an object underwater. The solution introduced here is conceptually based on both ANI and multi-static active solutions, where the active sources are produced by surrounding foraging sperm whales at greater depths (from 200 meters downwards), which vocalize on their way down and at foraging depths, and in reported cases, likely on their way up until a few minutes before surfacing. A non-acoustically transparent object placed in the ocean and illuminated by a sound source will inevitably create an acoustic contrast that can be relatively high if the object size is greater than the acoustic wavelength and its impedance greatly differs from that of water. The measurability of this contrast depends on the received signal-to-noise ratio (SNR) at the monitoring point. The sonar equation calculates the detection threshold (DT) of this object if the following parameters are known, *i.e.* source level (SL), transmission losses from the source to the object (TL_1) and from the object to the receiver (TL_2), object target strength (TS), reverberation level (RL), noise level at the receiver (NL), and the directivity index of the receiver (DI). Defining DT and SE as detection threshold and signal excess, the bi-static sonar equation is:

$$\mathbf{SE = SL - TL_1 + TS - TL_2 - (RL + NL) + DI - DT}$$

All variables here being frequency dependent, projecting the broadband problem into sub-bands can help detect the bandwidths contributing to greater Signal Excess. In a simple scenario, where only free-field sound pressure levels are simulated, in a homogenous ocean where moreover propagation is considered spherical, the bi-static detection of a whale using others clicks can be therefore simulated solving the bi-static sonar equation.

The 3D simulation of wave propagation from source-to-receiver and source-to-object-to-receiver in the bounded medium is implemented by a ray tracing software designed by the LAB. This well documented and thoroughly utilized method provides good approximation of the full wave equation solution when the wavelength is small compared to the water depth and the bathymetric features. An arbitrary number of acoustically active whales and one passive object defined by a 3D target strength function can be arbitrarily positioned in the three dimensions. All active whales can be assigned a different and arbitrary waveform, the spectral information of which is estimated and affects the absorption parameter as well as the source radiation pattern. The simulation also provides room for an array of hydrophones at the receiver location, the advantage of which stands in the possibility to recreate the full modified click waveforms at all sensors and hence test the efficiency of a beamformer.

Figure 4 shows the resulting image and received level plots, function of time and angle of arrival. The Ø4m-32- sensor-antenna forms 32 beams in azimuth, the levels of which are represented. The image colorbar is adjusted so that only levels between ambient noise level + 6 dB are displayed. This adjusted contrast allows clear highlight of the silent whale response to the others clicks at 330º. A projection of the cumulated result over the 25 second period is plotted below the image. Beams are affected by the direct and reverberated paths taken from the vocal whales clicks directly to the buoy (all over 70dB)

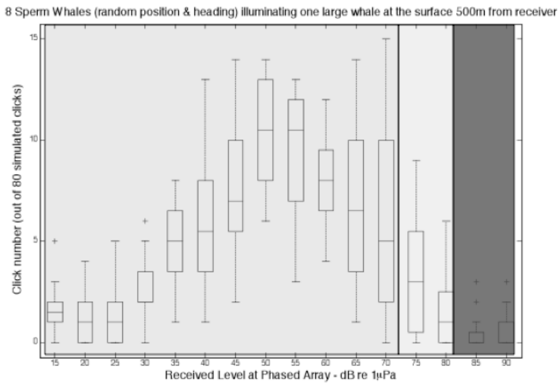


Figure 4. Expected Signal Levels (dB) from a 10-15m whale in a 3D plane, 500m from receiver, illuminated by 8 Sperm whales with random position & heading – BW = 1-10kHz, SL=220dB, DI=15dB

4. Conclusions

The TS experiments on small squids at 15kHz confirmed theoretical measurements and gave values of around – 36 dB for squid with a mantle length of 25cm. The sperm whale on-axis click would allow to detect a single 0.25m squid at a range of 1.2 to 2.2km depending on sea state noise levels, with a reasonable directional hearing. Large aggregation of squids would extend this range and allow the detection at several kilometres. Sperm whale usual clicks appear to be suited for mid-range echolocation on very low reflective and relatively small organisms like squids (< 1m), at ranges of at least several hundreds of meters.

The bistatic detection of echolocating and silent whales is possible through passive acoustics and ambient noise Imaging. Sperm whales seem to be a good candidate as an illuminating source, due to a broader low frequency spectrum and a more powerful broadband beam, Above Sea-state 2, detection needs filtering and/or higher resolution array. Behavioural data are needed to build a proper 3D statistical model on whale positions and headings. Real conditions experiments are planned to validate these results.

Acknowledgments

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