# GUIDELINES FOR PREDICTION AND EVALUATION OF ACOUSTIC IMPACT ON UNDERWATER FAUNA

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For human beings, the most important sense is vision. In case of aquatic mammals, hearing plays a fundamental role in the interaction with the surrounding medium. Unlike light, which dissipates quickly underwater, sound can travel farther and with greater speed under water than in air, allowing animals to communicate over long distances. Noise produced by human activities have the ability to modify the underwater acoustic environment, potentially altering natural processes such as mating, hunting and survival of living beings that inhabit it, even causing permanent hearing loss. The noise associated with construction activities of port sectors (such as underwater blasting, pile driving, welding, dredging, etc.) as well as seismic exploration, could have harmful effects on marine life. In this paper are reviewed the major technical and methodological issues involved in the assessment of noise impact on underwater animals, providing guidelines to address specific projects, considering, inter alia, acoustic descriptors, the differentiation between natural and anthropogenic underwater noise sources, sound attenuation factors in underwater environment, effects of noise on marine life, and regulation commonly used in Chile
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## 1. Introduction

In recent years, noise pollution has been recognized as the biggest threat to cetaceans [1]. Chilean west border is made-up by 6400 kilometres of the Pacific Ocean, one of the twenty longest coastlines of the world. This coast has 51 species of marine mammals, 36% of the world's diversity, including subjects of three groups: Whales, otters and pinnipeds (seals and sea lions). One of the biggest concerns with the background noise in the ocean is the possibility of an inability of the species to listen to each other in a noisy environment in the ocean. This concern is significant because many marine animals rely on sound for their most basic needs like food, communication, protection, reproduction and navigation. According to Jason Gedamke, marine biologist at NOAA (National Oceanic and Atmospheric Administration, US Department of Commerce), "Being able to produce and detect the sound is of vital importance for many marine species, so changes in the natural sound background of landscapes can have more impact on the health of ecosystems than previously thought" [2].

The ocean is naturally noisy with sounds of physical origin (wind, waves, rain, ice) and biological sources (whales, dolphins, fish, shellfish, etc.). The human contribution to underwater noise has increased rapidly in the past century. In some parts of the world, the low-frequency ambient noise has increased by more than 3 dB (the double) per decade between 1950 and 2007, which was attributed to commercial shipping [3].

Many marine animals have evolved to rely primarily on their auditory system for guidance, communication, foraging and detecting their environment. Underwater noise can interfere with all these functions in an individual or even a population level. The effects of noise and ranges in which happen depend on the acoustic noise characteristics (level, spectral distribution, duration, operating cycle, etc.), the sound propagation environment, and the characteristics of the acoustic receiver (the animal).

As investigated by the authors of this study, there is not a large amount of material at a legal level nor as university research linking noise with marine fauna in Chile, so it is considered of high interest to consider this topic especially bearing in mind the great length of our coast and the fact that we have endangered species such as the southern right whale (Eubalaena australis).

This paper makes an introduction to the most important issues of the treatment of the subject from a practical view and provides tools to professionals who must address the issue of assessing the noise impact on marine species in Chile, delivering thus guidelines that could be used as part of environmental impact studies in the country.

## 2. Acoustic descriptors

In underwater acoustics unit of measurement for sound pressure used internationally is the Pascal (Pa). Given the wide range of sound pressure levels that commonly occur in the underwater environment, similar to what happens in the air, underwater noise is measured in terms of sound pressure level (SPL) in decibels (dB), considering a standard reference sound pressure 1 μPa. Thus, typical levels range between 50 and 250 dB re 1 μPa [4]. Moreover, the sound pressure levels are commonly expressed in linear decibels, since usually the analysis refers to species of marine wildlife, which does not apply the scale dB(A) or dB(C). The latter is attributed to the wide expanse of audible frequency range of marine animals (7-180000 Hz) and the difference in hearing sensitivity between species.

The main acoustic descriptors to quantify effects of underwater noise are [5]: (A) Sound pressure level (SPL) – Average noise level over the measurement period expressed in dB re 1 μPa. For impulsive sources, such as impact piling and blasts, the measurement period is the time period that contains 90% of the sound energy [6]. Continuous sources, such as vibro-piling and shipping, are commonly described in terms of an SPL. (B) Sound exposure level (SEL) – Total noise energy over the measurement period expressed in dB re 1 μPa2·s. The SEL is commonly used for impulsive sources because it allows a comparison of the energy contained in impulsive signals of different duration and peak levels. (C) Peak level – Maximum noise level recorded during the measurement period expressed in dB re 1 μPa. The peak level is commonly used as a descriptor for impulsive sources. (D) Peak-to-peak level – Difference between the maximum and minimum noise level recorded during the measurement period, expressed in dB re 1 μPa. The peak-to-peak level is used as a descriptor for impulsive sources.

While there is no standard metric commonly used, acoustic descriptors are associated with the characteristics of the noise source, defining two main types of sounds: pulse and non-pulses. For the pulses kind of sound there are single pulse and multiple pulses. In practice, the distinction between such signals is unclear, since it depends on factors such as (a) the source type, (b) the propagation characteristics in the environment where it is generated the sound pulse and (c) the distance between the sound source and receiver in the underwater environment. Some signals have characteristics of both pulse and continuous, while sometimes the same source can generate two types of sound; for example, a motorized vessel that drag and operates an air gun array.

## 3. First page of the manuscript Noise sources

### 3.1 Noise from natural sources

According to numerous studies [7][8], the ambient noise in the underwater environment is a conformation of several components, among which are the turbulent pressure fluctuations, wind dependent noise from surface agitation, oceanic traffic, marine life and seismic activities, to name a few. Each of these components presents an extensive spectrum range. The sound from waves or wind range from 100 Hz to 50 kHz. The contribution from seismic or volcanic activities are below the 100

Hz. The noise from rain, snow or hail is in the range from 100 to 500 Hz, and can increase the levels up to 35 dB. In some cases, ice can decrease ambient noise in the range from 10 to 20 dB [9]. In general, this noise are short in duration, repetitive and include a variety types of sound (cries, moans, grunts, chirps, whistles, among others) [7]. The marine mammals occur in three orders: Cetacea, Sirenia and Carnivora [10]. Among the Cetacean are two groups, odontocete and mysticete. Odontocete communicate between the frequencies of 1-20 kHz with level from 100 to 180 dB [10], and many of them use echolocation, which operates in the 20-150 kHz with level that can reach >210 dB. Mysticetes are apparently sensitive between 12 Hz to 8 kHz, and don't have an echolocation system. In both orders, the mobility is from nearshore to deep waters. In Chile it is possible to find many species of Mysticeti and Odontocete, among which it is worth mentioning Cephalorhynchus commersonii, Cephalorhynchus eutropia, Lagenorhynchus australis, Lagenorhynchus cruciger, Lagenorhynchus obscurus, Phocoena spinipinnis among others.

Another biological sources are fish and invertebrates. Sharks are mainly silent, but respond to sound from preys [9], however the acoustic behavior or most fish species are unknown, the major contribution is in the choruses from fishes, which can increase up to 20 dB the ambient noise levels in the 50 Hz to 50 kHz band.

## 3.2 Anthropogenic sources

(A) Commercial navigation: Worldwide, the greatest contribution of acoustic energy at low frequency (5-5000 Hz) is from this source. Vessel noise is generated primarily by the action of the propeller, the drive motor and the water flow under the body of the boat (hull). Propeller noise is associated with cavitation, consisting in the generation of vapor cavities in form of bubbles, product of movements which decrease the fluid pressure. Cavitation noise, which has components of broadband and tonal components, accounts for 80-85% of the acoustic energy generated by a boat [11]. A 54 kGT container ship has a broadband source level at 188 dB re 1 μPa@1m [12] (B) Sonar: The sonar systems (Sound Navigation and Ranging) are used for ocean exploration, seeking information of objects within the water column, on the seabed or in the sediment. To do this, the method sonar system creates the acoustic energy and then listens for the sound energy reflected and / or dispersed. These systems are classified as low-frequency (below 20 kHz) and are used in military, commercial and civilian applications [11]. Military sonar is used for the detection, location and classification of targets. Compared to the commercial sonar, this application involves a wider frequency range and higher levels of power. Among them, active sonar low frequency is used for surveillance, tactical sonars medium frequency are used for submarine detection, and high frequency sonar, commonly incorporated in weapons (such as torpedoes) or defense systems. Commercial sound systems are used for finding fishing, probing deep and profiling of the water column. The devices used for search fishing range around 12 kHz with source levels of 125-133 dB (Leq re 1μPa) [13]. "Civil" sound applications are diverse, including their use for research is highlighted. The main applications of this type correspond to deep water measurement, seabed and sedimentary layers mapping and location of fish banks or other objects. Generally using medium frequency signals (> 12 kHz) depending on the object to be located and depth. They generally use medium frequency signals (> 12 kHz) depending on the object to be located and depth [11]. (C) Seismic exploration: Conducting seismic surveys in the marine environment generally aims to analyze the composition of the seabed, as well as being the main technique for locating oil reserves and natural gas. They are also used to gather information on the origin of Earth and the movement of the plates of the earth's crust. The sources used in geophysical studies are characterized by generating high sound pressure levels, at low frequency and short duration. The most used sources are air guns, Sleeve Exploders and gas guns and Vibroseis, the most prevalent today are gas guns. These devices generate pulses every 10 to 15 seconds, and involve higher levels of power compared to the other methods, and can reach levels around 250 dB ref 1 μPa @ 1m [15]. (D) Exploration and production of gas: Production activities of oil and gas generate low frequency underwater noise, which is mainly associated with drilling activities [10]. The vessels most commonly used for development are commonly called "jack-up rigs" (towers or jack-up rigs). The noise is mainly produced by the drilling machinery, and propellants and propellers used to maintain the position of the boat. The activities associated with oil exploration industry have become historically the biggest source of acoustic activity of surface water (<200m). In recent years these activities are moving to deep water (up to 3000 m). Drilling and gas production in deep waters have the potential to generate higher levels of noise production in surface water due to the type of ships and drilling machinery employees, and floating production platforms. In addition, the noise generated in deep water can easily be associated with a deep channel, where sound spreads long distances [11]. (E) Industrial activities and construction. (E1) Dredging: These tasks are often carried out in coastal waters, to get deeper into channels and / or ports, extend seaward land or harvest marine resources. As for the main sources of noise are two types, the dredger ship and the machinery used for digging and material movement. Registered levels ranging from source 160 to 180 dB re 1 µPa at 1m, between 50 and 500 Hz. (E2) Drilling: These activities are commonly carried on construction of maritime infrastructure. To a lesser extent, the drill is used in oil and gas exploration. The emission generated by this source is known as a continuous moderate noise level and low frequency omnidirectional. Registered source levels are within the range 145-190 dB re: 1 µPa @1m [16]. While these emissions do not have the ability to generate damage in marine mammals, it is judged to have the potential to generate mild discomfort related to masking and behavioral disturbances [16]). (E3) Pile driving: These activities are mainly related to construction works carried out in coastal areas. The noise generated by the pile driving is manifested as low frequency pulses and can reach up to 20 kHz, usually with a high sound pressure level. While the magnitude of emissions depends on factors such as the technology used and the type of substrate, the source level can exceed 220 dB re 1 µPa and sometimes multiple pulses can be perceived above the background noise (> 120 dB) more than 10 km from the site of operation [17]. (E4) Blasting: The noise generated by blasting corresponds to low frequency pulses, which can be received by a diverse number of mammalian species, given the magnitude of sound pressure level generated. This activity is considered one of the greatest potential within the sources of anthropogenic noise. While the duration and extent of underwater sound pulse depends on the characteristics of each project, being important the location of the explosion and the mass of explosive charges, among others, the generated sound pressure levels usually range from 250-300 dB re: 1 µPa @1m [16]. This shows that underwater blasting have enough potential to cause physical injury or even death of marine mammals. Moreover, small detonations can be perceived hundreds of kilometers away as they propagate through a sound channel. For example: 100 kg loads detonated in the deep sound channel in Australia have been detected in Bermuda [15].

## 4. Underwater sound propagation

The ocean is an extremely complex medium due its inhomogeneous nature. Acoustical oceanography describes the role of the ocean as an acoustic medium by relating oceanic properties to the behavior of underwater acoustic propagation. The main effect of propagation is to decrease the signal amplitude, by geometrical spreading and absorption. In addition, the sound is also affected by the conditions of the surface and bottom boundaries of the ocean as well as by the variation of sound speed within the ocean volume [5] [18].

The prediction of the sound power loss dB due to propagation it is characterized with the Transmission Loss (TL) parameter, whose various components are detailed below. It is noteworthy that, for convenience, in this study are listed only the most relevant aspects related to wildlife impact assessment, even though there are other underwater phenomena and additional variables that can influence the underwater acoustic propagation.

### 4.1 Transmission Loss by geometrical spreading (TLS)

As during the propagation of an acoustic wave in the air, under water acoustic energy radiated from a source is distributed over an ever larger as surface issue spreads, and since energy is conserved, its intensity decreases inversely proportional to said surface [18]. Attenuation geometric divergence can be approximated by equation (1) where R is the distance (range) from the source, in meters, and X is a factor depending on the type of propagation. Near the source, where the sound is spread evenly in all directions, their propagation is spherical, and therefore X = 20. However, in shallow water, the spread is cylindrical and which is limited by the seabed and the surface, using a value of X = 10 [8].

$$TL_S = X \cdot log(R)\ [dB] \qquad \textbf{(1)}$$

While some authors propose the use of an X = 15 [19], a mixed model which consider first a spherical propagation to a distance R = H (depth) and then a cylindrical propagation is also proposed. In the Figure 1-A an example of TLS for a source of 200 dB @1m re 1µPa seen. In the combined case, the sound spreads spherically until R = H = 100 meters, and cylindrically thereafter. Note that the TLS is f-independent [8].

## 4.2 Transmission Loss by absorption (TLA)

Seawater is a means of sink propagation as it absorbs part of the energy of the transmitted wave due to his viscosity, which effect is proportional to the square of the frequency, and also due to some chemical reactions, as in the case of sulfate magnesium (MgSO4), and boric acid (B(OH)3) [18].

The absorption attenuation in dB is mainly determined by the attenuation coefficient in the propagation medium, α [dB/km], and the distance covered in kilometers [18]. The α parameter is often the most limiting acoustic propagation models due to the complexity of its estimate, mainly because of its high dependence on the frequency.

Since the beginning of the study of underwater acoustics, it has paid much attention to its modeling and several models have been proposed [5]. Equation (2) developed by Thorp (1967) [20] is probably the most widely used as a basic model, which is valid under the 50 kHz and where f is the frequency in kHz.

$$\alpha(f) = 1.0936\left[\frac{0.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2}\right]\ [dB/Km] \qquad (2)$$

More recent formulas for the absorption coefficient have been described by Fisher and Simmons (1977) [21] and Francois and Garrison (1982) [22] [23]. Ainslie and McColm (AM) (1998) [24] simplified a version of the Francois–Garrison (FG) equations for viscous and chemical absorption in sea water by making explicit the relationships among acoustic frequency, depth, sea-water absorption, pH, temperature, and salinity. In the Figure 1-B it can be seen that this simplification, valid between 100 Hz and 1 MHz, is very similar to the original model.

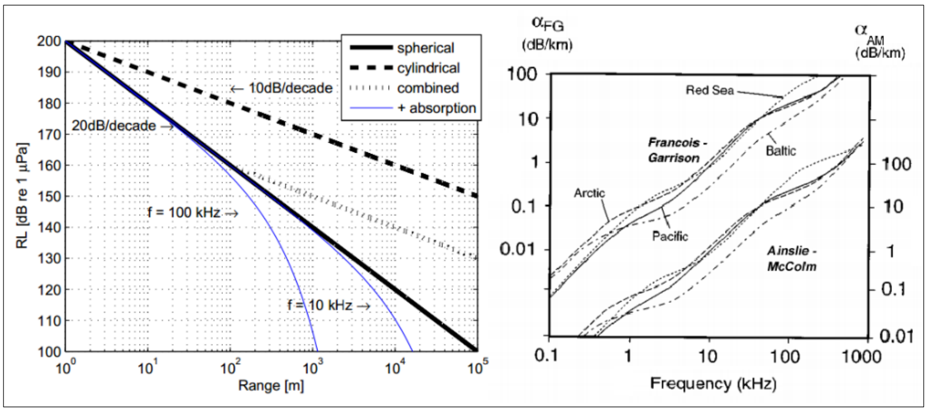

Figure 1: A (left): TLS. Thin lines: Spherical spreading + f-dependent absorption for f = 10 kHz and f =100 kHz. B (right): Absorption coefficients for four oceans calculated using FG method and AM simplification. (See the oceanographic parameters in Table I of [8])

### 4.3 Refraction and reflection phenomena

The speed of sound (c) varies spatially in the ocean, mostly with depth (z), because of temperature and pressure constraints. The form (profile) of curve of c(z) and the distribution of the sound velocity gradient with depth, rather than an absolute value of the sound velocity, are more important for the propagation of sound in the ocean. The different components can combine to form very varied sound velocity profiles, depending on environment conditions and local processes (currents, thermal fronts, eddies, surface with very cold water). This way, the paths of sound waves are refracted, depending on the velocity variations encountered, which of course complicates the modeling and interpretation of the sound field spatial structure [18] [9]. For a negative gradient of velocity, the sound is refracted downward direction, while for the positive gradient of velocity, the sound is refracted upward, in both cases according to the famous law of Snell-Descartes. Because of this phenomenon, in the horizontal layer of water, whose axis is named Sound Axis Channel corresponds to the minimum speed, a wave can travel long distances with minimal attenuation [3]. In some cases a surface layer (surface channel) in which a pattern with reflections and refractions up on the surface (down) is generated. So, for one type of profile c(z) the sound can propagate hundreds and thousands of kilometers, and for another type, sound of the same frequency propagates only as far as a few tens of kilometers or even less [25].

In addition, the transmission path is often not only the direct path between the source and receiver. Multiple transmission paths can occur due to reflections from the surface and seafloor [4]. As the underwater propagation medium is limited by two well-marked interfaces (the bottom and the surface), the propagation of a signal is often accompanied by a series of multiple paths generated by reflections at these two interfaces which generate a pattern of spatial interference fringes and losses related to certain frequencies, ranges and depths [18]. Also, a rough surface or seafloor causes scattering of the source noise, and some of the noise impacting on the seafloor is absorbed. These transmission loss mechanisms are generally frequency dependent, and depend on the seafloor geo-acoustic properties and the surface and seafloor roughness [4]. Knowledge of the state of the sea surface as well as the composition and topography of the sea floor is important for specification of boundary conditions [5].

### 4.4 Propagation recommendations

Considerations for the calculation of TL in the context of predicting the noise impact on wildlife should simplify the phenomenon and at the same time take into account a conservative approach. Thus, for geometric divergence it is suggested to apply the mixed model for TLS, either directly using a value of X = 15, or the combined model of Figure 1-A for cases in which the depth is known. Meanwhile, in terms of absorption, if the analysis includes frequency values lower than 50 kHz, it is recommended to apply the basic formulation of Thorp (equation (2)), considering more complex models only if another spectrum or other requirements of precision is required. Finally, if is taken into account the worst case for the spread (low attenuation) associated with the phenomena of refraction and reflection, this corresponds to propagation depth axis of the sound channel, in which there are no reflections on surfaces and therefore no interference patterns cancellations. Considering the above, the overall formula is suggested for TL:

$$TL(R,f) = TL_S + TL_A = X \cdot log(R) + \alpha(f) \cdot R \cdot 1000[\mathrm{dB}] \qquad (3)$$

## 5. The effects of noise on marine fauna

The threats on marine life can include physiological and behavioral effects [9]. A powerful noise can cause rupture or hemorrhage on ear, body parts. Also high levels of noise can trigger hearing loss, and interfere with the echolocation abilities, deteriorating the communication of detection of important natural sounds. The observed behavioral effects vary temporary local displacement to non-reaction from strong man made noise in hauled-out pinnipeds [10]. In the Islote Lobería of Cobquecura, Chile, has been observed that sea lions (Otaria flavescens) cease vocalization in the presence of fireworks during New Year celebrations. The sound level recorded in reach the 86 dB (Reference 2*10-6 Pa.) of airborne noise [26]. Disturbance can force whales to dive deeply, causing decompression sickness on rising. And in other cases, has been observed that humpback whale increase the length of their mating songs. But most of this studies are short-term behavioral observations, and a few-long term studies have been conducted [10]. This represent a few of the cautions to consider when assessing noise in fauna. Marina mammals are very adaptable and tolerant to noise, but the limits of this tolerance are unidentified. The effects of masking important sounds, such as predators or important natural sources; and the adaptability to adjust the frequency or strength of their signals, are mainly unknown.

## 6. Regulation used in Chile

In Chile there are some experiences in the evaluation of the effect of noise and vibrations in the underwater environment for port projects. The "Underwater Pilling Noise Guide", a guide developed by the Department of Planning, Transport and Infrastructure (DPTI) of South Australia (2012), has been used in particular for the impact generated by piloting. This document is applicable on construction activities of piles diving, potentially impacting on marine mammals on the coasts of South Australia. The main objectives of this guide are: (1) To advise the contractor personnel regarding their legal responsibilities according to the local regulations regarding conservation of the environment and biodiversity; (2) To promote practical measures for control and management that minimize the risk of harm to marine mammals living in the vicinity of piloting activities; and (3) Provide a framework that minimizes the risk of significant impacts on mammals Important biological habitats or during critical habitats (such as breeding and childbirth).

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