SOUND RADIATION OF SEAFLOOR-MAPPING ECHOSOUNDERS IN THE WATER COLUMN, IN RELATION TO THE RISKS POSED TO MARINE MAMMALS.

By Xavier Lurton [1] (IFREMER - France) **&**
Stacy DeRuiter [1,2] (Biology Department, Woods Hole Oceanographic Institution - USA)

Abstract

Currently, more and more attention is focusing on the impact of anthropogenic sound sources on marine life, particularly marine mammals. Indeed, several unusual cetacean strandings linked to the use of high-power sonar have been observed over the past years. Hydrography and seafloor-mapping make extensive use of acoustic sources; this paper aims to present the order of magnitude of sound radiated by such echosounders, and hence estimate their potential impact on marine mammals. The paper begins with a presentation of the main issues related to sound-mediated risks to marine life and a reminder of echosounder characteristics and geometry. Next, the numerical results from several case studies are compared with currently accepted threshold values for marine mammal sound exposure. This comparison makes clear that, while echosounders may transmit at high sound pressure levels, the very short duration of their pulses and their high spatial selectivity make them unlikely to cause damage to marine mammal auditory systems, according to current knowledge. There remains a possibility that echosounders may affect marine mammal behaviour at ranges on the order of kilometres; however, the likelihood and biological effects of such behavioural responses to sound remain poorly understood at present.

Résumé

De plus en plus d'attention est portée aujourd'hui à l'impact du bruit d'origine humaine sur la vie marine, et spécialement les mammifères marins. Un certain nombre d'échouements accidentels de cétacés ont été, au cours des dernières années, reliés à l'utilisation de sonars de forte puissance. L'hydrographie et la cartographie des fonds marins font un large usage d'émetteurs acoustiques ; cet article vise à présenter les ordres de grandeur des sons émis par ces sondeurs, et à estimer leur impact potentiel sur les mammifères marins. On présente d'abord les grandes lignes décrivant les risques acoustiques pour la vie marine, et on rappelle les caractéristiques et la géométrie des sondeurs. Les résultats numériques pour plusieurs cas typiques sont ensuite comparés aux valeurs acceptées couramment pour les seuils d'exposition sonore des mammifères marins. Cette comparaison fait apparaître que, bien que certains sondeurs puissent émettre des signaux de forte intensité, la brièveté des émissions et leur forte directivité spatiale rendent improbables des lésions aux systèmes auditifs des mammifères marins, d'après les connaissances actuelles. Il reste la possibilité que les sondeurs puissent affecter le comportement des mammifères marins, sur des distances kilométriques ; la possibilité et les conséquences biologiques des tels effets comportementaux sont encore peu connus.

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[1] Institut Français de Recherche pour l'exploitation de la Mer (IFREMER), IMN/NSE/AS, BP 70, 29280 Plouzané, France. lurton@ifremer.fr

[2] Biology Department, Woods Hole Oceanographic Institution, MS #50, Woods Hole, MA 02543. stacy_deruiter@yahoo.com

Resumen

Actualmente, se dedica cada vez más atención al impacto de las fuentes sonoras antropogénicas en la vida marina, particularmente en los mamíferos marinos. Se han observado durante los últimos años varias varadas poco comunes causadas por cetáceos, vinculadas al uso de sonares de alta potencia. La hidrografía y la cartografía del fondo marino utilizan de forma considerable las fuentes acústicas; el objetivo de este artículo es presentar el orden de la magnitud del sonido radiado por similares sondas acústicas y por tanto estimar su impacto potencial en los mamíferos marinos. Este artículo empieza con una presentación de los principales temas relativos a los riesgos causados por el sonido a la vida marina y con un recordatorio de las características de las sondas acústicas y la geometría. Luego se comparan los resultados numéricos de varios casos prácticos con los valores de umbral corrientemente aceptados para la exposición al sonido de los mamíferos marinos. Esta comparación deja claro que, aunque las sondas acústicas pueden transmitir a niveles de presión de alta intensidad, la muy breve duración de sus impulsos y su alta selectividad espacial hacen que sea muy poco probable que causen daños a los sistemas auditivos de los mamíferos, según los conocimientos que se poseen actualmente. Queda la posibilidad de que las sondas acústicas puedan afectar al comportamiento de los mamíferos marinos en campos de cobertura del orden de kilómetros; sin embargo, actualmente siguen entendiéndose muy poco la probabilidad y los efectos biológicos de dichas reacciones del comportamiento.

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1. Introduction

Because marine mammals depend on sound and hearing for essential activities including communication, navigation, and foraging, anthropogenic sound in the ocean may impact them negatively. For example, it may mask sounds that are important to the animals or even (at high levels) injure their auditory systems. They may alter their behaviour in response to certain sounds [1, 2]. Mid-frequency military sonars, which are used in anti-submarine warfare, have been associated with several unusual strandings of marine mammals, particularly beaked whales (reviewed in [3]). A significant amount of attention has thus focused on quantifying and preventing the negative impacts of human-generated sound on marine mammals, resulting in the development of regulations and operational procedures designed to protect the animals [4-9]. Most such regulations focus on military sonars (transmitting long-duration modulated signals in the range of a few kHz) and airgun arrays (which are very powerful sources of low-frequency pulsed sound used in geophysical research and oil exploration). The rules generally require visual (and sometimes passive acoustic) monitoring to ensure that animals do not come within a specified distance of the sound source. That distance is often defined on the basis of an allowable exposure level threshold, which is combined with an ocean sound propagation model to convert the level to a source-receiver range. Recommended exposure thresholds for damage to the auditory system and behavioural responses have recently been proposed, with thresholds varying by sound type and marine mammal group [2].

Military sonars and airguns are far from the only anthropogenic sound sources at sea. Many other active acoustic devices are commonly used for various underwater activities, such as the echosounders used in hydrography, seafloor mapping, navigation and fisheries applications. In contrast to naval mid-frequency sonar, no unusual stranding events have been linked with echosounder use [3], which may explain the lack of public and regulatory attention. Echosounders usually generate lower-level sound than the highest-powered military sonars, and they often use ultrasonic frequencies that are attenuated relatively efficiently in sea water. However, they still have potential to affect marine mammals, especially considering the fact that many of them operate in frequency ranges used by toothed whales for echolocation and communication. In some cases, behavioural responses of marine mammals to these devices have been documented, including sound source avoidance and changes in sound production patterns (reviewed in detail by [1]).

The purpose of this paper is to estimate the order of magnitude of the risks to marine mammals caused by the sonar systems currently used in hydrography and in seafloor mapping. These systems are mostly echosounders, either single beam or multibeam. The first part of the paper presents a brief discussion of the risks posed to marine mammals by powerful sound transmissions. The second part of the paper describes the general characteristics and transmission geometry of echosounders. The details of the systems will be simplified in order to provide representative values for radiated sound levels and geometry of several archetypal systems. The third part of the paper is devoted to a limited number of case studies. These case studies will show that echosounders are not likely to cause injury to marine mammal auditory systems except at very limited ranges, although they may still affect behaviour at greater ranges. Considering the very selective directivity of the transmission patterns, the areas in which hearing damage may be expected to occur are minimal, especially compared to acoustic systems of wider horizontal radiation, such as naval low-frequency active sonar (LFAS) or seismic airguns. The last part of the paper will build upon the previous sections to draw conclusions about the potential risks that echosounders may pose to marine mammals.

2. Risks posed to marine mammals by anthropogenic sound

2.1. Marine Mammal Bioacoustics

Marine mammals rely on their hearing and sound production abilities for many important activities. They produce a wide variety of sounds related to foraging, navigation, communication, and sensing the environment [3]. Because of their extensive use of sound, most marine mammals have sensitive, specialized auditory systems. For example, all toothed whales (sperm whales, beaked whales, dolphins, and porpoises) studied to date produce clicks thought to be used for biosonar-based foraging and navigation. Except for sperm whales, toothed whale echolocation clicks include mostly ultrasonic frequencies; many dolphin species also produce lower-frequency tonal whistles for communication [3, 10]. These species generally have sensitive hearing over a wide frequency band including the frequencies at which they produce clicks and communication calls, although only a limited number of species have had their hearing tested (see Figure 1); measured audiograms reveal sensitive hearing at frequencies up to about 20-140 kHz, depending on species. Thus, the frequency ranges of toothed whale biosonar and auditory systems overlap significantly with the frequency range used by hydrographic sonars. Most baleen whales, for example blue whales, fin whales, and humpback whales, produce longer, lower-frequency tonal or frequency-modulated sounds for communication with conspecifics [3]. These sounds range from pulses at 20 Hz or less to more complex calls and songs with components at frequencies as high as several kHz. Given the variety of sounds they produce, and by analogy to terrestrial mammals and toothed whales, baleen whales are also thought to have an acute sense of hearing. However, measuring their hearing poses obvious practical difficulties.

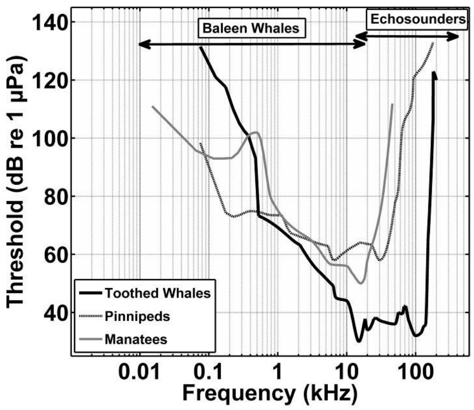

Figure 1. *Measured audiograms of toothed whales, pinnipeds, and manatees. The curve for each group is a composite audiogram for all species tested, showing the lowest observed detection threshold at each frequency. The plots include data from all species reviewed in [3], including 15 toothed whale species, 9 pinniped species, and 2 manatee species. No audiograms are available for baleen whales, but the frequency range in which they are expected to hear best is indicated [11-13]. The frequency domain of echosounders is also plotted for comparison.*

In the absence of actual hearing threshold data for baleen whales, a few anatomical studies and computer models have been used to predict their hearing capabilities. They do not provide absolute sensitivities, but they do agree that the range of best hearing is probably from tens of Hz to about 20 kHz (***Figure 1***) [11-13]. Uncertainty about the acuity and upper frequency limit of baleen whale hearing makes it more difficult to assess the potential risks echosounders may pose to these species. However, all evidence suggests that they mainly use lower frequencies, which may mean they are less susceptible to effects of echosounders. Pinnipeds (seals, sea lions and walrus) also produce a wide variety of sounds underwater, mainly in the sonic frequency range, and these sounds are often associated with mating rituals [3]. These species also have quite sensitive hearing, and are unique in that they are able to hear and localize sound relatively well both in the air and underwater. The frequency range in which they hear overlaps with that used by echosounders (Figure 1). Even manatees use low-frequency calls, presumably to communicate with one another. Among the few individuals tested so far, the upper limit of frequency sensitivity was lower for manatees than for most toothed whales or pinnipeds [3] (***Figure 1***). Like baleen whales, they may thus be less susceptible to potential impacts of echosounders.

Exposure to anthropogenic sounds can negatively impact marine mammals in a variety of ways [1, 2, 14].

Effects may include injury to body tissues, the most common being auditory system damage that leads to temporary or permanent hearing loss. These conditions are often called Temporary and Permanent Threshold Shift (TTS and PTS). Sound exposure can also have other effects, from increased stress levels to behavioural shifts including changes in dive cycles, breathing patterns, sound production rates, or behavioural states. Marine mammals can also respond to sounds by approaching or avoiding the sound source, which could have negative impacts on their energy budgets or cause them to abandon important habitat.

2.2. Regulation and Mitigation Measures

Given the potential effects of active acoustic devices on marine mammals and other animals, regulations designed to mitigate such impacts have been put in place by a number of concerned countries. However, the resulting level of protection against risks posed by acoustic devices varies widely. In the European Union, marine mammals are legally protected, but the relevant regulations do not place specific limitations on sonar or airgun operation, and practical guidelines and mitigation procedures are left to the judgement of individual operators (Habitats and Species Directive of 1992, Council Directive number 92/43/EEC).

Inside this framework, some countries have more specific laws. For example, in the United Kingdom, regulations prohibit the deliberate capture, injury, killing or disturbance of marine mammals, and also actions that cause damage, destruction or deterioration of their breeding sites and resting places (Offshore marine conservation regulations of 2009). These regulations include disturbance and injury mediated by anthropogenic sound, and the U.K. Joint Nature Conservation Committee (JNCC) has also enacted specific regulations related to industrial seismic surveys in U.K. waters [4]. The regulations do not define allowable or prohibited sound exposure levels, but the seismic survey guidelines do prohibit commencement of airgun use when marine mammals have been sighted within 500 meters of the airguns within 30 minutes of the sighting.

In the United States, legislation related to the effects of sound on marine mammals includes the Marine Mammal Protection Act, which prohibits harassment of marine mammals. The National Marine Fisheries Service (NMFS), the responsible regulatory agency, oversees a permitting process for all operations that may subject marine mammals to level A harassment (permanent physiological damage) or level B harassment (disruption of behaviour), generally basing its judgments on sound exposure levels; there are also specific regulations requiring mitigation (including visual observers and sometimes passive acoustic monitoring) for seismic surveys in the Gulf of Mexico [6]. Several other countries or areas (Australia, New Zealand, Brazil, and the Sakhalin region, for example) have also put in place regulations related to airgun operation [15, 16]. Most regulations require trained marine mammal observers to carry out visual surveys before and during airgun operations, stopping sound production if an animal is sighted within a certain range (500-3000 m) of the sound source.

2.3. Definition of Risk Thresholds

A common approach to the regulation of underwater sound involves definition of a safe sound exposure threshold which must not be exceeded during operation of an underwater sound source. Other approaches might involve spatial or temporal limitations on the operation of certain sound sources, according to the status of marine mammal populations in the area. When an exposure threshold is used, it is sometimes defined in terms of a range from the sound source, but source level can vary widely between sonars, even within one class of devices. Source level usually also depends on the angular direction of sound radiation. In addition, underwater sound propagation can result in complex, environment-specific patterns of received level as a function of range from the source. Therefore, definition of a sound exposure level (which is then translated to a range on a case-by-case basis) may provide more consistent results. Historically, marine mammal sound exposure threshold levels of 180 dB re 1 µPa for injury and 160 dB re 1 µPa for behavioural response were commonly cited, particularly in the United States [2], but these levels did not effectively incorporate available scientific data. Such science-based recommended exposure thresholds for any anthropogenic sound that may negatively affect marine mammals have recently been proposed, with proposed thresholds varying by sound type (pulsed or non-pulsed sounds) and marine mammal group [2]. The recommendations for exposures that risk permanent physiological damage can be summarised as follows:

- Peak exposure levels not to exceed 230 dB re 1 µPa for cetaceans, 218 dB re 1 µPa for pinnipeds underwater, and 149 dB re 20 µPa for pinnipeds in air;

- Frequency-weighted sound exposure levels not to exceed 198 dB re 1 $\mu Pa^2 * s$ for cetaceans exposed to pulsed sounds, 215 dB re 1 $\mu Pa^2 * s$ for cetaceans exposed to non-pulsed sounds, 186 dB re 1 $\mu Pa^2 * s$ for pinnipeds in water exposed to pulsed[3] sounds, 203 dB re 1 $\mu Pa^2 * s$ for pinnipeds in water exposed to non-pulsed sounds, 144 dB re $(20 \mu Pa)^2 * s$ for pinnipeds in air exposed to pulsed sounds, and 144.5 dB re $(20 \mu Pa)^2 * s$ for pinnipeds in air exposed to non-pulsed sounds.

Currently available data are insufficient to quantitatively define threshold levels above which marine mammals alter their behaviour in response to a sound stimulus [2]. Although numerous studies have documented such reactions, species, sound type, and exposure level cannot fully explain the observed variability of responses. Reactions probably also depend on additional factors like age, sex, initial behavioural state, environmental conditions, and source proximity.

In the absence of validated threshold values, one conservative approach would be to use the response thresholds of the most sensitive species studied to date in assessing the potential risks posed by a particular sound source. Among marine mammals studied so far, beaked whales and harbour porpoises seem to show behavioural responses to sound at the lowest received levels. A small number of beaked whales have responded to ship noise and simulated military mid-frequency sonar sounds at received levels of about 135 dB re 1 µPa [17, 18]. Beaked whales and harbour porpoises also respond to pingers (active acoustic devices attached to fishing nets to help prevent bycatch of marine mammals) with source levels between about 130-140 dB re 1 µPa [19-23]. These devices seem to be generally effective over short ranges, up to perhaps a few hundred meters, although they may be audible to the animals at ranges up to several kilometres.

It seems likely that responses to pingers may thus depend on source proximity as well as received level. Taking the above data into consideration, 130 dB re 1 µPa rms might be a reasonable rough estimate for the behavioural response threshold of sensitive marine mammal species. Of course, this value is a gross approximation. Some dependence on signal frequency and content is expected; some animals may respond at even lower levels, and less sensitive species may not respond even at significantly higher levels. Even so, in the absence of more accurate estimates, this value can be used to obtain a rough estimate of the area over which a given sound source might affect the behaviour of sound-sensitive marine mammal species.

3. Basic Echosounder Characteristics

Echosounders have been the most widespread acoustic systems used for hydrography and seafloor mapping [24] since their invention in the 1920s. Long limited to the basic geometry of one single vertical beam, today they are very commonly multibeam systems, able to cover a very large swath width at once.

In terms of acoustic radiation, echosounders are characterised by:

- Frequencies in the range of 12 kHz to several hundreds of kHz;

- Transmitted pulses of short duration, typically on the order of milliseconds; however, the most sophisticated recent systems may transmit long modulated pulses;

- Source levels typically ranging from 210 to 240 dB re 1 µPa @1 m;

- Pulse rate frequencies controlled by the water depth, with highly variable values, typically between 0.1 and 10 Hz;

- Limited angle aperture designed to provide a good spatial resolution.

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[3] In this context, pulsed sounds are defined as sounds for which the sound pressure level measured in a 35 ms time window is at least 3 dB greater than that measured in a 125 ms time window.

Single beam echosounders (SBES) operate at various frequencies. Typical values are 12, 24, 30, 38, 50, 100, 120, or 200 kHz. Some systems dedicated to very shallow waters may work as high as 700 kHz, while navigation echosounders normally operate at 50 or 200 kHz. The most common geometry is one conical vertical beam (***Figure 2***), with a fixed aperture[4] of a few degrees (most commonly between 5° and 15°), which is usually not steerable. The sidelobes, generating unwanted radiation of acoustic energy outside the main lobe, are typically 20 dB to 30 dB below the main lobe level. The maximal transmit powers may be as high as 210 to 230 dB re 1 µPa @1 m, depending on frequency (the highest levels are used in low-frequency deep-water applications).

The pulse duration depends on the frequency and water depth. It is typically about 0.1% to 1% of the two-way travel time from the sounder to the seafloor, hence pulse duration may reach several milliseconds for the lowest frequencies used in deep water. The pulse repetition frequency (PRF) is imposed by the two-way travel time: no signal is transmitted before the previous echo (and possibly 2 or 3 multiple echoes) has been received. Consequently, the duty cycle[5] values also lie in a typical range of 0.1% to 1%.

Multibeam echosounders (MBES) are far more complicated systems, providing the capability to collect bathymetry data and image the seafloor very efficiently over wide areas. They normally transmit a short pulse inside a narrow fan in a vertical plane perpendicular to the ship's axis (see ***Figure 2***). In the most recent models, several adjacent sectors can be transmitted simultaneously, hence widening the along-track angular aperture and requiring transmission at several different neighbouring frequencies. Various frequency ranges are used, depending on the water depth: 12, 24 or 32 kHz for deep -water; 70 to 150 kHz for continental shelf applications; and 200 to 400 kHz for very shallow applications. The transmit sector width is typically as narrow as 1° along-track (values between 0.5° and 2° are encountered), and reaches 120° to 150° across-track; some systems even radiate over the whole 180° aperture. Special care is taken to minimize sidelobe levels in transmission, and the practical results are usually in the range of –25 to –35 dB. As for SBES, the achievable maximum level depends on frequency: it is around 210 to 220 dB re 1 µPa @ 1 m for high-frequency systems, but may exceed 240 dB re 1 µPa @ 1 m for the most powerful 12-kHz systems. The pulse durations are normally about 0.1% to 1% of the echo reception delay, hence typically between 0.1 ms and 10 ms, with longer pulses corresponding to lower frequencies and deep waters. However, the transmit duration is often increased because of the need to transmit several adjacent pulses at slightly different frequencies in the various sectors. The recently-introduced use of FM signals for MBES, which generally last tens of milliseconds, also increases the duration of acoustic energy radiation. The pulse repetition frequency of MBES is normally adapted to the reception of the extreme lateral beams, whose propagation delay is typically 4 times the two-way travel time of a vertical beam. Under this constraint, the PRF in very deep water may be as low as 2 pings per minute, while the maximum PRF of very-high frequency systems may reach 10 to 20 pings per second, if not more. Similar to SBES, the duty cycle is on the order of 0.1% to 1%.

The detailed characteristics of echosounders are normally accessible to users through the documentation provided by manufacturers along with the hardware. Some information may also be obtained from the manufacturer web sites.

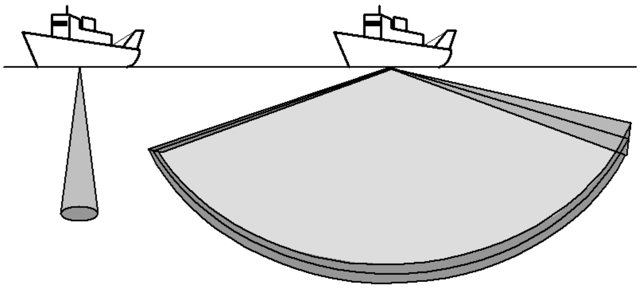

Figure 2. *Sketch of water column ensonification by a SBES (a vertical conical lobe) and a MBES (presented here with two adjacent fan-shaped sectors).*

4. Case Studies

4.1. Main Formulas

The level received by an animal present inside the ensonification volume is expressed as:

$$RL = SL - TL \qquad (1)$$

where RL is the received level in dB re 1 µPa; and SL is the source level (which depends on transmission angle, according to the directivity pattern), expressed in dB re 1 µPa @ 1 m. TL is the transmission loss in dB, approximated for a homogeneous propagation medium [24] as:

$$TL = 20\log(R/1\text{ m}) + \alpha R \qquad (2)$$

where R is the oblique sonar-receiver range, and α the absorption coefficient in the water in dB/m. ***Table 1*** gives typical values for α as a function of frequency. The strong frequency-dependence of the absorption coefficient helps explain why received sound levels at a given range vary widely with source frequency.

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[4] All the beamwidth values given here are always correspond to a fall-off of –3 dB of the directivity pattern measured at transmission.

[5] The duty cycle is the fraction of time that a sounder is actually transmitting.

F (kHz)	12	24	32	38	50	70	100	120	150	200	300	400
α (dB/km)	1.2	4.3	7.1	9.6	14.9	24	36	42	50	61	80	101

Table 1. *Absorption coefficient values (in dB/km) as a function of frequency (in kHz), computed at depth 10 m, temperature 13°C, and salinity 35 p.s.u (see [25]).*

For instance, considering a 12-kHz MBES transmitting at a maximum *SL* of 242 dB re 1 µPa @ 1 m, the received level at a range of 1 km is *RL* = 242-20log (1000)-1.2 = 180.8 dB re 1 µPa.

The sound exposure level is defined as the time integration of the squared acoustic pressure (hence proportional to the received energy):

$$E = \int p^2(t)dt \qquad (3)$$

Considering one ping of duration *T*, and assuming the received pressure amplitude to be constant over reception time (a good first approximation since many echosounders transmit pings with approximately square envelopes), the received energy is given by $E = p_{rms}^2 * T$.

In logarithmic units, considering a reference level of E_0 = 1 µPa² * s, the sound exposure level may be written as:

$$SEL = 10\log(E/E_0) \qquad (4)$$

in dB re 1 µPa² * s. Finally, assuming a constant-level received pressure, *SEL* is conveniently computed as:

$$SEL = RL + 10\log(T_T) = SL - TL + 10\log(T_T) \qquad (5)$$

where T_T is the total exposure time (in s) to consider. This duration is a function of the transmitted pulse duration *T*, the pulse rate frequency f_P, and the total time of presence T_P of the receiver inside the ensonification volume:

$$T_T = T_P \times f_P \times T \qquad (6)$$

For instance, considering the case of an animal present for 10 minutes in the transmit beam of a low-frequency MBES sending a 50-ms pulse once every 20 s, the total exposure time is $T_T = 600 / 20 * 0.05 = 1.5$ s. At a range of 1 km, the sound exposure level is then *SEL* = 242-20log(1000)-1.2+10log(1.5) = 182.8 dB re 1 µPa² * s.

We have not included animal-group-specific frequency weighting in these calculations, for the purpose of simplicity of presentation. This simplification is conservative in that frequency weighting effectively filters out sounds outside the marine mammal's range of best hearing, while retaining the original level of sounds inside the best hearing range. In effect, the weighting will sometimes decrease the effective SEL of a particular source, but never increase it.

4.2. Frequency Dependence

In addition to sound exposure level, it is important to consider the correspondence between the frequency band perceptible by marine mammals (ideally expressed as an audiogram, i.e. hearing threshold *vs* frequency) and the signals transmitted by echosounders. As presented above in §2.1, audiograms are available for various marine mammal groups (***Figure 1***). Regarding baleen whales, despite the lack of audiometry data, they are expected (based on anatomical studies and analysis of the sounds they produce) to hear best at low frequencies, probably below about 20 kHz [3]. Comparing the frequency ranges of marine mammal hearing with those used by echosounder reveals that:

- High-frequency echosounders (200 kHz and beyond) are presumably not generally audible to marine mammals;
- Mysticetes are unlikely to detect any frequency used by echosounders, except the lowest one (12 kHz); and
- The maximum effect is expected for odontocetes, since their frequencies of best hearing (10-100 kHz) overlap with low-and medium-frequency echosounder signals.

4.3. Direct Ensonification

The first case considered here is when sound can propagate directly from the sonar to an animal inside the echosounder transmission lobe. In this case, the received level is estimated from Equation (1). The risk area is hence defined by the range within which *RL* exceeds a certain threshold (here called *RLT*). The condition leads to the limit value of transmission loss *TL* given by:

$$TL = SL - RLT \qquad (7)$$

The transmission loss value is then converted into a range value by solving Eq. (2) for *R*. For instance, considering *SL* = 242 dB re 1 µPa @ 1 m, the *RL* value first falls below the threshold of 230 dB re 1 µPa (see §2.3 above) at a range corresponding to a transmission loss *TL* = 12 dB, i.e. a range of about 4 m.

The same approach holds for the Sound Exposure Level, which is to be compared to the threshold value (here called *SELT*) to consider. The condition leads to the limit value of transmission loss:

$$TL = SL + 10\log T_T - SELT \qquad (8)$$

For instance, again assuming *SL* = 242 dB re 1 µPa @ 1 m and T_T = 1.5 s (see §4.1), *RL* falls below the 198 dB re 1 µPa² * s threshold at a range corresponding to a transmission loss *TL* = 46 dB, i.e. a range of about 200 m.

4.3.1. RL in direct ensonification

Received levels from any echosounder fall below the *RL* threshold value for cetaceans defined by Southall et al. (230 dB re 1 µPa) [2] at very short ranges. Many systems transmit at source levels below this value, and a *SL* of 250 dB re 1 µPa @ 1 m would be required to exceed this *RL* at a range of even 10 m.

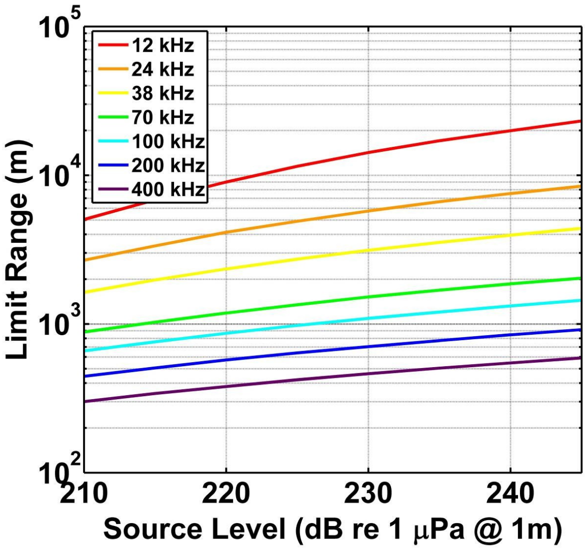

Figure 3. Limit range corresponding to a received level of 130 dB re 1 µPa (putative behavioural response threshold), as a function of SL and frequency

Of course, echosounder received levels will exceed the *RL* threshold value (130 dB re 1 µPa) associated with the behavioural response threshold at much larger ranges. For echosounders transmitting at 210 to 240 dB re 1 µPa @ 1 m, the 130-dB threshold level corresponds to significant propagation losses, ranging from 80 dB to 110 dB. We present in *Figure 3* the limit range for various values of *SL* and frequency. The results show that for values of *SL* within the usual range (220 to 230 dB re 1 µPa @ 1 m), received levels exceed the *RL* threshold at ranges up to several kilometres (up to 20 km at 12 kHz for a *SL* of 240 dB re 1 µPa @ 1 m).

4.3.2. SEL in direct ensonification

In calculating *SEL* for an animal in the sonar beam, we consider a cumulative exposure duration of 1 second. This is a good conservative order of magnitude estimate, since it would correspond to tens of pings of a typical low-frequency system operating in deep water, and several thousands for a high-frequency echosounder in a shallow area. Both scenarios would correspond to an animal staying in the ensonified sector for tens of minutes.

The limit range corresponding to the *SEL* threshold of 198 dB re 1 µPa² * s is computed for various values of *SL* and frequencies. The results are plotted in *Figure 4*; they show that for *SL* within the usual range (220 to 230 dB re 1 µPa @ 1 m), the *SEL* threshold is reached at ranges between 10 and 40 m. Limit ranges of 100 to 200 m are possible for low-frequency transmissions at 240-250 dB re 1 µPa @ 1 m.

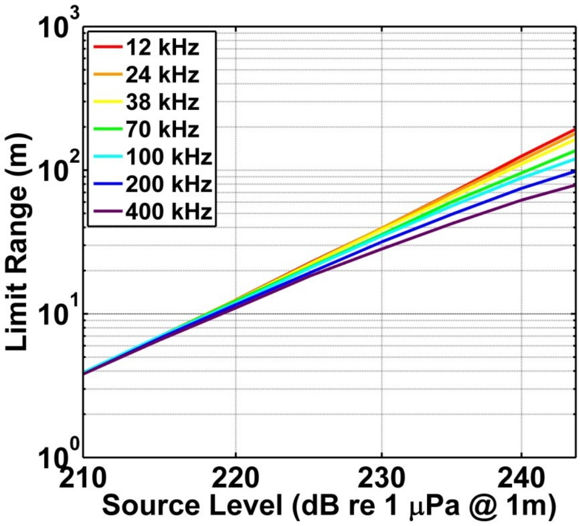

*Figure 4. Limit range corresponding to a sound exposure level of 198 dB re 1 µPa² * s (given in [2]), as a function of SL and frequency; the SEL is computed for a cumulated exposure duration of 1 s.*

4.4. Effect of Transmission Directivity

Source directivity can strongly affect the risks posed to animals by underwater sound radiation. Low-frequency, wide-aperture, powerful sources, such as airguns used for seismic exploration or naval sonars used in military applications, radiate with little or no selectivity in the horizontal plane. Thus, exposure levels vary with depth and range from the source but do not depend further on source-receiver geometry. On the other hand, a directional source (such as a seafloor-mapping sonar) is expected to have a much more limited impact on the environment if its ensonification volume is sufficiently narrow in the horizontal plane.

While the angular selectivity provided by the echosounder directivity may be considered as a mitigating factor on average, it is still necessary to consider the case where an animal is actually present inside the ensonified volume. In this case, the issue is to estimate the duration of the sound exposure.

We consider here the case in which an animal is at a fixed location (or travelling at negligible speed) relative to the survey ship carrying the sonar. If R is the oblique sonar-animal range (see ***Figure 5***), the ensonified along-track segment has a length ϕR, where ϕ is the longitudinal transmitting lobe aperture. The animal is present inside the ensonified area for the time it takes the ship to run the distance ϕR at speed V, or $\phi R/V$. Finally, the number of transmitted signals contributing to the exposure is equal to $\phi R/V * f_R$, where f_R is the pulse repetition frequency.

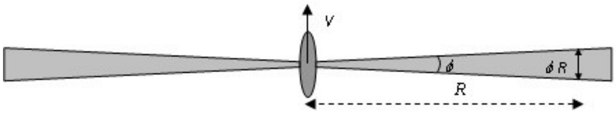

Figure 5. *Geometry of ensonification by an MBES on both sides of the ship that carries it, represented for simplicity in a horizontal plane.*

The number of received signals increases as range R increases; however, the level of each received signal decreases with range because of propagation loss, so *SEL* still generally decreases with range.

Figure 6 displays the *SEL* variation with range R for the same 12-kHz MBES as considered previously. Assuming the capability to simultaneously transmit four adjacent sectors of 1° each, an along-track aperture of ϕ=4° is considered.

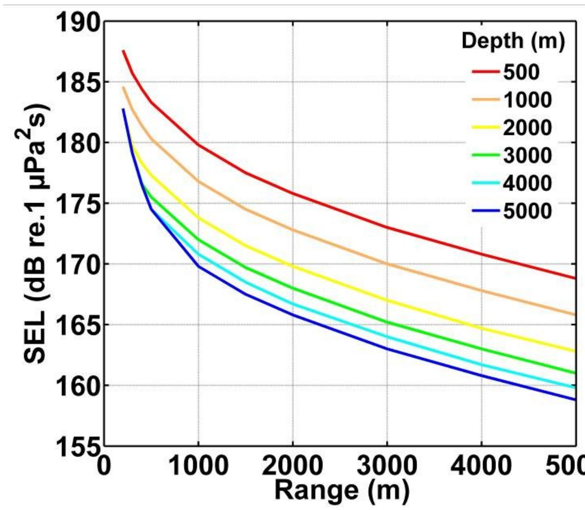

Figure 6. *Maximum SEL value for a stationary animal ensonified by a LF MBES surveying at 8 knots, presented as a function of water depth.*

To incorporate source transmission geometry and directivity into an estimate of the average impact of a given sonar, a good first approach is to consider the sector ensonified by the sonar as a ratio of the total available space (half a sphere, or 2π radians, for a source close to the surface). This Radiation Directivity Factor (here called *Rdf*) represents the probability that a receiver is located inside the transmission sector:

$$Rdf = \Psi/2\pi \qquad (9)$$

Hence *Rdf* features the equivalent solid aperture angle Ψ of the transmitting sector, and is closely related to the classical directivity index $DI = 10\log(\Psi/4\pi)$ of a sound source [24]. For instance, considering a single beam echosounder of conical beam aperture 5°, the *Rdf* value is about $Rdf \approx \pi * \tan^2(2.5°)/2\pi \approx 10^{-3}$. For a multibeam echosounder transmitting in a fan-shaped sector 2°x120°, one can estimate $Rdf \approx 2 * 120 * (\pi/180^2/2\pi \approx 0.012$. Of course, for an omnidirectional source (in a 2π half-space), the *Rdf* value approaches unity.

The *Rdf* value expresses the probability that a given receiver, one among a set of receivers equally distributed in space, is located within the transmitted sonar beam. It gives an estimate of the average exposure level over a given area when the relative positions of the sonar and receiver cannot be accurately specified. In cases where exact source-receiver geometry is known, *Rdf* should of course be replaced by estimates accounting for this geometry.

5. Discussion and Conclusions

The analysis presented above indicates that, in terms of the risk of auditory system damage, hydrographic and bottom-mapping sonars pose minimal threats to marine mammals, according to the state-of-the-art understanding of this risk. Compared to military sonars and seismic air-gun arrays, they feature:

- lower source levels (although low-frequency multibeam systems can transmit sound levels around 240 dB re 1 μPa @ 1 m), minimizing the risk of auditory damage related to peak amplitude of sound;
- transmission of very short pulses at limited ping rates, decreasing the practical sound exposure level (corresponding to the received sound intensity integrated over time);
- selective angular directivity, decreasing the probability of ensonification (by comparison with omnidirectional sources) and minimizing the duration of the ensonification when it happens.

Since seafloor-mapping sonars pose a reduced risk of auditory system injury in comparison to military systems or seismic sources, their use may not require the same extensive mitigation measures.

The potential effects of such devices on marine mammal behaviour, on the other hand, are less clear. First, the threshold levels above which animals may show behavioural responses are poorly understood at present. Available data suggest that the drivers of responses are solely on the sound type and the exposure level. Moreover, the biological significance of observed responses is not always clear. In this paper, for purposes of illustration, we have adopted a conservative (low) estimate of a behavioural response threshold level. If this estimate is accurate, even for a subset of sensitive species, then many sonars may indeed have potential to influence marine mammal behaviour over relatively wide areas. Quantifying the practical significance of this type of impact would enhance understanding of the general issue of underwater ambient noise increase, of which echosounder transmission is one component among others. These results could have useful management implications, as regulations evolve to better control anthropogenic underwater noise.

Given the somewhat hypothetical nature of several elements of the analysis presented here, this paper cannot provide answers to all the questions raised by the use of seafloor-mapping sonars and their risk to marine life. These matters need to be considered in the political, social and scientific arenas. We present the above results in order to summarize knowledge related to this particular issue for the concerned community. Moreover, we broach this topic in the hope of motivating further discussions, and promoting a rational, comprehensive and science-based approach to address the effects of active acoustic devices on marine mammals.

References

1. Richardson, W.J., et al., *Marine Mammals and Noise*. 1995, San Diego, CA: Academic Press. 576.
2. Southall, B.L., et al., *Marine mammal noise exposure criteria: Initial scientific recommendations.* Aquatic Mammals, 2007. **33**(4): p. 411-521.
3. DeRuiter, S.L., *Marine Animal Acoustics*, in *An Introduction to Underwater Acoustics: Principles and Applications*, X. Lurton, Editor. 2010, Praxis Publishing Limited: Chichester, UK. p. 425-474.
4. Joint Nature Conservation Committee (JNCC), *JNCC guidelines for minimising the risk of disturbance and injury to marine mammals from seismic surveys*, Joint Nature Conservation Committee, Editor. 2010: Aberdeen, U.K. Available online at http://www.jncc.gov.uk/page-1534 (last accessed 8 Dec. 2010).
5. New Zealand Department of Conservation, *Guidelines for minimising acoustic disturbance to marine mammals from seismic survey operations*, Department of Conservation, Editor. 2006: Wellington, New Zealand.
6. Minerals Management Service (MMS), *Notice to lessees and operators (NTL) of federal oil, gas, and sulphur leases in the outer continental shelf, Gulf of Mexico OCS Region: Implementation of seismic survey mitigation measures and protected species observer program*, United States Department of the Interior Minerals Management Service (MMS) Gulf of Mexico OCS Region, Editor. 2007: New Orleans, LA. Available online at www.nmfs.noaa.gov/ocs/mafac/meetings/2010_06/docs/mms_2007_ntl.pdf (last accessed 8 Dec. 2010).
7. Fisheries and Oceans Canada, *Statement of Canadian practice with respect to the mitigation of seismic sound in the marine environment.* , Fisheries and Oceans Canada, Editor. 2005: Ontario, Canada. Available online at http://www.dfo-mpo.gc.ca/oceans/management-gestion/integratedmanagement-gestionintegree/seismic-sismique/statement-enonce-eng.asp (last accessed 8 Dec. 2010).
8. IBAMA, *Guia de monitoramento da biota marinha em atividades de asuisição de dados sìsmicos (Abril 2005)*. 2005, IBAMA, Ministério do Meio Ambiente, Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renovaveis, Diretoria de Licenciamento e Qualidade Ambiental, Coordenaçâo Geral de Licenciamento, Escritório de Licenciamento des Atividades de Petróleo e Nuclear: Brasil.
9. Dolman, S.J., C.R. Weir, and M. Jasny, *Comparative review of marine mammal guidance implemented during naval exercises.* Marine Pollution Bulletin, 2009. **58**(4): p. 465-477.
10. Au, W.W.L., *The sonar of dolphins*. 1993, New York, NY: Springer-Verlag.
11. Houser, D.S., D.A. Helweg, and P.W.B. Moore, *A bandpass filter-bank model of auditory sensitivity in the humpback whale.* Aquatic Mammals, 2001. **27**(2): p. 82 -91.
12. Ketten, D.R., *Structure and function in whale ears.* Bioacoustics, 1997. **8**: p. 103-135.
13. Parks, S.E., et al., *Anatomical predictions of hearing in the North Atlantic right whale.* The Anatomical Record, 2007. **290**: p. 734–744.
14. Wright, A.J., et al., *Do marine mammals experience stress related to anthropogenic noise?* International Journal of Comparative Psychology, 2007. **20**: p. 274-316.
15. Compton, R., et al., *A critical examination of worldwide guidelines for minimising the disturbance to marine mammals during seismic surveys.* Marine Policy, 2008. **32**(3): p. 255-262.
16. Weir, C.R. and S.J. Dolman, *Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard.* Journal of International Wildlife Law & Policy, 2007. **10**: p. 1-27.
17. Aguilar Soto, N., et al., *Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (Ziphius cavirostris)?* Marine Mammal Science, 2006. **22**(3): p. 690-699.

18. Tyack, P., et al., *Effects of sound on the behavior of toothed whales.* Journal of the Acoustical Society of America, 2008. **123**(5): p. 2984.
19. Culik, B.M., et al., *Reactions of harbor porpoises Phocoena phocoena and herring Clupea harengus to acoustic alarms.* Marine Ecology Progress Series, 2001. **211**: p. 255-260.
20. Kastelein, R.A., et al., *The influence of three acoustic alarms on the behaviour of harbour porpoises (Phocoena phocoena) in a floating pen.* Marine Environmental Research, 2001. **52**(4): p. 351-371.
21. Carretta, J.V., J. Barlow, and L. Enriquez, *Acoustic pingers eliminate beaked whale bycatch in a gill net fishery.* Marine Mammal Science, 2008. **24**(4): p. 956-961.
22. Carlström, J., et al., *A field experiment using acoustic alarms (pingers) to reduce harbour porpoise by-catch in bottom-set gillnets.* ICES Journal of Marine Science, 2002. **59**(4): p. 816-824.
23. Barlow, J. and G.A. Cameron, *Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery.* Marine Mammal Science, 2003. **19**(2): p. 265-283.
24. Lurton X. *An Introduction To Underwater Acoustics – Principles and Applications, Second Edition*, Springer-Verlag, Berlin, 2010
25. Francois, R.E. and G.R. Garrison, *Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption.* Journal of the Acoustical Society of America, 1982. **72**(6): p. 1879-1890.

Biographies of the authors

Xavier Lurton received the PhD degree in Applied Acoustics from the University of Le Mans (France) in 1979. He then worked for eight years with Thomson-Sintra ASM, mainly specializing in sound propagation modelling for naval applications. In 1989, he joined Ifremer in Brest as an R&D engineer for underwater acoustical applications to oceanography. He is now head of the Underwater Acoustics service of Ifremer, and in charge of technological research programs on advanced methods for seabed-mapping sonars. His current interests are in seabed backscattering physics, sonar signal processing and engineering of sonar systems, especially multibeam echosounders. He has also been teaching underwater acoustics in French technical universities for many years.

Stacy DeRuiter is a marine biologist and bioacoustician. After earning a PhD (2008) in the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program, she did postdoctoral work at Ifremer in Brest, France, where she helped develop strategies to assess and mitigate the potential negative impacts of active acoustic devices on marine mammals. She is currently a postdoctoral researcher at Woods Hole Oceanographic Institution, examining cetacean behaviour and bioacoustics as well as the effects of military sonar on marine mammals.

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