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Recommendations to limit the impacts of manmade underwater acoustic emissions on marine wildlife

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Foreword

The introduction of noise energy into the marine environment and its effects on marine wildlife are now considered a major issue. Thus, noise pollution is now included in environmental impact studies in the same way as chemical pollution. However, this issue is sometimes difficult to grasp, due to its technical nature and the lack of available information.

In this light, these guidelines are intended as a tool to aid in the understanding and management of this issue. The development of these guidelines is one of the measures taken within the Marine Strategy Framework Directive (MSFD or DCSMM for Directive-cadre Stratégie pour le Milieu Marin in french) under the Sea Basin Strategy Documents (Documents Stratégiques de Façade or DSF). It is in line with the M021-NAT2 action plans for the marine environment from June 2016.

These guidelines focus on anthropogenic acoustic emissions in the marine environment, their effects on marine wildlife and the methods or techniques available to limit these impacts. It includes theoretical elements on acoustics in general and the particularities related to underwater acoustics. It presents an inventory of the various anthropogenic activities generating noise in the marine environment and identifies the information available on and the characteristics of the noise emissions related to these activities (expected noise levels, frequency ranges, etc.). It also provides information for the understanding of the potential impacts of these activities on marine wildlife. Finally, these guidelines establish, where appropriate, recommendations for better assessing and controlling these impacts, by presenting the means available to avoid, reduce or even compensate for the effects of each activity.

These guidelines are mainly aimed at government agencies and their local branches. Its general purpose is to assist these departments in the appraisal of document files relating to coastal or land-use planning actions and projects. However, it can provide useful information for all those involved in environmental impact assessment (Marine Protected Areas managers, industrial managers, engineering offices, etc.).

However, these guidelines are not intended for the recommendation of monitoring protocols, which must be adapted to the projects, the areas under consideration and the objectives of each study.

These guidelines only address anthropogenic noise sources and impacts related to civilian activities and excludes from its scope noise emissions related to military activities.

Glossary

ACCOBAMS	Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic Area
ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas
ARC	Avoid/Reduce/Compensate
CBD	Convention on Biological Diversity
CMS	Convention on the Conservation of Migratory Species of Wild Animals
GES	Good Environmental Status
IFREMER	French Research Institute for the Exploitation of the Sea
IMO	International Maritime Organisation
IUCN	International Union for Conservation of Nature
JNCC	Joint Nature Conservation Committee
MAP	Marine Action Plan
MMO	Marine Mammal Observer
MRE	Marine Renewable Energy
MSFD	Marine Strategy Framework Directive
NMCS	National Maritime and Coastline Strategy
PAM	Passive Acoustic Monitoring
PTS	Permanent Threshold Shift
SBSD	Sea Basin Strategy Documents
TTS	Temporary Threshold Shift

Abstract

The introduction of anthropogenic noise sources into the marine environment has been an increasingly worrying issue in recent decades. Indeed, the rise in maritime uses contributes to the increase of underwater ambient noise, which directly and indirectly impacts marine wildlife. The introduction of anthropogenic noise into the ocean is therefore today considered as pollution, in the same way as other types of pollution (chemical, microbiological, etc.) and must be integrated into environmental impact assessment (EIA) by project developers.

Sound is generated by acoustic waves. It can be perceived as a pressure variation or particle motion. A sound is characterized by a frequency (in Hz), a level (in dB) and a duration (in s). Its propagation in water is about four times faster than in air (~1,500 m/s). However, this propagation depends on environmental conditions, in particular bathymetry, seabed nature, temperature and water column salinity.

A sound can be of impulsive or continuous in nature. Different measures exist for the assessment of underwater sound level. The choice of the most relevant measure depends on the nature and characteristics of the sound. A sound wave propagation model is used to map its spatial footprint.

Many anthropogenic noise sources are likely to have an impact on marine wildlife. These sources are emitted by various activities: the oil & gas industry, marine renewable energy, professional fishing and aquaculture, port activities, coastal development, marine aggregates extraction, laying cable and pipe, shipping, scientific research activities and recreational motorboat activities. Each of these activities produces one or more noise types, characterized by their nature (impulsive or continuous), frequencies and emission levels.

Hearing sensitivity differs from one taxon to another among marine species. In marine mammals, hearing is an important sense and these abilities are well developed. Generally speaking, marine mammals perceive sounds between 10 Hz and 200 kHz, with minimum hearing thresholds close to 60 dB re 1 µPa. However, six hearing groups have been defined (low, high and very high-frequency cetaceans, sirenians, phocids and other carnivores) and each group is characterized by a significantly different hearing range and minimum hearing threshold.

In sea turtles, hearing is less developed, but it is documented that they can perceive underwater sounds between 30 and 2,000 Hz. However, the minimum hearing threshold varies from one species to another.

Among fish, several organs are involved in sound perception: the otoliths organs, the lateral line and the swim bladder. Generally speaking, fish are able to perceive sounds below 100 dB re 1 µPa between 50 and 300 Hz. However, their hearing abilities vary greatly from one species to another, with some species being able to perceive sounds of 80 to 100 dB re 1 µPa up to several thousand Hz.

Crustaceans and molluscs are also able to perceive sounds through sensory organs and cells. They detect low-frequency sounds (< 3,000 Hz) but at high levels (> 100 dB re 1 µPa).

The underwater hearing of diving birds is still very poorly known. Only the great cormorant

has been studied. This species is able to perceive sounds between 1.5 and 6 kHz with a hearing threshold below 80 dB re 1 µPa.

Due to the physiology and lifestyle of some species, noise exposure can have varying degrees of significant impacts. In the short term, these impacts include behavioural responses (avoidance, diving or surfacing, changes in swimming speed, foraging interruption, etc.), acoustic masking (leading to changes in communication patterns), permanent or temporary non-lethal physiological injuries (barotrauma, organ damage, metabolic stress, etc.) and direct lethal injuries (damage to vital organs) or indirect lethal injuries (stranding, predation). In the long term, underwater noise can cause behavioural disturbances (habituation, adaptation and moving) and influence species demography.

Assessing the impact of anthropogenic noise on marine life is essential but challenging. The acoustic impact assessment must evaluate the expected noise level by modelling sound wave propagation. This modelling must be based on knowledge of the species present in the area, their hearing sensitivities and environmental conditions (bathymetry, nature of the seabed, temperature and salinity in particular).

Recent studies have established thresholds at which species (marine mammals, fish and turtles) are likely to suffer from temporary or permanent hearing loss. Based on these thresholds and the predictions of the sound wave propagation model, it is therefore possible to implement measures to reduce the impact of anthropogenic noise on these species.

It is a priority to avoid and reduce these impacts, especially as there are no measures to compensate for the impact of noise on marine wildlife. Avoidance measures mainly consist in project sizing and/or adapting the work schedule and its spatial extent to periods or areas where no sensitive species are present, or using techniques that do not affect the species present.

Reduction measures apply at three levels. They can involve planning the work to avoid interfering with a biologically sensitive period or functional area. It is also possible to adopt quieter techniques or technologies that reduce noise at the source (bubble curtains, isolation casings, cofferdams) to reduce emissions. Finally, measures aimed at controlling the presence and keeping the species away from the worksite can also be implemented.

Taking it further, accompanying measures can be added to these avoidance and reduction measures. This may concern the acquisition of additional knowledge on the species (impacts or biology), on the noise emissions generated (levels and frequencies), the dissemination of this knowledge or participation in research programmes. It is also possible to restore degraded habitats or promote awareness-raising actions regarding underwater noise and improved techniques.

In order to consolidate knowledge about the impacts of noise on marine wildlife, there is a need to encourage the acquisition of knowledge and fundamental research. These elements will enable stakeholders to have a better approach to their impact assessment and put forward better sized projects, technical alternatives and appropriated avoidance/reduction measures.

Contents

Lexicon

A

Abundance:

The absolute abundance of a species/group corresponds to the number of individuals of that species/group in a defined geographical area or in a given population.
Relative abundance corresponds to the number of individuals of a species per unit area (or volume) in relation to the total number of individuals of all species together (in the sense of the specific composition of a population). Abundance can also be described as relative when the abundance estimate is not corrected for detection and availability biases.

Absorption:

Physical phenomenon of acoustic energy transformation into another form of energy (mechanical energy, heat, *etc.*). This phenomenon is responsible for some of the energy loss from the acoustic wave in contact with an interface (e.g. water/air) or in the propagation medium.

Acoustic impedance:

Acoustic impedance is the ratio between sound pressure and particle velocity (oscillation speed of the particles in the medium). In practice, the impedance corresponds to the resistance of the medium to the passage of an acoustic wave. For a plane progressive acoustic wave, it is calculated by multiplying the density of the medium and the speed of the wave in the medium:

$$Z_{ac} = \rho_m \times c$$

Acoustic signature:

The acoustic signature is the temporal representation of sound pressure. It integrates all the frequencies generated by a sound source and enables the source to be characterised.

Acoustic spectrum:

The acoustic spectrum of a sound represents the distribution of the sound level generated as a function of the frequencies produced.

Ambient noise:

Ambient noise corresponds to the overall noise perceived at a given point for a given time interval considered lacking any unusual disturbance or noise. It includes all sound sources present in the environment. Ambient noise therefore has three components: anthropophony, biophony and geophony.

Amplitude:

Amplitude is the intensity of the pressure variations generated by a sound wave. Like sound level, it indicates the "strength" of a sound.

Anthropophony:
Anthropophony refers to all the sounds emitted by human activities. It is one of the three components of ambient noise, along with geophony and biophony.

Audiogram:
Graphic representation of hearing ability. It represents the lowest level (in decibels) of sound perception as a function of frequency.

B

Barotrauma:
Injury caused by too rapid changes in external pressure (air or water) in organs containing gas-filled cavities.

Biophony:
Being the biological component of ambient noise, biophony refers to all sounds of non-human biological origin, emitted voluntarily (vocalisations, clicks, *etc.*) or involuntarily (movement).

Broadband noise:
Overall noise measured over a wide range of frequencies.

C

Cavitation:
Phenomenon of vaporisation of a fluid subjected to low pressure levels. Vapor-filled cavities (bubbles) are then formed. This phenomenon is commonly observed around propeller blades.

Celerity:
Propagation speed, in m/s, of a wave-like phenomenon such as an acoustic wave. The velocity of a sound depends on the properties of the medium in which it propagates: it is 340 m/s in air at 15°C and varies between 1,450 and 1,550 m/s in seawater (depending on temperature, salinity and pressure).

Complex tone:
A complex sound is composed of several pure tones of different frequencies and amplitudes.

Cutoff frequency:
Critical frequency (in Hz) below which the water column ceases to act as a waveguide and thus causes a strong attenuation of sound wave propagation. The medium thus acts as a high-pass filter.

D

DeciBel (dB):

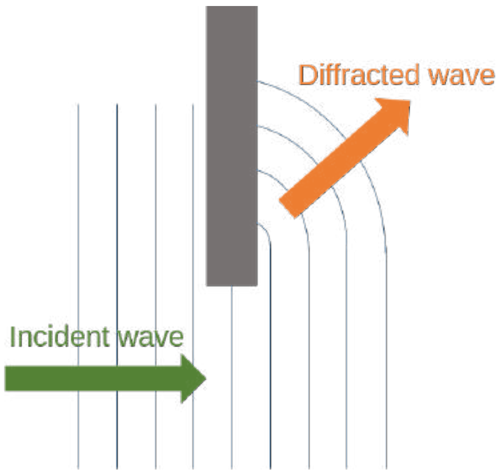
Logarithmic unit for quantifying sound level (denoted in dB). It can quantify sound intensity or sound pressure. The decibel is an approximation of the auditory sensation.

Density:

Abundance of a population expressed by the number of individuals per unit area (e.g. per km²). It is based on the analysis of direct counts, capture and recapture methods, sampling, or indirect methods (e.g. analysis of footprints left by animals).

Diffraction:

Modification of the direction of sound wave propagation by an obstacle or surface relief:



Diffusion:

Modification of the direction of sound wave propagation due to the cumulative effect of the phenomena of reflection, refraction and diffraction.

Doppler effect:

Frequency shift observed between measurements at the transmission and reception of an acoustic wave. This shift is due to the moving of the emitting source or receiver: the sound becomes higher pitched when the source and receiver move closer together and lower pitched when they move apart.

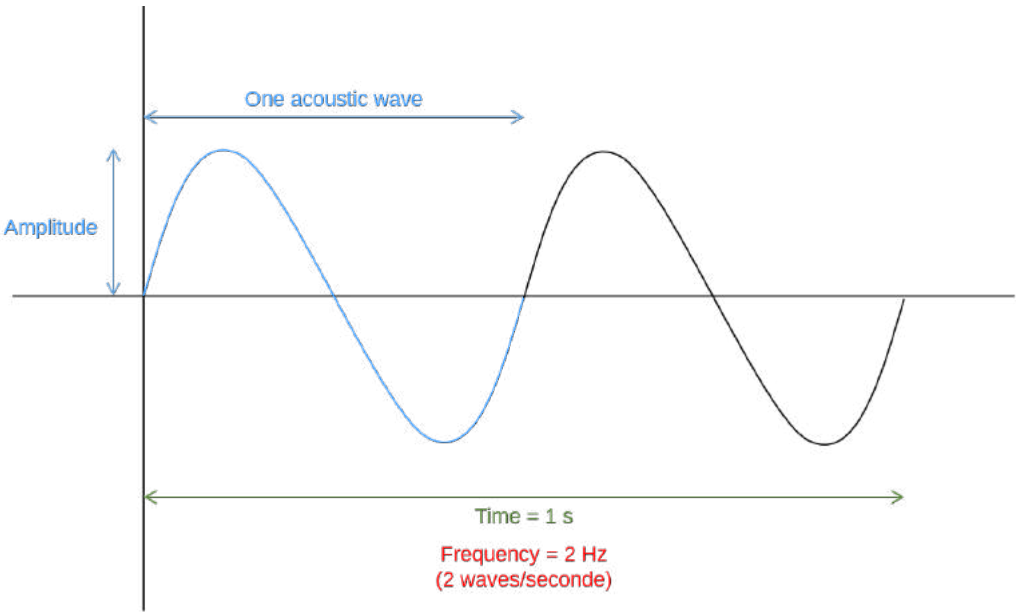
F

Fitness or selective value:

The ability of an individual to produce mature offspring (viable and reproductive), relative to other individuals in the same population and at the same time. The fitness of an individual (and therefore of a population) is therefore defined by its ability to survive as well as by its reproduction frequency (average rate of descendants per unit of time or in absolute values). Can also qualify the contribution of a gene or genotype to the next generation, relative to the contribution of other genes or genotypes in the same population and at the same time.
Fitness is often difficult to assess; indirect measures of fitness are thus used (reproductive success, survival of the young, *etc*.).

Frequency:

Denoted by *f* and expressed in Hertz (Hz), the frequency corresponds to the number of acoustic waves passing per second at a given point.
Frequency corresponds to the "pitch" of a sound: the higher the frequency, the higher the pitch.



Fundamental:

In the case of a pure tone, the fundamental refers to the frequency *f* of that sound. In the case of a complex sound spectrum, which reveals several harmonics, the fundamental frequency, or fundamental, designates the first harmonic, the smallest frequency interval between harmonics of the same origin. Harmonics therefore refer to sinusoidal signal frequencies:

$$f_n = f \times n$$

Where *n* is a positive integer called the harmonic rank, and *f* is the fundamental.

G

Geophony:

Ambient noise component relating to sounds of natural but non-biological origin: wave and wind noise, thunder, sedimentary landslides, earthquakes, *etc.*

H

Harmonic:

Spectral component of a sound whose frequency is an integer multiple of a so-called fundamental frequency.

Hearing acuity:

Ability to perceive sound. Hearing acuity varies with frequency. It can be very different from one species to another. It can be represented by an audiogram.

Hearing threshold:

Minimum sound level that can be perceived by an individual, for a given frequency, in the absence of significant background noise.

High-pass filter/Low-pass filter:

A frequency filter that allows only sounds above (high-pass filter) or below (low-pass filter) to pass through at a certain frequency called the cutoff frequency.

M

Masking:

Masking, or "masking effect", is the process by which the perception of a sound is made more difficult due to parasitic noise (often of the same frequencies), or significant ambient noise. The hearing threshold for the sound is therefore increased.

Mitigation:

Operation designed to reduce or moderate an event or action with a strong influence.

Mysticetes:

Baleen whales. This taxonomic group (suborder of cetaceans) includes right and rorqual whales.

N

Near field/far field:

The near field is the immediate environment of the sound source, within a zone where the sound intensity is rapidly oscillating, passing through maxima and minima, with a constant average value. Conversely, the far field corresponds to a distance beyond which the sound intensity decreases proportionally with distance.

Noise footprint:

During an impact study, the noise footprint of a project represents the geographical area (or perimeter) within which the noise level will be modified by the project.

O

Odontocetes:

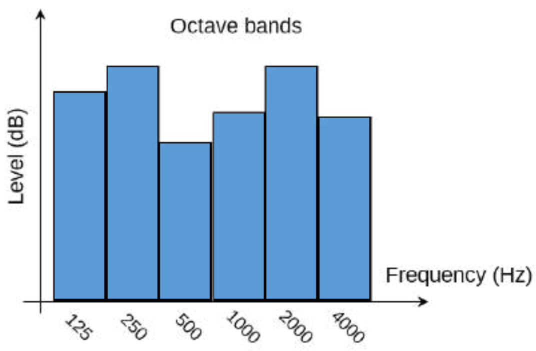
Toothed cetaceans. This taxonomic group (suborder of cetaceans) includes dolphins, porpoises, sperm whales, killer whales, pilot whales, Narwhal and Beluga.

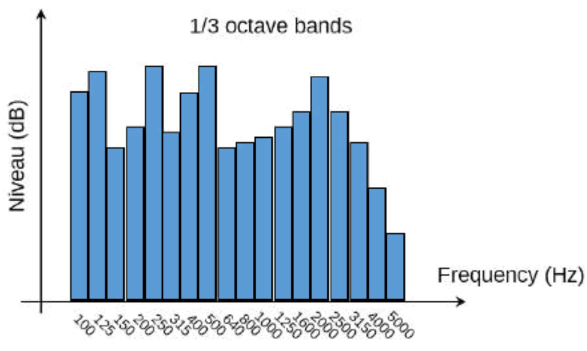
Octave:

Frequency interval with an upper limit that is twice the lower limit.

One-third octave:

In spectral analysis, a one-third octave represents a subdivision of the octave band and is used to refine analyses. In view of the specificity of frequency sensory perception, these analysis bands are standardised and are focused on certain frequencies:





P

Pascal (Pa):
Unit of pressure, symbolised by Pa, corresponding to one Newton per square metre (1 Pa = 10^{-5} bar)

Period:
The period, symbolised by T, corresponds to the duration in seconds of an acoustic wave cycle (see acoustic wave). It is the inverse of frequency *f*:

$$T = 1/f$$

Pinnipeds:
Semi-aquatic mammals of the order Carnivora. This taxonomic group includes Phocidae (seals and elephant seals), Otariidae (fur seals and sea lions) and Odobenidae (walruses).

Population:
A group of individuals with common ancestors who are more likely to reproduce with each other than with individuals from another population. These individuals belonging to the same species live on a territory whose limits are generally those of the biocenosis of which the species belongs. A population is a real entity that has its own organisation, its own parameters of spatial distribution, structure density, natality or mortality.

Propagation losses:
Acoustic energy (and therefore intensity) losses related to the distance between the source and the receiver. Also known as "transmission losses", they are related to environmental characteristics.

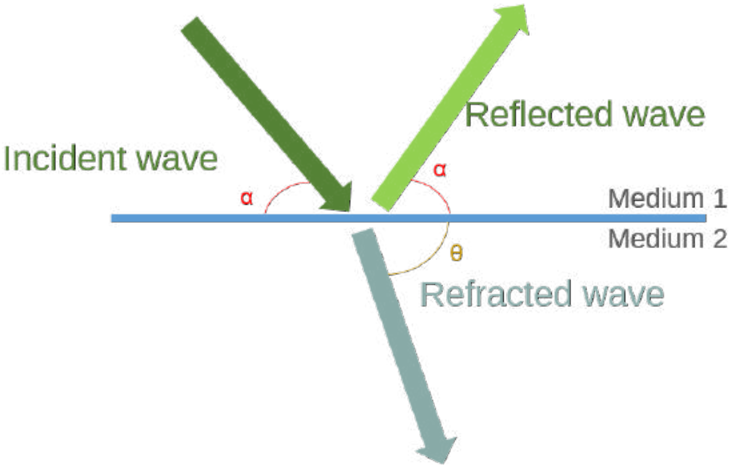
Pure tone:
A pure tone corresponds to a sinusoidal wave with a constant frequency and amplitude throughout the entire emission period. Its spectrum has only one harmonic: the fundamental.

R

Radiated noise:
All or part of the noise generated by a source, which propagates in the environment and can be intercepted by a receiver (hydrophone or individual). This radiated noise thus represents the acoustic signature of the source.

Reflection:
When a sound wave encounters an obstacle or changes medium (at the water-air interface for example), part of the wave is reflected and leaves with an angle of reflection equal to the incident wave (see figure below).

Refraction:
When a sound wave encounters an obstacle, or changes medium (at the water-air interface for example), part of the wave is refracted and crosses the interface while being deflected (see figure below).



S

Self-noise:
Receiver noise (e.g. at a sonar receiving antenna).

Sirenians:
Order of aquatic mammals including Dugongidae (dugongs) and Trichechidae (manatees).

Sonar:
Acronym for SOund NAvigation and Ranging. A system for detecting and locating underwater landmarks by transmitting/receiving (active sonar) or receiving (passive sonar) a sound signal.

Sound:
Pressure variation caused by an acoustic wave (vibration).

Sound emergence:
Corresponds to the difference between the noise level in the environment when the sound source we are trying to characterise emits and the ambient noise level when the source does not emit: Emergence (dB) = Perceived noise level (source on) - ambient noise (source off).

Sound exposure level:
The Sound Exposure Level ($L_{E,p}$ or SEL) is a measure of received noise that takes into account both received level and duration of exposure. This metric corresponds to the pressure level generated by a sound impulse (sonar emission, pile driving) of duration *t* that is reduced to one second.

Sound intensity (I):

A sound wave emits a sound with a certain acoustic power, expressed in watts. Sound intensity (or acoustic intensity) is the average power received per unit of time through a unit area (perpendicular to the axis of propagation). The symbol is I and it is measured in watt per square meter (W/m^2).

Sound level (L):

Sound level (or noise level), denoted *L* and expressed in dB, is related to sound intensity or sound pressure by the formula:

$$L(db) = 10 * \log_{10}\frac{I}{I_0} \quad \text{or} \quad L(dB) = 20 * \log_{10}\frac{P}{P_0}$$

With *I*: sound intensity of the acoustic wave expressed in W/m^2, *P*: sound pressure in Pa, I_0: reference sound intensity and P_0: reference sound pressure. For a reference sound pressure of 1 µPa, I_0 = 6.5.10^{-19} W/m².

The sound level makes it possible to express the intensity of a sound on a logarithmic scale, therefore being more restricted and easier to represent.

Sound pressure:

A sound propagates in a medium in the form of a periodic pressure oscillation around a reference value. The value of this oscillation constitutes the sound pressure. This sound pressure describes the amplitude of the perceived sound. It is measured in Pascal (Pa). In the marine environment, the reference sound pressure is equal to 1 µPa.

Sound power:

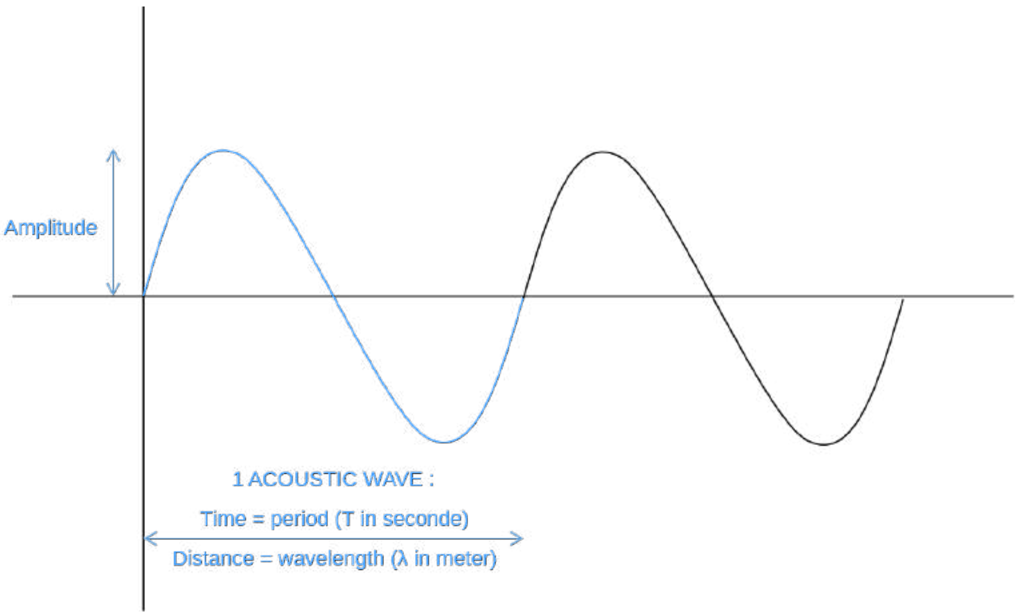
Sound power is the amount of energy that generates the sound wave per unit of time. It is measured in Watts (W).

Sound pressure level:

The Sound Pressure Level, denoted L_p or SPL, reflects the amount of energy received by a receiver (hydrophone, individual) at a given distance from the emitting source.

Sound wave (or acoustic wave):

Mechanical disturbance (due to compression-dilation of the medium) which propagates in a material medium by energy transfer but without material transfer. An acoustic wave is a periodic wave with a disturbance that is repeated at regular intervals and therefore characterised by an amplitude, a wavelength (distance travelled during a cycle) and a period (duration of a cycle):



Source spectrum model:

A source spectrum model represents the spectral signature (levels as a function of frequency) representative of a noise source in a given configuration.

Strong tonal components:

A strong tonal component is detected in a third-octave spectrum when the difference in level between the third-octave band and the four nearest third-octave bands (the two bands immediately below and the two bands immediately above) reaches or exceeds a certain level. This results in peaks in the acoustic spectrum.

W

Wavelength:

Wavelength, symbolised by *λ*, is the distance in metres travelled by a wave in a single cycle (or during a period). It therefore corresponds to the shortest distance between two similar points of two successive cycles of an acoustic wave (e.g. two points of maximum amplitude). Wavelength is a function of the frequency (and therefore the period) and the celerity of the wave in the medium:

$$\lambda = c/f = c \times T$$

Introduction

For several decades, the scientific community has raised the alarm about the introduction of anthropogenic noise sources into the marine environment [8, 16, 116, 158]. In recent decades, the rise in maritime uses (commercial trade, marine energy, offshore works, recreational uses, etc.) has led to an increase in the level of anthropogenic underwater ambient noise, particularly in mid and low frequencies [30, 78, 79, 127]. Many anthropogenic noise sources add to an environment already rich in physical sounds, such as swell, rain or tectonic movements, and biological sounds (marine mammal communications, sound generated by crustacean claws, etc.).

Therefore, sound is an important component of marine habitats. Indeed, the marine environment favours the propagation of sound waves and many species have evolved by taking advantage of this property. Notably marine mammals have particularly developed hearing. They use sound to interact, move and orient themselves or to detect their prey and predators. Some cetaceans have developed a high-performance biological sonar system which enables them to orient themselves in space three-dimensionally and locate their prey [61, 183]. For these animals, a modification of the sound environment can thus have a significant impact. Anthropogenic underwater noise can indeed interfere with the acoustic signals emitted via an affect of masking which thus limits the information perceived by marine mammals [41, 61]. However, the consequences can also be more dramatic, and some studies have, for example, highlighted the link between the use of military sonars and mass cetacean strandings [68, 165, 88]. As a result, it has now been established that conservation of marine mammal species must take account of disturbances linked to anthropogenic underwater noise [10, 16].

Marine mammals are not the only group of species to be impacted by underwater noise. Although the effects are less well known and poorly documented, several studies have demonstrated the sensitivity of fish to sound waves. In both fish and marine mammals, communication between individuals can be masked in areas with high levels of shipping and ambient noise [33]. Impulsive noise sources, which introduce a large amount of acoustic energy into the environment, can alter the vital functions of some fish, causing their death [151].

Sea turtles do not use sound to communicate, but they use acoustics to help them move around, locate their prey, avoid predators and obtain information from their environment [45]. Although the auditory capacities of sea turtles are still poorly known, their conservation status (6 of the 7 sea turtle species are considered threatened, with an IUCN status of vulnerable, endangered or critically endangered) has led to increased research about the pressures that threaten them. The results of this research show, among other results, that the sea turtle auditory range intersects with the frequency range of the noise generated by the airguns used during seismic surveys [40, 134]. The effects of this type of noise on sea turtles range from disturbance to hearing loss. The assessment of the effects of acoustic emissions at sea on these species must therefore not be underestimated.

Other marine species may also be affected by anthropogenic noise emissions in the marine environment. For example, low-frequency noise can cause behavioural responses in cephalopods [7, 24, 122] and decapod crustaceans; in the latter, physiological injury has also been observed when subjected to high amplitude sounds [52, 173]. Finally, some anthropogenic sound sources can also affect egg and larvae development, thus affecting population and ecosystem balance and sustainability [3, 148, 152].

The effects of anthropogenic noise emissions on marine wildlife therefore concern a wide range of species and the effects can be very diverse, ranging from disturbance likely to cause flight and habitat abandonment to physiological injury that may indirectly lead to death of the individual, via the masking of communication signals. These effects are therefore likely to affect a species at the level of the individual or group of individuals, but also at the population level. As a result, studies carried out in recent years have led to a better understanding and appreciation of these effects, and noise pollution is now recognised a threat to the marine environment in the same way as chemical pollution [2].

Regulation

Although there are currently no regulations governing noise emissions at sea on a global scale, several international conventions, to which France is a signatory, now include the impact risk related to the introduction of noise into the marine environment on marine wildlife.

- The International Whaling Commission has been working on the subject since 2008 and adopted a specific resolution in 2018 encouraging States Parties to put in place measures to reduce the impact on cetaceans.
- The IMO published in 2014 guidelines on the reduction of underwater noise from merchant shipping in order to address the adverse effects on marine life.
- The CBD Conference of the Parties adopted a resolution in 2016 on the impacts of marine debris and anthropogenic underwater noise on marine and coastal biodiversity.
- The CMS Conference of the Parties approved guidelines in 2017 on the assessment of the environmental impact of underwater noise generated by human activities.
- The Convention for the Protection of the Marine Environment of the North-East Atlantic, or OSPAR convention, has been integrating an Ambient Noise Monitoring Strategy since 2015; an assessment of the pressure related to impulsive noise was included in the Intermediate Assessment of the state of the North-East Atlantic in 2017.
- The Convention for the Protection of the Mediterranean Sea against Pollution, or Barcelona Convention, has set 11 ecological objectives (EO) for the

contracting parties. EO 11 refers to the introduction of energy, including acoustic energy.

- The intergovernmental agreement ACCOBAMS (Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area), set up under the aegis of the Bonn Convention, took resolutions as early as 2004 and up to the most recent meeting of the Parties in November 2019 to encourage the Parties to reduce their noise emissions at sea. ACCOBAMS also conducts underwater noise study projects aimed at protecting cetaceans from anthropogenic noise, and runs an "underwater noise" working group jointly with ASCOBANS (Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas) and CMS (Convention on the Conservation of Migratory Species of Wild Animals). It organises training courses for on-board observers and passive acoustic monitoring operators concerning the implementation of measures to reduce the impact of noise emitted during operations at sea on marine mammals.

Within the European Union, the Marine Strategy Framework Directive (MSFD)[1], adopted in 2008, aims to "*maintain the biological diversity and dynamism of the oceans and seas and ensure their cleanliness, good condition and productivity*". The Directive requires EU Member States to each define a marine strategy to reduce the pressures exerted by human activities on the marine environment to levels compatible with achieving or maintaining good environmental status (GES) in the marine waters under their jurisdiction.

Marine Strategies of the Member States include:

- a national definition for the good ecological status of marine waters;
- a diagnosis of the ecological state of marine waters and the pressures exerted on them;
- a programme for monitoring changes in marine environmental state;
- objectives expressing the ambition of State Members in terms of limiting and reducing the pressures necessary to achieve or maintain good environmental status;
- a programme of measures to achieve the environmental objectives and thus achieve or maintain good environmental status in marine waters.

Achievement of good environmental status is assessed through eleven descriptors, including the introduction of energy, comprising underwater noise sources at levels that do not harm the marine environment[2].

In the framework of the D11 descriptor, GES is assessed on the basis of two criteria dealing exclusively with noise emissions in marine waters regarding **impulsive sound** (D11C1) and **continuous low-frequency sound** (D11C2).

Criterion D11C1 for anthropogenic impulsive sound is defined as follows: "*the spatial distribution, temporal extent and levels of*

[1] Directive 2008/56/EC of the European Parliament and Council of 17 June 2008 establishing a Framework for Community Action in the field of Marine Environmental Policy (Marine Strategy Framework Directive).

[2] Definition of descriptor D11 according to Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria for methodological standards for the good environmental status of marine waters, specifications and standardised methods for monitoring and assessment, and repealing Directive 2010/477/EU.

anthropogenic impulsive sound sources do not exceed levels harmful to marine animal populations". Two measurements are used to measure this: the risk of disturbance and the risk of excess mortality. They correspond to the temporal and spatial distribution of impulsive emissions (varying in strength depending on whether disturbance or excess mortality is involved), expressed as the number of days with impulsive emission sources per quarter (or per month) and to the spatial distribution of the cumulative number of days per quarter (or per month) per grid resolution.

Criterion D11C2 for continuous low-frequency anthropogenic sound is defined as follows: "*the spatial distribution, temporal extent and level of continuous anthropogenic sound do not exceed levels harmful to marine animal populations*". It is measured according to the masking risk, i.e. the spatial distribution of the ambient noise level according to the annual maximums reached per grid resolution in the water column.

To define the threshold values for these two criteria, Member States cooperate at the EU level, taking into account regional or sub-regional particularities.

Several countries have taken national initiatives to reduce the impacts of marine noise emissions in their territorial waters. For example, Ireland has put in place strict protocols since 2014 to control noise emissions in the marine environment[3]. In Germany, the BSH (*Bundesamt für Seeschifffahrt und Hydrography*), the federal agency responsible for approving offshore installations, has published *minimal* technical recommendations to be implemented when assessing the impacts related to the installation of offshore wind farms. These recommendations include a protocol for assessing underwater noise [21]. Germany has also set noise thresholds not to be exceeded during pile-driving operations in 2013[4]. Belgium has had this type of measure in place since 2012[5]. Other European countries, such as Denmark and the Netherlands, have also issued recommendations. Finally, in the United Kingdom, the JNCC (Joint Nature Conservation Committee), statutory adviser to the British government and local authorities, has drawn up several directives to minimise the noise impacts associated with pile driving, the use of explosives or geophysical prospecting [89-91].

In France, the MSFD is transposed by articles L. 219-7 to L. 219-18 and R. 219-2 to R. 219-10 of the Environment Code. It applies only in mainland France.

The marine strategies, of which the adoption is required by the MSFD, were defined in 2012 under the term marine action plans. An action plan was adopted for each of the four marine sub-regions of mainland France (North Sea and Channel, Celtic Seas, Bay of Biscay, Western Mediterranean) between 2012 and 2016. For the second cycle of Directive implementation, the action plans of the Sea Basin Strategy Documents (Documents Stratégiques de Façade or DSF) guarantee the implementation of the MSFD. Within this framework, the MSFD marine waters assessment and the environmental objectives adopted in 2012 were updated in autumn 2019. The monitoring programme and the programme of MSFD measures adopted respectively in 2015 and 2016 under the first cycle will be revised in 2021.

[3] Mandatory prior visual monitoring, 1000 m exclusion perimeter, mandatory soft-start/ramp-up procedure if noise levels are likely to exceed a level $L_{p,\mathrm{pk}}$ of 170 dB re 1 µPa @ 1 m.

[4] Thresholds of 160 dB ($L_{E,\mathrm{p}}$) and 190 dB ($L_{p,\mathrm{pk}}$) at 750 m from the noise source. Thresholds set as part of the "*Noise Mitigation Concept*".

[5] Threshold $L_{p,\mathrm{pk}}$ of 185 dB at 750 m from the noise source.

In 2019, environmental objectives were adopted by the prefects to control underwater noise. They correspond to two criteria for achieving good ecological status in terms of impulsive and continuous underwater noise.

Two measures will be used to assess the achievement of objective D11-OE1: "*Reduce the level of noise linked to impulsive emissions with regard to the risks of disturbance and mortality of marine mammals*":

- the spatial influence of events recorded from "strong" to "very strong"[6] in percentage on the sea basin. This right-of-way will be defined, concerted and adopted on the sea basin at the same time as the DSF action plans.
- the amount of projects generating impulsive emissions presenting a risk of disturbance and mortality to marine mammals (following the environmental assessment) and having put in place measures to reduce acoustic impact, with a target of 100% of projects authorised from the adoption of the sea basin strategy.

In order to measure the achievement of objective D11 OE2: "*Maintain or reduce the level of continuous noise produced by anthropogenic activities, in particular maritime shipping*", the measurement used will be low-frequency anthropogenic noise in the water (maximum level and spatial extent)[7], with a reduction target.

In all French territorial waters, marine mammals and turtles are protected by interministerial decrees that, among other provisions set out in Article L. 411-1 of the Environment Code, prohibit the intentional disturbance of individuals and the alteration of their habitats. The Environmental Code also provides, under Article L. 122-1, that "*public and private work, works or development projects, which, by their nature, size or location are likely to have a significant impact on the environment or human health must be preceded by an impact study*", which includes the assessment of noise impacts. The purpose of these guidelines are therefore to provide technical and scientific elements at the national level to the State's investigating authorities for taking into account the disruptions linked to the introduction of sound sources in the examination of authorisation reports. The publication of these guidelines are part of action 2.3 "*Reducing the impact of anthropogenic underwater noise emissions on cetaceans*" of the action plan for the protection of cetaceans adopted in December 2019.

Guideline contents

In this context, it is therefore important to be able to identify the different sources of anthropogenic noise, to know their potential impact on the environment and marine wildlife, as well as the tools available to limit these impacts. Anthropogenic underwater noise can be introduced intentionally or accidentally and the sources are multiple. The aim of these guidelines is to list them exhaustively, describe them and explain their effects on marine wildlife. It also presents the measures that make it possible

[6] For the purposes of the Good Environmental Status Order, and under criterion D11C1, impulsive emissions are qualified as high to very high if they exceed the following thresholds:
- 22 kg TNT eq. for underwater explosions;
- 28 Mj for pile driving;
- 253 N0-p dB re 1 µPa @ 1 m for airgun emissions;
- 230 Ne dB re 1 µPa2 m2 s @ 1 m for other impulsive sources;
- 220 N0-p dB re 1 µPa @ 1 m for other sources.

[7] Function of criterion D11C2 of the GES decree: the spatial distribution of the ambient noise level (63 and 125 Hz), corresponding to the continuous noise level expressed in dB re 1 µPa2 over the third octave band centred on 63 Hz, respectively on 125 Hz.

to assess *in situ*, predict, avoid and/or reduce the impacts of the introduction of anthropogenic sound sources on marine wildlife.

These guidelines introduce some basic notions of acoustics and the particularities of underwater acoustics. The first part lists the civil anthropogenic activities likely to generate underwater noise, and presents for each of these activities the expected noise levels. The second part describes the impact of these activities on marine wildlife. The third part of these guidelines lists the procedures or technologies available to assess, avoid and reduce these impacts and, in addition, the accompanying measures that may be relevant. Finally, in the fourth part, summary sheets are put forward as per activity; they present a description of the noise generated by the activity (frequency range, expected levels, etc.), list the marine species that are most sensitive to it and the measures available to limit their impact.

Preamble:
Basics of Underwater Acoustics

Acoustic Waves

Sound is a physical phenomenon generated by vibrations or acoustic waves. These waves are the result of a mechanical compression-expansion movement of the medium, which creates a pressure variation that then propagates from one place to another. As the wave passes, each molecule transmits a quantity of energy to neighbouring molecules.

An acoustic wave is therefore a periodic series of compressions and dilations of the medium which propagate without transfer of matter but only by transfer of energy.

Therefore, it is possible to characterise the acoustic wave by the variation in pressure it generates in relation to the surrounding average static pressure. This pressure variation is called "acoustic pressure". It is measured in pascal (Pa). In addition to this "pressure variation" component, a sound wave can also be characterised by the movement of particles (molecules of water, gas, etc., depending on the medium through which it passes) it generates. This "particle motion" component provides information on the intensity of the sound, but also on its direction. The motion of particles induced by an acoustic wave can be measured in terms of displacement (in m), speed (in m/s), or more commonly, acceleration (in m/s^2).

A sound is characterised by:

- **its frequency** (in Hz), which corresponds to the number of cycles (or waves) per second and defines the "pitch" of the sound: the higher the frequency, the higher the sound (Figure 1). The frequency *f* corresponds to the inverse of the period T (duration in seconds of a cycle): f = 1/T;
- **its level,** determined by the amplitude of the maximum pressure variation with respect to a reference pressure, which corresponds to the "volume" (or intensity) of the sound;
- **its appearance duration,** corresponding to the time during which the sound is emitted.

Given the large measurable pressure variations, from a few µPa to 1012 µPa [109], a logarithmic scale is used to quantify the measured acoustic energy level and thus to estimate auditory sensation. This unit, the decibel (dB), is a relative unit, which is a function of the logarithm to the decimal point of the quadratic ratio between the sound pressure measurement *P* and a reference pressure P_0:

$$\text{Sound level in dB} = 20 \log_{10} \times (P/P_0)$$

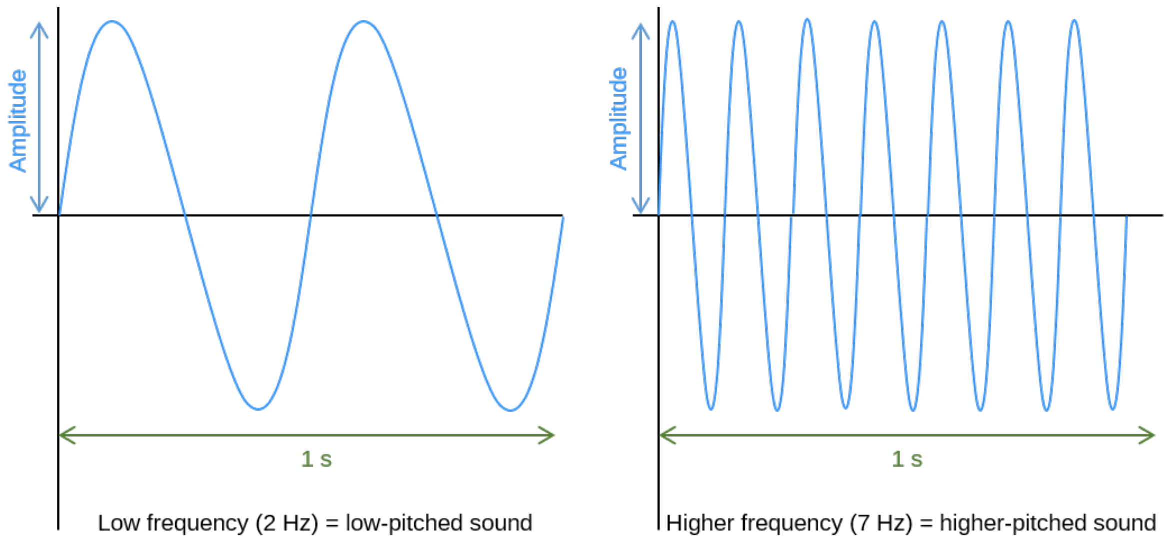


Figure 1: The frequency of a sound defines its "pitch": the higher the frequency, the higher the pitch of the sound.

In the marine environment the reference sound pressure P_0 is 1 µPa. **The absolute sound pressure level in the marine environment is therefore expressed in dB with respect to 1 µPa or dB re 1 µPa[8].**

Given the decibel is a logarithmic quantity, sound levels cannot be added up, and doubling the sound pressure measurement does not result in a doubling of the sound level, but in an increase of 6 dB. Thus, for a sound pressure P measuring 1 Pa, the associated sound level is 120 dB re 1 µPa, while for a sound pressure P measuring 2 Pa the associated sound level is 126 dB re 1 µPa. The sound level can also be calculated from the sound intensity measurement I, compared with a reference intensity I_0:

$$\text{Sound level in dB} = 10 \log_{10} \times (I/I_0)$$

For a reference sound pressure of 1 µPa, $I_0 = 6.5.10^{-19}$ W/m². In this case a doubling of the sound intensity results in an increase in the sound level of 3 dB.

Propagation of Acoustic Waves in the Marine Environment

Seawater is a favourable environment for the propagation of acoustic waves. In water, sound propagates about 4 times faster than in air. This propagation speed, or celerity, does not depend on the characteristics of the acoustic wave; it depends solely on the characteristics of the medium, and mainly on temperature, salinity and pressure (it with the same trend as these three parameters). The celerity therefore differs spatially and temporally and is not homogeneous throughout the entire water column (Figure 2). **Generally speaking, the speed of sound in seawater is between 1,450 and 1,550 m/s (compared with 330 to 350 m/s in air).**

[8] In air, the reference sound pressure is 20 µPa.

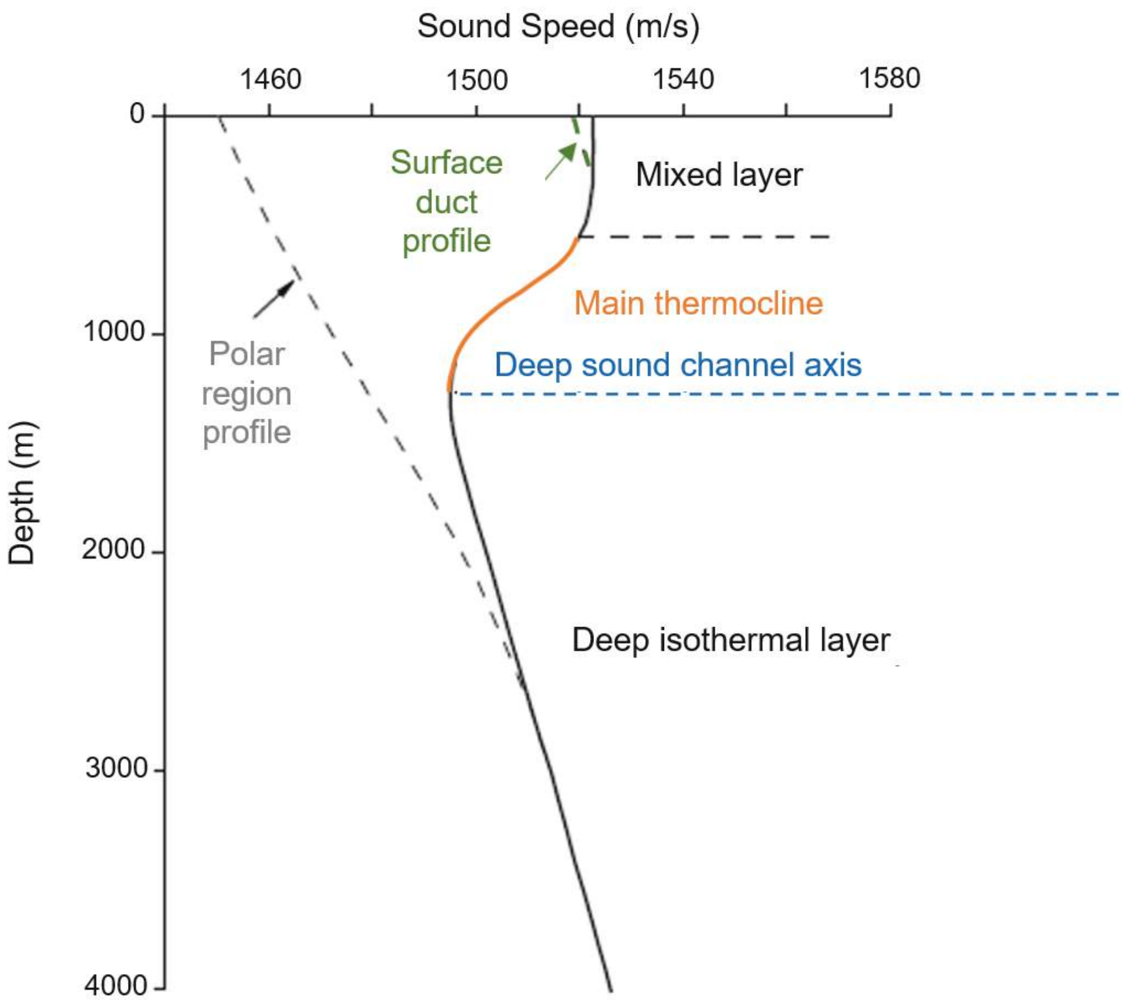


Figure 2: Generic sound speed profiles in an open marine environment (according to [87]).

While seawater is a medium that favours sound propagation, acoustic waves do not propagate linearly through the ocean from point A (source) to point B (receiver). The environmental conditions of the propagation medium play an important role and include the following parameters:

- **bathymetry.** The propagation of sound waves is very different in shallow and deep waters. In coastal or shallow water environments, the medium acts as a "high-pass filter": below a certain frequency (called the cut-off frequency), sound waves undergo significant losses;
- **seabed nature.** Sediments have, depending on their nature, the ability to reflect (e.g. rock) or absorb (e.g. silt) sound waves;
- **temperature and salinity profiles of the water column.** Variations in temperature and salinity create propagation channels (Figure 2), which affect the speed of the sound wave.

Depending on the frequency of the signal, these parameters have varying extents of influence.

As a result, the propagation of the sound wave can be disturbed by many phenomena.

These include:

- **variations in celerity.** As mentioned above, celerity depends on the characteristics of the environment. It varies with depth and local changes in temperature and salinity;
- **phenomena of reflection,** due to the presence of water/air and water/sediment interfaces, obstacles in the wave path, or stratification of the water column (thermocline, freshwater intrusion, etc.), which change the direction of wave propagation;
- **absorption and refraction phenomena,** which will lead to energy loss;
- **diffraction and diffusion phenomena,** which cause a change in the direction of the acoustic wave.

These phenomena lead to a change in direction and attenuation of the signal intensity transmitted between the source and the receiver, and induce interference in the multiple paths that the acoustic waves generated by a noise source can take. These phenomena are all the more important and complex in a coastal environment (shallow water), where the propagation of sound waves is subject to numerous surface/ground reflections.

The physical propagation medium, seawater, will also contribute to attenuating the intensity of the acoustic wave, on the one hand by spherical divergence (the energy of the acoustic wave will "spread" as it progresses and thus dilute in the medium) and on the other hand by damping (absorption of the acoustic energy dissipated due to the viscosity of the medium and chemical interactions).

The transmission of sounds in the marine environment is also linked to their frequency. Indeed, low-frequency (lower) sounds propagate better than high-frequency (higher) sounds. For example, a 100 Hz sound can travel hundreds or even thousands of kilometres, whereas a 100 kHz sound will travel a much shorter distance [194].

The loss of sound intensity between the transmitting and receiving points is referred to as transmission loss or propagation loss. These losses depend on the characteristics of the environment moved through and the characteristics of the sound wave (frequency).

Propagation losses can be estimated either by carrying out *in situ* measurements by performing a series of calibrated emissions (of known frequencies and levels) and measuring the levels received at a known distance, or by a theoretical propagation loss model (see Part 2 - III - 1.b) - Assessing acoustic wave propagation).

All these phenomena help to explain the differences in levels measured between the sound emitted by a source and the sound received by a receiver (Figure 3).

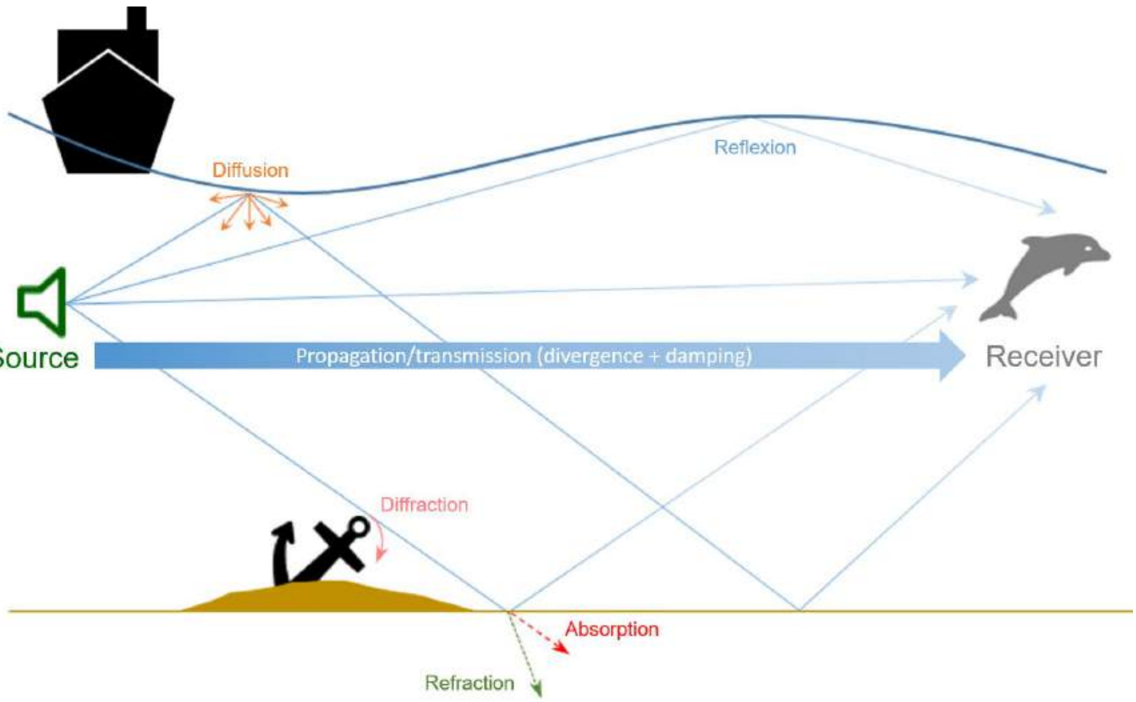


Figure 3: Phenomena contributing to the attenuation of acoustic wave intensity between the source and the receiver.

Ambient Underwater Noise

Ambient noise is the overall noise measured at a given point. It is defined as the sum of the acoustic contributions of a myriad of sources that cannot be distinguished from each other. It excludes noise that could be related to the recording conditions (noise related to electronics, anchorage, currents, etc.).

During an acoustic impact study, the ambient noise corresponds to the underwater sound environment before work is carried out, apart from the noise-generating activity whose impact is to be assessed.

Ambient noise is made up of all the sounds emitted by the sound sources that influence the measurement taken. In the marine environment, several sources contribute to ambient noise:

- sources linked to natural phenomena, or geophony (rain, swell, wind, etc.);
- biological sources, or biophony (benthic macrofauna and marine mammals in particular);
- anthropic sources, or anthropophony (maritime traffic and activities generating permanent noise).

Generally speaking, far-field maritime traffic and wind (through turbulence, friction, vaporisation, etc.) are the main sources contributing to global ambient noise [179].

Wenz's model, established in 1962 [188], synthesises the contribution of different sound sources to ambient underwater noise in the open ocean (Figure 4).

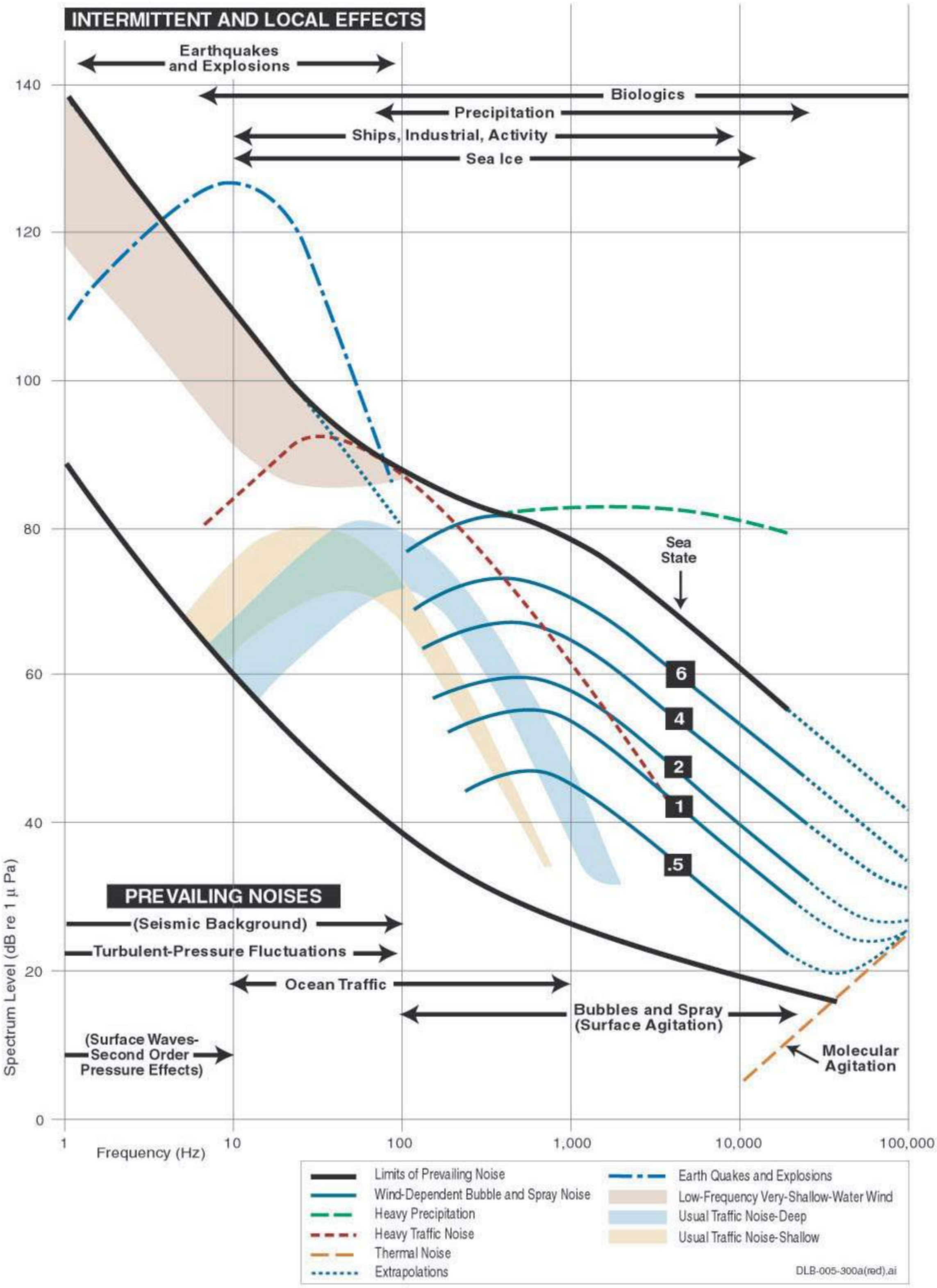


Figure 4: Characteristics and components of underwater background noise ([127] adapted from [188]).

According to Wenz's model (Fig. 4), the level of ambient underwater noise is particularly high at very low frequencies (< 10 Hz). This is mainly due to the contribution of geophonic sources (seismic activity, pressure fluctuations, waves). Between 10 and 1,000 Hz, maritime traffic accounts for most of the ambient underwater noise. Above 100 Hz, the contribution of sea state is significant and the noise level is correlated to weather conditions.

Ambient Underwater noise is therefore highly variable in level and frequency, temporally and spatially. This variability is mainly related to the amount of maritime traffic and the influence of weather conditions. The variability in sound wave propagation conditions (related to the physical properties of the propagation environment and depth) also influences ambient noise [158].

When trying to assess the effect of anthropogenic noise on marine wildlife, it is important to take into account the ambient noise in the study area. Indeed, the level of ambient noise has a direct influence on the perception of sound waves. The higher this level is, the more likely it is to mask a particular noise. Indeed, sound emergence depends directly on the ambient noise level and the emission level of a sound source could be overestimated without taking this into account.

Assessing underwater noise

1) Noise characterisation according to the type of signal

The evaluation of underwater noise first requires characterising the type of noise that we want to assess. There are two types of noise: impulsive noise and continuous noise.

Impulsive noise

Impulsive noise is a transient sound impulse that occurs for a short duration, corresponding to a sudden increase in sound pressure [136]. It applies, for example, to the noise generated by the impact of a hammer on a pile.

In order to characterise an impulsive noise, it is required to determine:

- its frequency parameters: central transmission frequency, bandwidth (difference between the minimum and maximum frequencies);
- its temporal parameters: impulse duration, transmission duration, interval between two transmissions, number of transmissions;
- the emission level.

Continuous noise

Continuous noise cannot be defined by its duration (it is sometimes impossible to define emission start and end). It does not correspond to a sudden change in sound pressure [136]. The most commonly cited example of continuous underwater noise is that of maritime traffic, but it can also apply to noise generated by a drill string, for example.

In order to characterise continuous noise, it is required to determine:

- its spectral level (power spectral density);
- frequency (or frequency band) corresponding to the maximum level

2) Noise emitted, noise received and noise perceived

To assess noise level, it is necessary to differentiate between the emitted noise level, which corresponds to the noise generated by a sound source, and the received noise level, which corresponds to the same noise arriving at a receiver after having undergone all the physical phenomena that contribute to attenuating the signal. The received noise level is therefore generally lower than the emitted noise level.

The received noise is also different from the noise actually perceived by the receiver. This is because the receiver has its own signal integration capacities, which modify the signal, in particular by retaining only certain frequencies. For example, the human ear only picks up frequencies between 20 Hz and 20 kHz on average, with greater sensitivity in the 200-5,000 Hz range. The difference between emitted noise, received noise and perceived noise is shown in Figure 5.

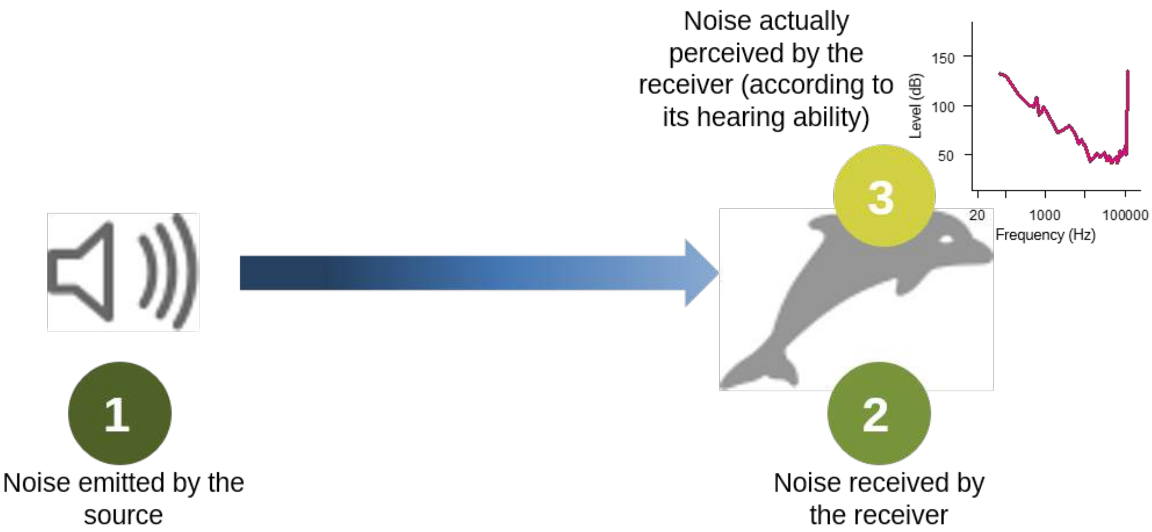


Figure 5: Difference between emitted noise, received noise and perceived noise. At each stage, the noise level (in dB) and its frequency spectrum is subject to change.

3) Different measures for assessing noise level

Noise measurement terminology

ISO 18405: 2017 Underwater acoustics - Terminology defines standard terms for acoustic measurements. As these standards are relatively recent, they are not systematically used and other terms may be used in study reports or literature. This paragraph therefore lists all the commonly observed terms for each measurement, in addition to the **standard (ISO) measurements shown in bold in this paragraph** (up to and including Table 1). It is nevertheless necessary, as far as possible, to use standards in order to strive towards a harmonisation of terminology in underwater acoustics.

a) Measurements of emitted noise level

Source level: L_S (or SL)

Measuring the emitted noise is equivalent to quantifying the noise level that would be measured at a distance of 1 metre from the source (noted @ 1 m). Denoted L_s or SL, **the source level is measured in dB re 1 µPa @ 1 m.**

Power spectral density: PSD

The power spectral density of the emitted noise represents the distribution of the emitted sound power as a function of frequency in a 1 Hz band (Figure 6). **This power is expressed in dB re 1 µPa²/Hz.**

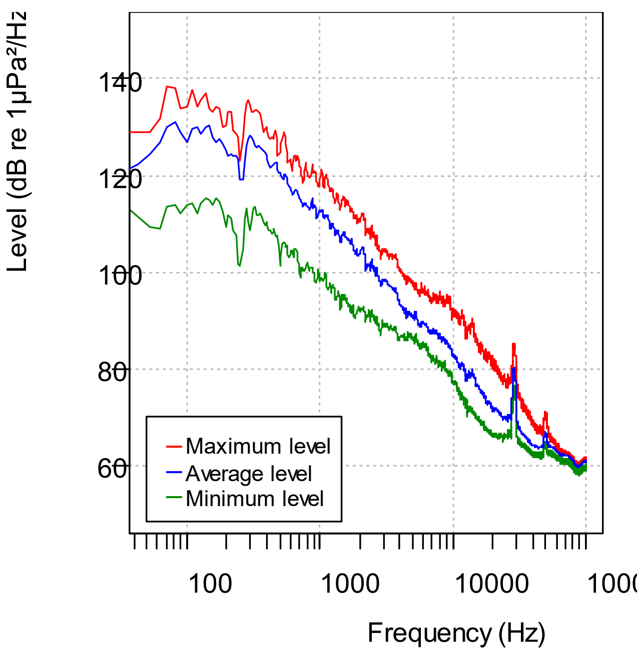


Figure 5: Example of power spectral density (PSD).

b) Measurements of received noise level

Sound pressure level: L_p (or SPL)

The sound pressure level expresses the amount of energy received by a receiver at a given distance from the emitting source. Denoted L_p or SPL, **the sound pressure level of received noise is expressed in dB re 1 µPa, specifying the distance to the source (e.g. @ 750 m).**

The sound pressure level L_p can be measured in different ways (figure 7):

- by measuring the maximum absolute value (maximum or minimum pressure difference from the reference pressure). This can be noted $L_{p,\mathrm{pk}}$, $L_{p,\mathrm{0\text{-}pk}}$, peak SPL, SPL_p, zero to peak SPL or $SPL_{z\text{-}p}$;
- by measuring the difference between the maximum and minimum pressure value. We see the following $L_{p,\mathrm{pk\text{-}pk}}$ or peak-to-peak SPL; it is possible to estimate the peak-to-peak SPL with this relation:

$$L_{p,\mathrm{pk\text{-}pk}} = L_{p,\mathrm{pk}} + 6\ \mathrm{dB}$$

- by calculating the Root-Mean-Square (RMS) pressure, which is the square root of the average of the squared pressures measured over a given duration. This RMS value, denoted $L_{p,\mathrm{rms}}$ or RMS SPL, is not suitable to measure impulsive sounds.

The sound pressure level L_p can also be expressed in **spectral noise level.** It thus corresponds to the energy contained in a given frequency band, measured over a period of time *t*. In this case, **it is expressed in dB re 1 µPa/√Hz.** This representation is preferred for continuous noise.

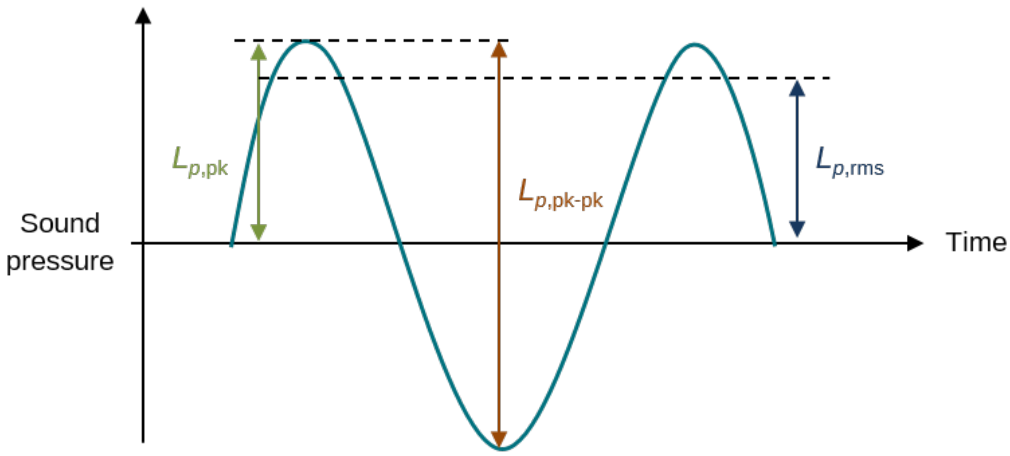


Figure 7: The different measures used to assess sound pressure level (L_p).

Power spectral density: PSD

The power spectral density of the received noise represents the distribution of the received sound power by a hydrophone as a function of frequency in a 1 Hz band (Figure 6). **This power is expressed in dB re 1 µPa²/Hz.**

Equivalent continuous sound pressure level: $L_{eq,T}$

$L_{eq,T}$ corresponds to the broadband level averaged over the entire recording period. **This measurement is expressed in dB re 1 µPa.**

Sound exposure level: $L_{E,p}$ (or SEL)

For impulsive noise, it is necessary to take into account the emission level of an impulse, but also its duration (usually less than one second). The sound exposure level, denoted $L_{E,p}$ or SEL, allows these parameters to be taken into account by integrating all the energy received during the duration *t* of an impulse and adjusting it to one second:

$$L_{E,p} = L_p + 10 \log_{10} t$$

$L_{E,p}$ therefore expresses the pressure level generated by an impulse adjusted to over one second. **The sound exposure level is expressed in dB re 1µPa².s.**

$L_{E,p}$ can be calculated for an impulse, one then notes $L_{E,p,ss}$ or SEL_{ss} for "*Single Strike"*, or for several impulses, this is then referred to as cumulative SEL, denoted $L_{E,p,cum}$ or SEL_{cum}. It is possible to link both indicators by the formula:

$$L_{E,p,cum} = L_{E,p,ss} + 10 \log_{10} n$$

with *n*: number of impulses.

c) Measurements of perceived noise level

The noise perceived by a receiver (marine mammal, fish, etc.) corresponds to the received noise weighted by the hearing ability of the receiver. To estimate the perceived noise, two indicators have been developed.

dB_{ht}

dB_{ht} is a measure developed by Nedwell *et al.* [132] which filters the spectrum of the received noise according to the audiogram of the species under consideration. This method applies a correction to the received noise level, for a given frequency, according to the ability of the species to perceive this frequency. For example, for a given species, if the sound level received by the animal is 100 dB at 2,000 Hz, and the animal perceives sounds for that frequency from 30 dB, the perceived level will be 70 dB_{ht} for this species (figure 8).

This method makes it possible to estimate the noise perceived by any marine species, provided that a reliable audiogram for that species has been established.

Thresholds are then proposed, in dB_{ht}, beyond which perceived levels may have effects (mild reaction, avoidance, injury, etc.) on the species under consideration.

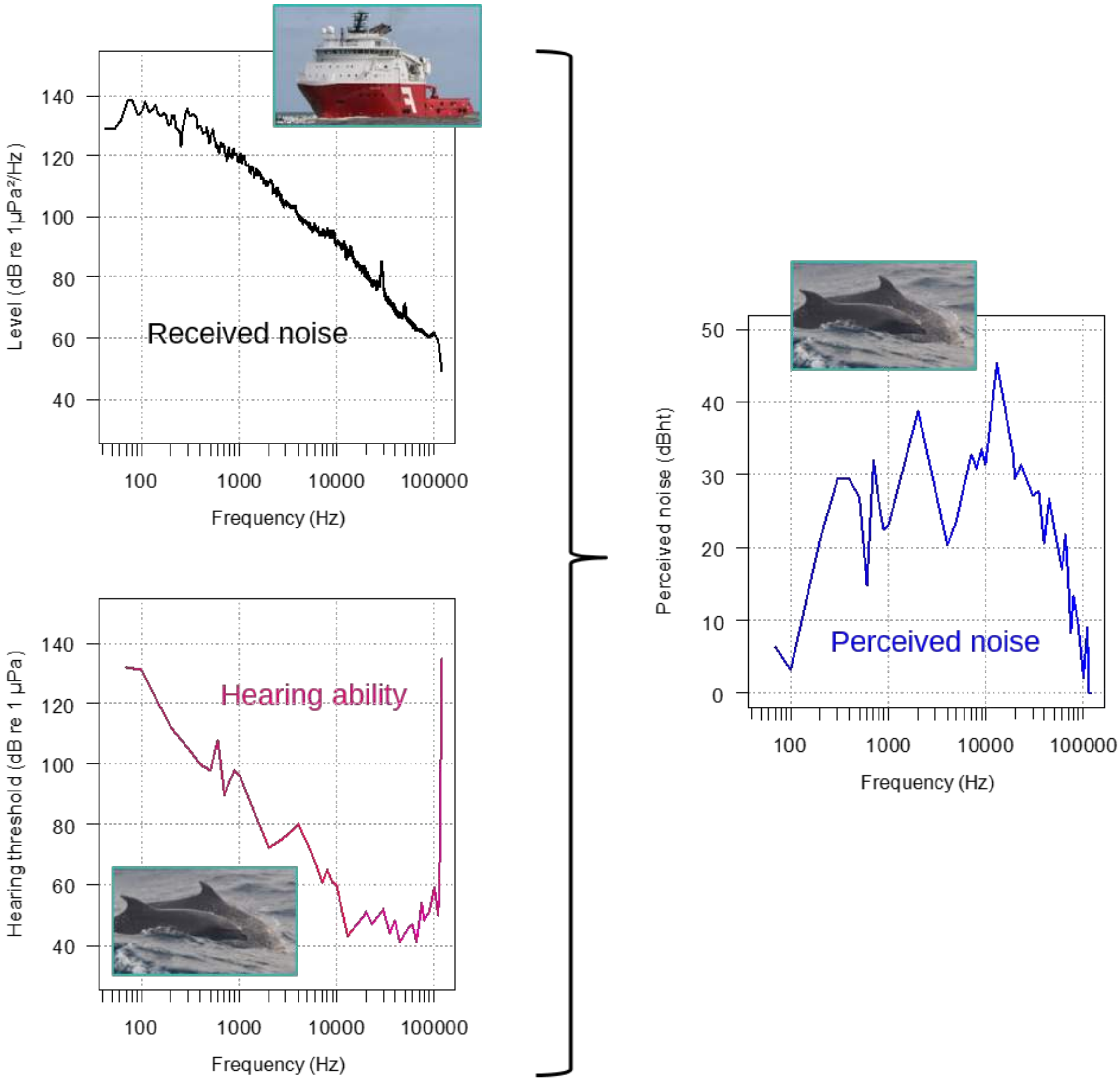


*Figure 6: Ship noise perceived, in dB_{ht}, by a Bottlenose Dolphin (*Tursiops truncatus*) according to hearing ability (audiogram from [93]; Photo courtesy: James D. Paterson/Marine Transport and COHABYS).*

Weighted sound exposure levels

Another method for taking into account receiver hearing sensitivity was developed by Southall *et al*. in 2007 [167] which was subsequently further developed and corrected [136, 168]. Similar to the weighting functions developed for human hearing[9], Southall *et al.* have developed weighting functions adapted to the hearing of marine mammals (*Auditory Weighting Functions*). These weighting functions integrate the hearing ability of marine

[9] A, B or C weighting functions established to account for the average sensitivity of the human ear to received noise for each frequency band

mammals (audiograms), as well as other audiometric parameters specific to each group of species. They make it possible to evaluate perceived noise, giving less weight to very low and very high frequencies compared to frequencies to which the animal is more sensitive. There are therefore several weighting functions adapted to the different groups of marine mammals. These weighting functions are described in detail in Annex 1.

By integrating these weighting functions, Southall *et al*. then calculated weighted sound exposure levels from which a marine mammal is likely to suffer temporary (TTS) or permanent (PTS) hearing loss (see Part 2 - III- 3 - Setting tolerance thresholds and defining exclusion perimeters).

Table 1 below summarises the main measures available to assess the level of underwater noise.

Table 1: Quantitative measures for assessing the level of underwater noise.

	Measure	ISO notation	Common notation	Unit	Use
Noise emitted	Emission level	L_S	SL	dB re 1 µPa @ 1 m	Establishes the emission level of a sound source
	Power spectral density	-	PSD	dB re 1 $\mu Pa^2/Hz$	Establishes the acoustic spectrum of a noise source (distribution of noise level as a function of the frequency)
Noise received	Sound pressure level (peak)	$L_{p,pk}$ or $L_{p,0\text{-}pk}$	SPL peak	dB re 1µPa @ X m	Quantifies the pressure level received by a receiver at a given distance from the emitting source (maximum or minimum pressure difference according to the reference pressure).
	Sound pressure level (peak-peak)	$L_{p,pk\text{-}pk}$	SPL peak-peak	dB re 1µPa @ X m	Quantifies the pressure level received by a receiver at a given distance from the emitting source (difference between the maximum and minimum pressure value).
	Sound pressure level ("root mean square")	$L_{p,rms}$	SPL RMS	dB re 1µPa @ X m	Quantifies the pressure level received by a receiver at a given distance from the transmitting source (square root of the average of the squared pressures measured over a given period). It is rather used for continuous noise
	Power spectral density	-	PSD	dB re 1µPa/√Hz @ X m	Quantifies the pressure level received by a receiver at a given distance from the transmitting source per frequency band and over a given period of time.
	Power spectral density	-	PSD	dB re 1 $\mu Pa^2/Hz$	Determines the acoustic spectrum of noise received by a hydrophone (distribution of noise level as a function of frequency)
	Equivalent continous level	$L_{eq,T}$	Leq	dB re 1µPa	Quantifies the broadband level averaged over the entire recording period.
	Equivalent continous level	$L_{E,p}$	SEL_{ss}	dB re 1μPa^2.s	Evaluates the amount of energy received during a sound impulse by also integrating its duration.
	Cumulitive noise exposure level[10]	$L_{E,p}$	SEL_{cum}	dB re 1μPa^2.s	Evaluates the amount of cumulative energy received during several pulses by also integrating their duration.
Noise perceived	dB_{ht}	-	dB_{ht}	dB_{ht}	Evaluates the level of noise actually perceived by an animal based on its audiogram and the inherent effect (flight, injury).
	Weighted sound exposure levels	$L_{E,p,HG,24h}$[12]	TTS ou PTS SEL	dB re 1μPa^2.s	Defines the sound exposure levels at which the species groups under consideration are likely to suffer temporary (TTS) or permanent (PTS) hearing loss.

[10] HG for "Hearing Group": depends on the hearing group to which the animal in question belongs; 24 h because the level is calculated for 24 h of exposure.

4) Measuring sound in water

In water, sound is measured using an acoustic recorder equipped with a hydrophone. A hydrophone is a pressure sensor that measures the sound pressure generated by a sound wave. The hydrophone is a transducer that converts the measured pressure variation into a change in electrical voltage. The electrical signal thus produced is converted into a digital signal (by an analog-to-digital converter or ADC) which is then analysed by data acquisition and processing system integrated in the recorder.

An underwater sound recorder consists of several parts:

- the *data acquisition* part, which includes the acquisition electronics: hydrophone, preamplifier and then a system for analog/digital conversion of the acoustic signal;
- the *data storage* part, consisting of one or more hard disks or SD cards on which the collected acoustic data is stored. Storage capacity is one of the factors conditioning the duration of the recorder's use and the data acquisition strategy, continuously or according to a pre-set recording cycle (*duty-cycle*);
- the *power supply* part, which provides the electrical energy necessary for the operation of the recorder. Depending on the technologies used and the type of recorder, this power supply can be either packaged in the electronic part of the recorder body or in a remote position (via solar panels or a specific container);
- the *acoustic data processing* part. Certain acoustic processing operations, known as signal processing, can be carried out directly by the recorder;
- the *data transmission* part. Depending on the configuration of the recorder, raw or processed data transfer technologies can be used. These technologies allow, by means of radio or wifi communication, the transfer of all or part of the raw or processed data to a receiver.

Depending on the configuration chosen, two main recorder categories can be distinguished:

- self-powered acoustic recorders, set-up on a mooring and positioned on the bottom or in the water column (figure 9). This type of recorder is capable of storing a limited amount of data and is powered by batteries. In the case of long-term monitoring, it is necessary to intervene this type of recorder regularly in order to collect data, free the memory and change the batteries;

Figure 7: Autonomous acoustic recorder (OSEAN) equipped with a hydrophone and positioned on a mooring post before immersion (photo courtesy: NEREIS Environnement).

- floating acoustic buoys (Figure 10). Powered by batteries or solar panels, they allow radio or Wi-Fi transmission of recorded acoustic data and can therefore carry out real-time monitoring of underwater noise. Depending on the configurations chosen, the hydrophone can be deployed close to or far to the buoy.

Figure 8: Autonomous floating acoustic buoy (RTSys - photo courtesy: NEREIS Environnement).

The quality of the acoustic recordings depends directly on the characteristics of the hydrophone. These characteristics mainly include its:

- **sensitivity.** Sensitivity is a determining and characteristic element of the acoustic performance of the hydrophone. It corresponds to the ratio between the voltage U (expressed in volts) measured at the terminals of the hydrophone and a pressure P (expressed in Pa): S_h= (U/P). This sensitivity can be expressed in dB re V/µPa with $S_h = 20\log(U/U_0 / P/P_0)$, and U_0 = 1 V et P_0 = 1 µPa;
- **bandwidth**. This corresponds to all the frequencies that can be intercepted by the hydrophone and processed by the recorder's acquisition electronics. However, hydrophone sensitivity is not constant over its entire bandwidth (Figure 11). The frequencies for which the hydrophone exhibits a flat receiving response on a large bandwidth far away from its resonance frequency will be preferred for the interception of sound signals. The bandwidth of the hydrophone is therefore a determining criterion in the choice of the recorder which, depending on the bandwidth, will target a certain category of sound sources (cetacean emissions, maritime traffic, etc.);

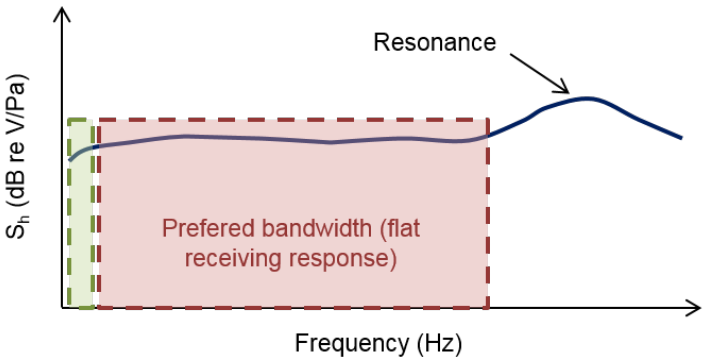


Figure 9: Example of a hydrophone sensitivity curve (according to [96]).

- **directionality.** This property characterises the ability of the transducer to intercept signals in different directions. In the context of an acoustic impact study, it is preferable to favour identical listening in all directions; the hydrophones used are therefore generally omnidirectional.

Another important parameter for optimising the quality of recordings is linked to the use of variable gain preamplifiers, which will enable the dynamics of the acquisition signal to be adapted to the characteristics of the recorder.

The choice of an underwater acoustic recorder therefore depends on the previously determined objectives and in particular:

- the type of study being carried out (long-term monitoring of ambient noise, study of cetacean populations, monitoring of a worksite, etc.);
- the type of data being collected (anthropogenic sources, biological sources, broadband ambient noise, etc.);
- the matching between the parameters of the recorder and the sound source in order to optimise recordings and avoid saturation of the recorder or vice versa;
- the sampling strategy: the need to obtain acoustic information in real time or *a posteriori*, duration of data acquisition and type of recording (continuous or not), number of recorders set-up depending on the underlying issue and the surface area of the study area.

5) Modelling the propagation of acoustic waves

In order to assess the impact of noise of an activity at sea, the sound footprint of this activity must be mapped around one or more emitting source(s). This mapping is carried out using software (or coding) for modelling the propagation of sound waves.

This modelling is complex, particularly in areas where strong variations in bathymetry are observed. On the other hand, in open environments (deep sea), the propagation of sound waves is less complex and therefore predicted more easily. Sound propagation depends on the characteristics of the sound wave, but also on the environment. In order to provide a reliable representation, the modelling software must therefore be able to integrate a certain number of parameters in order to adapt its predictions to the study case. These parameters are described in Part 2 III- Assessing the impacts of a project on marine wildlife.

Sound wave propagation modelled in this way is represented in two dimensions. It is however possible to model this propagation at several depths in order to integrate the vertical component. The depth with the predicted maximum level is then retained for the 2D representation. Modelling the propagation of acoustic waves and mapping the sound footprint of an activity then makes it possible to define perimeters within which a species is likely to be harmed (temporary or permanent hearing loss). By integrating the hearing sensitivity of the species into the propagation model, as well as noise tolerance thresholds, it is possible to produce a map of potential impacts for the species concerned, and thus define exclusion zones in which it is necessary to ensure the absence of individuals of this species (Figure 12).

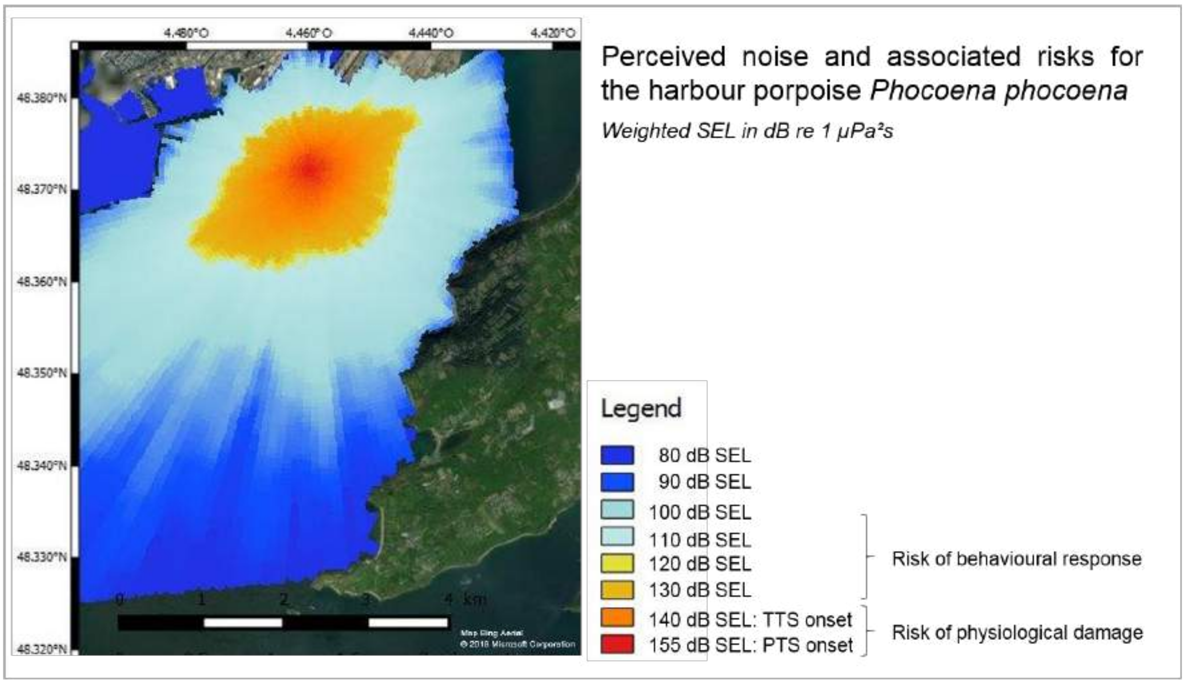


Figure 10: Map of potential impact related to pile driving operations for the harbour porpoise (Phocoena phocoena) (source: NEREIS Environnement, 2019).

Reminder

- Sound is generated by acoustic waves. It can be perceived according to its two components: "pressure variation" (succession of compressions-dilatations of the medium) or "particle motion" (agitation of the mediums molecules).
- A sound is characterised by:
  - its frequency (in Hz), which defines its pitch (low frequency: low pich, high frequency: high pitch);
  - its level (in dB), which corresponds to the volume of the sound (or intensity);
  - its occurrence duration (in s).
- In water, the reference pressure is 1 µPa (microPascal). The noise level is therefore expressed in dB re 1 µPa. In air, the reference pressure is 20 µPa.
- The celerity of sound in sea water is about 1,500 m/s (compared to about 340 m/s in air).
- The propagation of sound in sea water depends on the environmental conditions and mainly on:
  - the bathymetry;
  - the seabed nature;
  - the temperature and salinity profile of the water column.
- Ambient underwater noise consists of a set of sound sources, including sources related to natural phenomena (geophony), sources of biological origin (biophony) and sources of anthropogenic origin (anthropophony).
- Maritime traffic and wind are the main sources contributing to ambient underwater noise.
- There are different measures for measuring the noise level. The relevance of these measures depends on the type of noise being assessed (impulsive or continuous noise, emitted noise, received noise or perceived noise, etc.).
- Sound measurement in water is carried out using a hydrophone, whose characteristics (sensitivity, bandwidth, directionality) must be adapted to the noise being measured.
- It is possible to map the spatial footprint of a sound source, as a function of depth, using sound wave propagation modelling software. The calibration of the model and the choice of input data are essential to obtain consistent results.

Part 1

The various anthropogenic activities generating underwater noise and the different types of emissions they generate

This part presents the various anthropogenic activities that generate underwater noise in an exhaustive and synthetic manner. A summary of these activities, as well as the number of the corresponding descriptive sheet (see Part 4. Summary fact sheets), are presented in table 8 on page 72.

I. Oil and Gas Industry

Offshore oil and gas production accounts for 30% of the global production. About 6,000 oil and gas extraction rigs are located offshore around the world [164]. This industry contributes locally to ambient underwater noise, in coastal environments and at depths of around 3,000 m.

The exploitation of oil and gas resources at sea involves several phases: the prospecting phase, exploration and exploitation and the dismantling of structures.

1) Prospecting and searching for deposits

The prospecting phase includes the geological, geophysical and geotechnical studies required to locate and find the deposits. Some of the technologies used during this prospecting phase use sound waves. This is the case for sound, sonar and seismic surveys.

a) Echosounders and sonars

Echosounders and sonars emit high-frequency sounds (from 10 to 1,000 kHz) to measure depth (bathymetry), to visualise the morphology of the seabed (topography), but also to characterise the nature of the superficial layers of the seabed (imagery).

Echosounders and sonars emit continuous wave (CW) or frequency modulated (FM) sound pulses of a few milliseconds in repeated transmission intervals (typically 0.1 to 10 s [112]). The greater the depth, the greater the interval between pulses to give the sound wave time to reach the bottom and return to the receiver. The choice of transmission frequency depends on the type of data to be acquired and the resolution required. The quality of the information collected depends directly on the properties of the acoustic waves emitted: high-frequency waves of low amplitude will enable high-resolution information to be obtained but on a reduced scale, while waves of lower frequency and higher amplitude will propagate further but the information collected will be of lower definition.

There are several types of echosounders:

- **Single-beam echosounders** emit a sound impulse through a beam of reduced angle (5 to 30°) vertically to the boat. **These echosounders represent a pulse-wave source with a frequency**

between 1 and 500 kHz (the most commonly used values being 3.5, 12, 24, 30, 38, 50, 100, 120, or 200 kHz) **and a maximum level of emission at source (*$L_{p,pk}$*) in the order of 210 to 240 dB re 1 µPa @ 1 m** [1, 112] and are rather directional.

- **Multi-beam echosounders** emit in several directions, with a larger angular aperture in the transverse plane to the signal bearer (about 150°), which allows a larger surface area to be covered. They are, on the other hand, highly directional (about 1°) in the plane longitudinal to the signal bearer (Figure 13).

These echosounders generate an impulse emission at frequencies between 10 and 500 kHz (typically 12, 24 or 32 kHz in deep water, 70 to 150 kHz on the continental shelf and 200 to 400 kHz in very shallow water). **The emission levels (*L_S*) are in the order of 210 to 220 dB re 1 µPa @ 1 m for high frequencies and 240 dB re 1 µPa @ 1 m at 12 kHz** [1, 112].

Sonars, especially side-scan sonars, may have a larger transverse angular aperture (180°) and a very small longitudinal aperture. They use higher frequencies, which gives them a very fine resolution. The emission level of a side-scan sonar is of the same order as that emitted by a multibeam echosounder.

The strong directionality of echosounders and sonars and the rapid attenuation of the acoustic wave at these frequencies considerably limit the impact that these tools

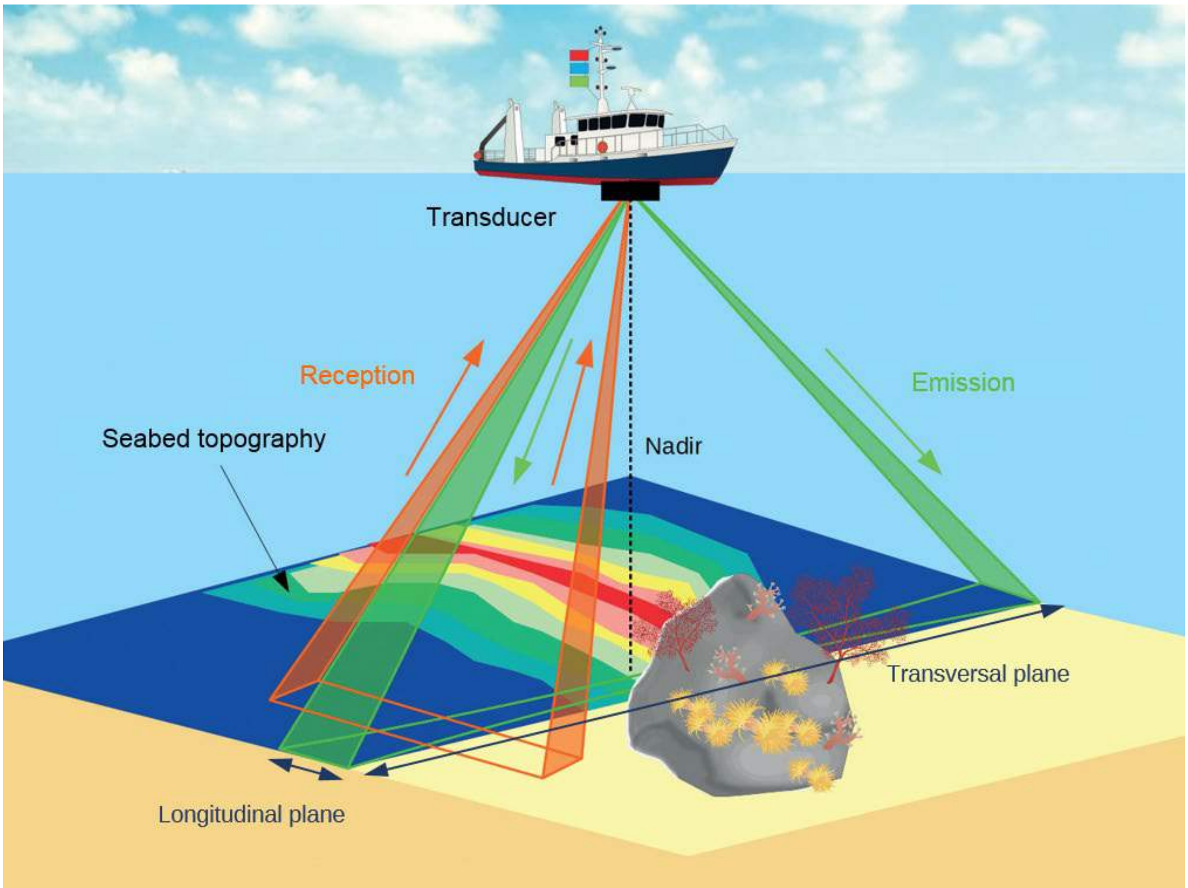


Figure 11: Operating principle of the multi-beam echosounder (according to [1]).

can have on pelagic species (marine mammals and fish present in the water column). Indeed, due to the high directionality of the sound emission generated and the very short emission durations, the animal would have to pass under the vessel or in its immediate vicinity to be impacted.

Low-frequency (10-40 kHz) multi-beam echosounders are potentially the most impacting, but the beam spread is still very limited. Sediment echosounders operate in lower frequency ranges (2 to 10 kHz), and with longer signals (up to a few tens of ms) but their emission levels are lower.

Single-beam echosounders are highly directional and therefore have little impact. Finally, high-frequency (> 100 kHz) echosounders and sonars are outside the marine mammal frequency range (except for very high-frequency cetaceans such as porpoises (see Part 2), and have a reduced range due to the high absorption of high-frequency signals in seawater [110].

It is also likely that the noise generated by the vessel's propulsion already acts as a deterrent to these species. However, this does not apply to benthic and demersal species (those living on or near the seabed).

b) Seismic surveys

Offshore seismic prospecting is a technique aimed at characterising the geological structure of the seabed by studying the different strata that make it up in order to identify the presence of hydrocarbons or natural gas. Each stratum reflects and refracts waves differently according to its physical properties. Seismic prospecting consists in sending high intensity, low-frequency acoustic waves from a vessel to the seabed. Unlike echosounders and sonars, the waves generated by seismic surveys are designed to penetrate deep into the sediment. It is then possible to study the reflection and/or refraction phenomena encountered by these waves before they are received by hydrophones integrated on one or more seismic streamers towed by the vessel (Figure 14).

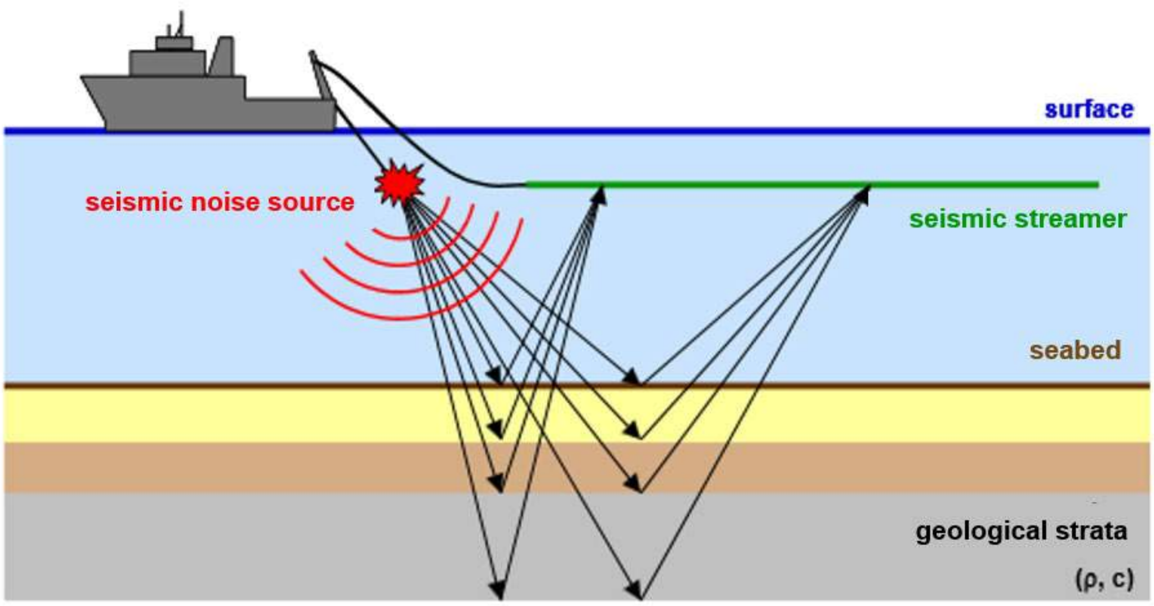


Figure 12: The functional principle of a seismic prospecting operation [143].

Analysis of the signals received then makes it possible to identify the nature of the different strata through which the waves pass.

Nowadays, seismic surveys mainly use airguns to generate acoustic waves. These airguns suddenly release a variable volume of pressurised air into the water column, thus creating **an impulse-type sound source with a wide frequency range (from 5 Hz to 15 kHz) with maximum energy between 10 and 100 Hz [24, 170]. The noise level generated is of high intensity and of short duration (a few milliseconds).**

The level emitted depends on the capacity of the gun (volume of air released), the pressure exerted on this volume and the number of guns used. **For a single low-volume airgun of 20 cu in GI[11] (i.e. 0.328 L), the maximum emission level ($L_{p,pk}$) is in the order of 230 dB re 1 µPa @ 1 m.**

During a high-resolution seismic operation, 1 to 2 guns are used. For large-scale prospecting, several dozen guns can be used. **The maximum emission level ($L_{p,pk}$) generated by an airgun array can thus reach 250 to 260 dB re 1 µPa @ 1 m.** [40, 127, 158]. Emissions are generated repeatedly at regular emission intervals (approx. every 10 to 60 s, depending on the total air volume) and can last for several hours.

Although they are directed towards the bottom, the noise generated by the airguns is generally not very directional. The low-frequency noise generated can propagate over long distances, hundreds of kilometres or even thousands of kilometres in deep-sea [106, 158].

Other seismic methods, using a boomer or sparker[12], allow the upper layers of sediment to be characterised (over a few dozen metres for the boomer or a few hundred for the sparker). The sound waves generated by these methods have higher frequencies, between 500 Hz and 12 kHz, emission levels (L_S) in the order of 215 to 230 dB re 1 µPa @ 1 m and an impulse duration in the order of a millisecond [29, 130].

[11] cu in GI = *cubic inch Generator Injected*. Indicates the amount of air injected into the compression chamber.

[12] Boomers generate noise by the sudden approach of two metal plates; this approach forms an air bubble which, by imploding, generates an acoustic wave. With sparkers, air bubbles are produced under the impulse of a shock wave generated by an electric discharge.

2) Exploration and production

When a deposit is detected, a rig is set up to drill the seafloor to first explore the reservoir and assess if it can be used, then begin extraction if the deposit is considered as exploitable. These exploration and production phases generate underwater noise via several activities, of which pile driving and drilling are certainly the noisiest. The noise levels generated by these activities are, however, lower than those observed during the exploration phase.

a) Pile driving

The installation of a drilling rig requires the installation of piles to support the structure. As the noise generated by pile driving is more widely documented in the context of offshore wind farm works, the acoustic aspect related to this activity is described in detail in Part 1 - II - Marine Renewable Energy.

b) Drilling

Drilling the seafloor is a temporary activity that precedes the production phase. The sound sources generated by drilling are **continuous wide frequency band types with maximum low-frequency power (< 1,000 Hz)**, mainly due to the equipment used for drilling (generators, drill string, pumps, compressors, etc.). The noise generated by the friction of the drill head on the substrate and by the shearing of the rock also contribute to the overall spectrum, but to a lower extent. This contribution would be limited to frequencies below 600 Hz [170, 194].

The transmission of noise into the marine environment is therefore highly dependent on the structure supporting the drilling equipment and the surface exchange area with the marine environment [4]. Drilling of the seabed is carried out from a rig on the surface. There are three types of rig:

- Fixed rigs, which rest on the seabed, are used when the depth is below 300 m;
- Floating rigs, connected to the seabed by means of cables, are preferred in deep-sea locations;
- Mobile rigs, jack-up rig or drillship types (figure 15), are mainly used for exploration of deposits.

The underwater noise generated by drilling depends on the type of rig, with fixed and jack-up rigs being the least noisy, while floating platforms and drillships emit the highest noise levels [78, 158]. Indeed, as the main source of noise is the drilling equipment on the rig, the noise transmitted into the marine environment is highly dependent on the exchange surface. In the case of floating rigs or drillships, this surface is much larger. Transmission via the hull of a drillship is particularly significant. In addition to this transmitted noise, there is also the noise generated by the ship itself, in particular the noise of the propellers and thrusters that enable the ship to maintain its position during drilling operations. The noise generated by drillships is therefore generally louder than that generated by other structures.

The noise generated by drilling from ships is wideband noise (10 Hz - 10 kHz) with $L_{p,\mathrm{rms}}$ levels in the order of 190 dB re 1 µPa/√Hz @ 1 m [158, 194]. The noise generated by an FPSO (Floating Production Storage and Offloading) floating type rig is in the order of 170 to 190 dB re 1 µPa/√Hz @ 1 m in the 20–2,500 Hz band, with the highest levels (> 170 dB) measured at frequencies below 80 Hz [60]. Finally, fixed rigs are the least noisy, with $L_{p,\mathrm{rms}}$ levels in the order of 120–130 dB re 1 µPa/√Hz @ 1 m [158, 194]. The low-frequency noise associated with drilling activities can propagate over several tens of kilometres, or even several hundred for deep-sea drilling (more than 1,000 m).

c) Production

The production phase consists in extracting the oil or gas and bringing it to shore. During this phase, many activities are likely to induce underwater noise, including pumping, pipelaying, maritime traffic related to the transport of resources, equipment and personnel, etc. The production phase is the phase when the oil or gas is extracted and transported to shore. While these sources may occasionally generate significant noise levels (in the order of 195 dB re 1 µPa/√Hz @ 1 m), the production phase is generally less noisy than the exploration phase since it no longer involves drilling rigs and is mainly carried out from fixed or jack-up rigs with a small surface exchange area with the marine environment [158]. Excluding impulse noise from one-off activities, the average noise generated by an oil rig during the production phase is 10-20 dB lower than that emitted during the drilling phase in the 20-500 Hz band, and even 30 dB lower in frequencies between 100 and 600 Hz [129, 170].

Figure 13: Cossack Pioneer mobile rig of FPSO (Floating Production Storage and Offloading) type [60], Astra jack-up rig (photo courtesy: EDC Ldt.) and West Gemini drillship (photo courtesy: Thierry Gonzalez/TOTAL).

The noise generated by vessels orbiting oil rigs (tankers, support vessels, pipeline laying vessels, etc.) is detailed in Part 1 - VIII - Maritime traffic (merchant ships and passenger transport).

Accidental explosions in oil wells, linked to the production of hydrocarbons, are also a potential source of noise. While there is no information concerning the noise level generated by this type of explosion, the noise generated by deliberate explosions at sea (excavation) is described in Part 1 - V - Coastal works and developments.

3) Dismantling

The dismantling of oil rigs requires the use of explosives and/or mechanical techniques (abrasive water jets, diamond saws, carbide cutters, guillotine shears, etc.) to section the structure, which can then be removed for dismantling onshore.

Currently, mechanical techniques account for about 35% of dismantling operations, but there are no published data on the noise levels generated by these techniques. However, the noise generated by the use of explosives at sea is known. This activity is described in detail in Part 1 - V - Coastal works and developments.

II. Marine Renewable Energy (MRE)

Marine renewable energy (MRE) includes all the technologies that make it possible to produce electricity from energy that can be recovered from the marine environment: wind, tidal currents, swell, temperature gradient between the surface and the seabed.

Numerous MRE-related projects are currently being developed off the French coast. The most advanced projects concern offshore wind power, both installed and floating, and to a lesser extent tidal power. Other projects are currently at the demonstrator stage (wave power, ocean thermal energy, Sea Water Air Conditioning or SWAC) Due to their diversity, renewable marine energies are likely to generate different types of underwater noise. However, certain noise-generating activities may be common to several types of MRE during the different phases of the project: field study, works phase, operational phase or dismantling phase.

Here, we will deal particularly with offshore wind energy, for which numerous studies have been carried out (the first installations in Europe date back to 1991). Indeed, there is very little data and feedback on the noise generated by other MRE technologies.

1) Field study

Before the works phase, it is necessary to know in detail the soil morphology and the seabed nature in the study area. For this purpose, geological, geophysical and geotechnical studies are carried out. Some of the technologies used for these studies use acoustics and generate underwater noise. These techniques are the same as those used for oil exploration (echosounders and airguns in particular) and are described in detail in Part 1 - I - Oil and gas industry.

Before the start of the works phase, a measuring mast is installed on the selected area. The conditions and techniques for installing this mast are generally the same as for the installation of wind turbines.

During this study phase, maritime traffic in the area of the future wind farm is likely to increase, which will lead to a higher ambient noise level in the area (see Part 1 - VIII - Maritime traffic (merchant ships and passenger transport)).

2) Works phase

The works phase of a MRE project involves many activities that generate underwater noise, from substrate preparation to machine installation.

The level of noise generated during the works phase is highly dependent on the type of foundation chosen (Figure 16). The installation of monopile foundations is the noisiest because they involve activities such as pile driving and drilling. The installation of tripod or jacket foundations, which use smaller diameter piles, generates lower noise levels. Finally, the installation of gravity foundations is the least noisy [138].

a) Pile driving

Pile driving consists in driving a steel pile into the substrate using a hammer (hydraulic in most cases). This activity generates high levels of underwater noise. However, these levels depend on many parameters, the most notable of which are:

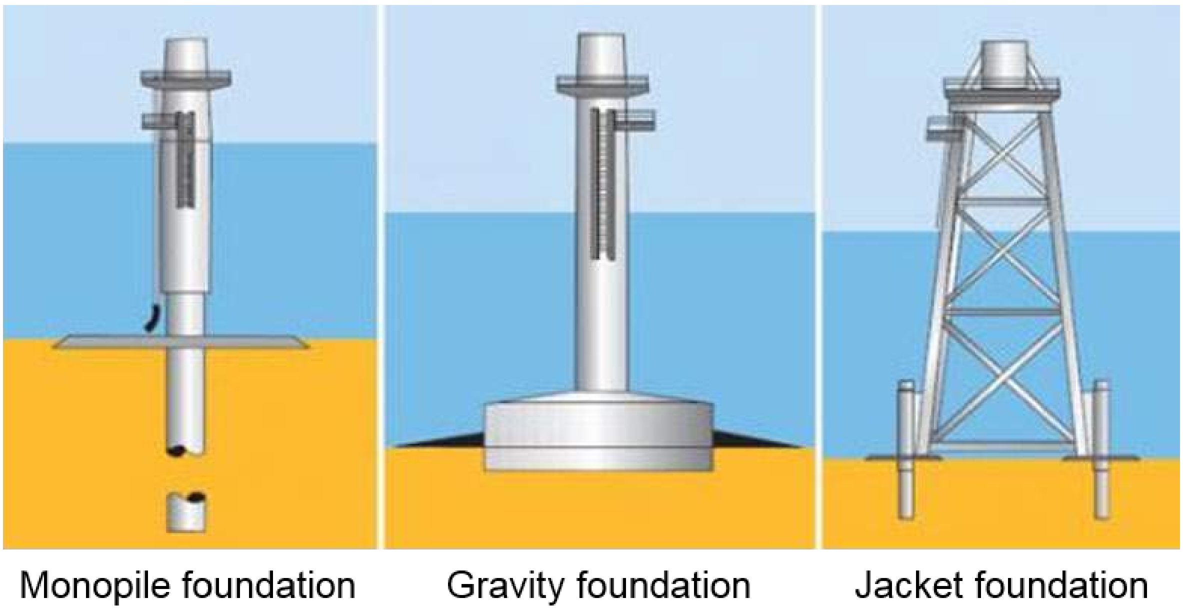


Figure 14: Examples of offshore wind turbine foundations laid (source: https://www.meretmarine.com/).

- pile diameter;
- seabed type;
- bathymetry;
- the depth at which the pile is to be driven into the seabed;
- the energy transmitted by the hammer (and therefore the type of hammer);
- penetration speed.

However, the diameter of the pile seems to be the most important factor [131], and the relationship between noise level and pile diameter has been repeatedly established[13]: the larger the pile diameter, the higher the noise level generated during pile driving. This is directly related to the fact that a larger pile diameter requires more mechanical energy, and therefore a more powerful hammer to be driven. The diameter of the pile is therefore here a measure of hammer power.

Factors such as the depth and nature of the substrate seem to have a direct impact on the propagation of the generated noise. The propagation of sound waves is indeed more complex in coastal environments, in shallow water, due to reflection phenomena, and the nature of the substrate can boost (rocky seabed) or hinder (muddy seabed) these phenomena. These parameters will therefore have to be taken into account in the prediction models for the noise generated.

Due to these many factors, it is difficult to give an average value for the noise level generated by pile driving. However, pile driving is one of the noisiest activities, with a sound intensity comparable to that of compressed airguns [138]. **Pile driving generates high levels of broadband impulsive noise (10 Hz-20 kHz) with maximum energy measured between 100 Hz and 1 kHz** [6, 10]. This noise is likely to spread over several tens of kilometres. [10, 138].

The levels emitted (L_S) by pile driving are generally in the order of 250 dB re 1 µPa @ 1 m for piles of about 4 m in diameter [130].

Table 2 below gives some examples published in the literature of noise levels $L_{p,\text{pk}}$ (or $L_{p,\text{0-pk}}$) received at 750 m as a function of pile type and environmental parameters.

Table 2: Noise level generated at 750 m by the driving of piles of different diameters (according to [138] and [6]).

Location	Diameter (m)	Foundation type	Power (MW)	Depth (m)	Level $L_{p,\text{pk}}$ (dB re 1 µPa @ 750 m)	Level $L_{E,p,\text{ss}}$ (dB re 1 µPa².s @ 750 m)
Thorntonbank (Belgium)	1.8	Jacket	5	~ 15	189	178
Alpha Ventus (Germany)	2.7	Tripod	5	~ 30	199	174
Horns Rev II (Denmark)	3.9	Monopile	2.3	9-17	195	176
Barrow (United Kingdom)	4.7	Monopile	3	15-20	195	-
Belwind (Belgium)	5	Monopile	3	15-37	194	166

[13] For example: $L_{S,\text{pk-pk}}$ = 24,3 D + 179 with D the pile diameter [133]

The noise level generated by driving a jacket foundation is lower than that of a monopile foundation (smaller pile diameter). However, the pile-driving time (and therefore the number of hits) is greater. As a result, the L_p levels are lower, but the levels expressed in $L_{E,p}$ are higher [138].

There are alternative methods to pile driving using a hydraulic hammer:

- vibratory pile driving (or vibropiling) consists in driving the pile by vibrating it. Vibratory driving is generally quieter than impact driving, with noise levels averaging 15-20 dB lower [6]. However, the noise generated by vibratory driving, which consists of continuous (vibration) and impulse (vibrator oscillation) emissions, is not directly comparable with the impulsive noise of pile driving;
- "HiLo" pile driving is a method of driving piles at a higher frequency (more hits per minute), which means that the pile is hit less hard and less energy is transmitted to the pile. The noise levels generated by this method are therefore lower than those of conventional pile driving;
- drilling is reserved for rocky or heterogeneous seabeds and can be used as an alternative to driving for piles less than 5 m in diameter. The noise generated is a continuous noise level lower than that of the pile driving (see Part 1 - I - Oil and gas industry).

The choice of method for installing a pile depends directly on the type of pile and the nature of the seabed. It is often necessary to combine these different methods (driving, vibratory driving, drilling) when installing wind turbine foundations.

b) Other works-related activities

Other techniques used for MRE works are generally quieter than pile driving. Tripod foundations for wind turbines, such as the installation of tidal power generators, generate much lower noise levels. This noise, which is mainly related to the increase in maritime traffic, has a $L_{p,rms}$ level in the order of 115 dB re 1 µPa/√Hz, or a few dB more than ambient noise [138]. However, the laying of tripod foundations requires seabed preparation, involving noisy activities, such as dredging (see Part 1 - IV - Port Activities).

The noise generated by the installation of floating wind turbine anchors is strongly linked to the noise emitted by the vessel carrying out the operation. Indeed, these vessels are in most cases equipped with a dynamic positioning system (DP vessels for Dynamic Positioning) which uses the vessel's propulsion system (propeller, thrusters) to maintain a position. This system generates continuous noise, sometimes at a high level but for a short period of time [196].

The installation of wave systems also does not require pile-driving operations. The installation is carried out either by anchoring, as in the case of floating wind turbines, or by drilling. Similarly, SWAC (Sea Water Air Conditioning) systems often require drilling operations (see Part 1- I - Oil and Gas Industry).

c) Laying underwater cables

The electrical cables of an offshore wind farm can either be buried in the substrate (or trenched) or laid on the substrate and covered with protective devices (riprap, mats).

The laying of underwater cables is described in Part 1 - VII - Installation of cables and pipelines.

3) Operational phase

a) Noise related to structure operation

For most MRE technologies, the operational phase is much quieter than the works and dismantling phases. For example, the noise associated with the rotation of a wind turbine is much less than the noise generated by its installation. However, **this noise is continuous,** given that offshore wind farms are expected to have a life span of 20 to 30 years, this noise will contribute to local ambient noise over the long term. Its effect is therefore potentially not negligible.

The underwater noise generated by a wind turbine is mainly related to the turbine (the noise generated by the blades is not transmitted to the marine environment [177]). The vibrations created at the nacelle propagate through the tower and foundations into the water column and sediments [113].

Feedback from wind farms in northern Europe (in Denmark, Sweden, Belgium, Germany and Scotland in particular) shows that the noise generated by a wind turbine in operation depends on several parameters, in particular:

- foundation type;
- wind speed;
- unit power of the turbines.

For example, the low-frequency noise generated by a 3 MW wind turbine with a monopile foundation is generally higher than that generated by a 6.15 MW wind turbine with a jacket foundation [138] (Figure 17).

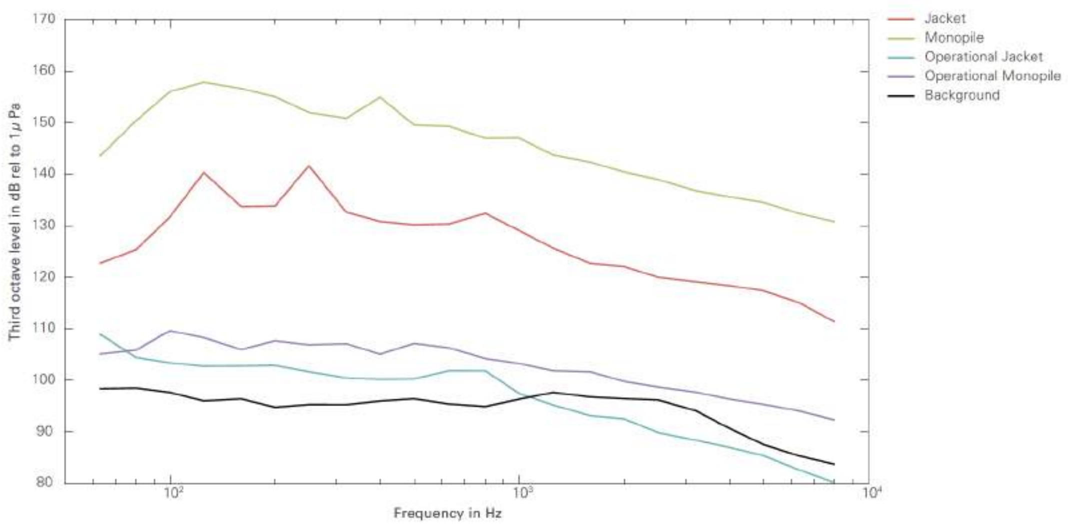


Figure 15: Third octave spectrum of ambient noise at the Bligh Bank site (Belgium) before construction of the offshore wind farm (in black), and noise generated by the installation and operation of a 6.15 MW turbine on a jacket foundation and a 3 MW turbine on a monopile foundation (from [138]).

A linear relationship between noise level and wind speed has been established for wind farms in Belgium depending on the type of foundation [139]:

- for jacket foundations, L_p = 1,1 x wind speed (in m/s) + 122,5 and $L_{p,\mathrm{pk}}$ = 0,96 x wind speed (in m/s) + 144,3
- for monopile foundations, L_p = 1,9 x wind speed (in m/s) + 120,3

However, these relationships are based on a limited number of observations.

In addition, while wind speed affects the noise emitted by operating wind turbines, it also affects the surrounding ambient noise. Therefore, the sound emergence (audible noise above ambient noise) will not necessarily be greater if the wind speed increases. This is also true for other MRE technologies.

In general, the noise generated by an operating wind turbine is continuous broadband noise with maximum energy in the low-frequency range. The $L_{p,\mathrm{rms}}$ level is in the order of 120 to 150 dB re 1 µPa/√Hz @ 1 m, and is audible above ambient noise only at low frequencies (< 500 Hz) [181, 17, 177, 138]. This noise could be audible over about twenty kilometres for a 6 MW turbine on a monopile foundation [114]. Some studies report peaks in the order of 125 dB re 1 µPa/√Hz ($L_{p,\mathrm{rms}}$) below 500 Hz at about a hundred metres from the source [17, 177].

There is very little published data on the noise generated by other MRE technologies in operation. Table 3 below gives some examples of available information for a floating wind turbine, a tidal power generator and wave-motion systems.

What these devices have in common is that they generate continuous broadband noise with a maximum amount of energy emitted at low frequencies. It should be noted, however, that in the case of a tidal power generator, noise is emitted directly into the marine environment by the turbine, whereas for other devices the main source of noise (turbines, floats, pumps, etc.) is emergent; the noise generated is transmitted into the marine environment via the submerged part of the structure. In the case of floating wind turbines and certain wave-driven devices, the noise generated by the anchoring system (vibrations, metallic banging) is also not negligible. These anchoring systems are made of metal chains and/or polymer materials. Depending in particular on the sea state, the anchor line chains can generate impulse-type noise.

Table 3: Noise levels generated by different MRE technologies.

Technology	Location	Power (MW)	Noise level $L_{p,\mathrm{rms}}$ (dB re 1 µPa/√Hz @ 1 m)	Maximum energy frequency	Biblio-graphical ref.
Floating wind turbine	Hywind (Norway)	2.3	162	25-100 Hz	196
Tidal power generator	Paimpol-Bréhat (France)	2.2	157 (in the 40-8 192 Hz band)	40-400 Hz	107
Wave energy	Summary of 7 studies		125-174	125-250 Hz	160

b) Maintenance-related noise

During the MRE operating phases, maintenance operations will lead to an increase in maritime traffic around the area. According to feedback, maintenance vessels are likely to generate $L_{p,\text{rms}}$ levels of 150-180 dB re 1 μPa/√Hz @ 1 m in the 20 Hz - 20 kHz band with maximum energy in frequencies below 1 kHz [142].

4) Dismantling phase

To date, apart from demonstrators or prototypes, the dismantling phase of MRE projects only concerns offshore wind energy. Four wind farms have been dismantled between 2016 and 2018 (Yttre Stengrund and Utgrunden in Sweden, Vindeby in Denmark and Lely in the Netherlands). Very little feedback is currently available on these dismantlements, and none of them report any noise measurements carried out during this phase.

For wind farms, dismantling includes the dismantling of turbines, towers and the electrical subplatform, the removal of cables, foundations and scour protection, the repatriation of the dismantled equipment to shore and the restoration of the site. The dismantling can be total or partial: depending on the type of foundation, it can be chosen either to remove the structure as a whole or to leave the base of the turbines in place (if they are buried or colonised); the same applies to the buried cables which could be left in place.

The noise generated by the dismantling phase is therefore mainly related to:

- the presence of the technical vessels in charge of dismantling and repatriation of the elements ashore;
- the cable removing process;
- foundation removing process(es);
- site restoration.

For the first two noise sources, the expected level is equivalent to the noise levels observed during the works phase, since the same type of vessel and the same process should be used for the installation and removal of wind turbines (turbines and towers) and cables [130].

The removal of foundations may involve several processes [175]:

- diamond saw cutting;
- abrasive water jets (spraying of water and abrasive substances under pressure);
- mining/excavation using explosives.

There are currently no published data available to assess the noise level generated during diamond saw cutting or abrasive water-jetting. On the other hand, underwater noise generated by explosives has already been measured on numerous occasions. Noise generated by mining/excavation activities is described in Part 1 - V - Coastal works and developments.

Finally, site restoration consists mainly in filling any cavities that may have been formed by the total removal of the foundations. This filling could involve technical vessels such as dredgers. The noise generated by this type of vessel is described in Part 1 - IV - Port Activities.

III. Fishing Activities

Fishing activities (including fishing and aquaculture) unintentionally generate underwater noise due to the use of motorboats and towed gears (bottom trawls and dredges). These activities also voluntarily introduce noise into the marine environment by using underwater acoustics, either to detect shoals of fish or to ward off predators.

1) Fishing

a) Noise generated by fishing vessels

The noise generated by fishing vessels depends on many parameters: vessel size, hull type, engine and propulsion characteristics, navigation speed, etc., and it is not possible to compare a small inshore fishing boat with a deep-sea fishing vessel. However, some notable acoustic characteristics are common to all fishing vessels [83]:

- the noise generated by fishing vessels is continuous broadband noise with a maximum amount of energy emitted at low frequencies between 100 Hz and 2 kHz;
- the highest contributions in low frequency are due to machinery (engines, generators, auxiliary equipment), while propulsion influences the whole spectrum. Electrical interference and echosounders influence the high-frequency signature;
- as with other types of vessels, the level of noise generated by fishing vessels is positively correlated with navigation speed.

For example, a 12-metre-long inshore fishing vessel sailing at 7 knots generates continuous level noise, $L_{p,\mathrm{rms}}$, in the order of 150 dB re 1 μPa/√Hz @ 1 m in the 250-1,000 Hz band, with maximum energy around 300 Hz [78].

Fishing vessels use echosounders to monitor bathymetry and locate schools of fish. These echosounders emit an impulse signal vertically above the ship at frequencies above 10 kHz. Fishing vessels may also be equipped with sonars that emit horizontally to locate schools of fish around the vessel. Echosounders emitting at 38 and 200 kHz are common on fishing vessels, but vessels are increasingly equipped with multi-frequency echosounders and sonars (from 20 to 200 kHz, with some 3D devices emitting up to 450 kHz, and even 800 kHz for the most recent ones). **The emission level (L_S) of echosounders and sonars is of the order of 220-230 dB re 1 μPa @ 1 m and the emission duration is generally in the order of a millisecond** [109, 111].

b) Fishing gear noise

Fishing gear, and in particular towed gear (bottom trawls and dredges) also generate underwater noise. Chains generate high-frequency noise, while the groundrope, in contact with the bottom, generates low-frequency noise. The friction of the gear on the substrate also generates emissions, in mid and high frequencies.

Trawls can also be equipped with acoustic net sonde. These are sensors that monitor the opening of the gear, the opening of the trawl doors, the depth and detect catches in the net (Figure 18). These devices emit at high frequency (typically between 40 and 200 kHz) at moderate levels.

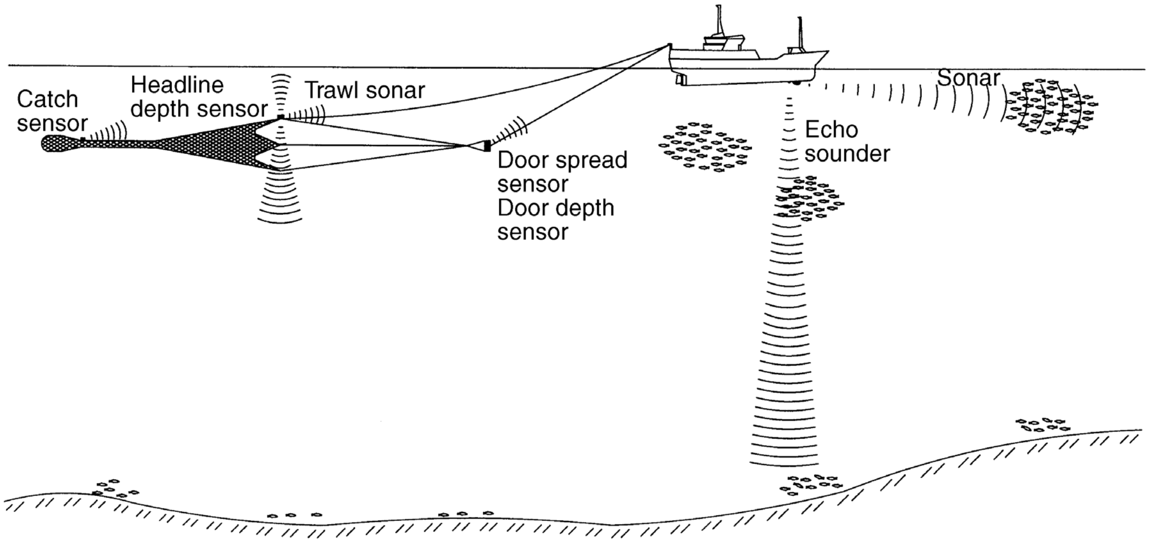


Figure 16: Acoustic devices used by fishing vessels (from [120]).

c) Acoustic deterrents (pingers)

In order to avoid the accidental capture of marine mammals, some fishing gear is equipped with acoustic deterrents, also known as pingers. These pingers are small devices (Figure 19) that emit a high-frequency impulse signal within the hearing range of marine mammals. There are several types of pingers; they can emit at one or more frequencies typically between 20 and 160 kHz. The emission level (L_S) is in the order of **130 to 180 dB re 1 µPa @1 m** [104].

2) Aquaculture

a) Noise generated by boats

The boats used in aquaculture operations are generally flat-bottomed aluminium barges equipped with powerful outboard engines.

The acoustic signature of these boats is essentially conditioned by the type of engine: with an outboard engine (two or four-stroke) or Z-drive propulsion (inboard engine with base and outboard propulsion), the acoustic signature is close to that of a recreational boat; with a "classic" inboard engine, the acoustic signature is close to that of a small technical vessel or a small fishing vessel (< 12 m).

b) Acoustic deterrents (pingers)

As with fishing, acoustic deterrents can be used in aquaculture, to avoid predation on crops in the sea. Deterrents used in aquaculture are generally more powerful than those used in fisheries, with emission levels (L_S) in the order of **180 to 200 dB re 1 µPa @ 1 m** and lower frequencies, around 10-15 kHz, to target mainly

Figure 17: AQUAmark® 210 (AQUATEC) acoustic deterrent used on fishing gear (photo courtesy: NEREIS Environnement).

pinnipeds. The transmission time is in the order of one second [142].

Other acoustic deterrents have been developed to limit the predation of shellfish farms by certain species of fish, such as sea bream.

The signals emitted are very low frequency (below 1 kHz) and the emission levels are moderate (below 170 dB re 1 µPa @ 1 m). The duration of the emission can reach a few seconds.

IV. Port Activities

Port activities likely to generate underwater noise mainly include the movement of service vessels and the dredging of basins and access channels.

1) Acoustic signature of service vessels

Service vessels (mainly tugboats, mooring boats and pilots who help large ships to enter and leave ports, sea rescue launches and buoy tenders) contribute to the smooth running of a commercial port: departure and arrival of commercial and passenger ships, buoyage maintenance, security, etc.

The noise generated by service vessels, like other vessels (see Part 1 - VIII - Maritime traffic (merchant and passenger ships)), depends on many factors, the most important of which are the size of the vessel and its navigation speed. Indeed, larger vessels tend to generate higher noise levels with maximum energy in low frequencies, while smaller vessels generate lower noise levels with a spectrum shifted towards mid frequencies (around 5 kHz). Similarly, the noise level is strongly correlated with ship speed [158].

Apart from deep-sea tugboats, port service vessels are mostly under 50 m in length, and their speed within the port area is in principle limited to 5 knots. The underwater noise generated by these vessels is therefore generally lower than that generated by merchant or passenger vessels.

Generally speaking, service vessels generate a continuous broadband noise in the order of **150 to 170 dB re 1 µPa/√Hz @ 1 m, with maximum energy between 100 and 1,000 Hz.** As an example, a 25 m tow in operation generates a level of around 170-180 dB re 1 µPa/√Hz @ 1 m [23, 158].

2) Dredging

Figure 18: The Samuel de Champlain suction dredger in action (GIE Dragages-Ports, photo courtesy: Fabien Montreuil).

Dredging of navigation channels is a common activity in ports and harbours. It is necessary to ensure access to ports for deep-draught vessels. Dredging consists in taking the sediment that regularly settles on the bottom of the navigation channels and depositing it offshore, in a so-called deposit area.

There are 4 main types of dredging:

- Self-supporting suction dredgers, or trailer suction dredgers, with a trailing suction hopper (TSHD for Trailer Suction Hopper Dredger - figure 20). This is a self-propelled vessel capable of sucking up sediment while travelling at low speed (1 to 4 knots). Sediment is sucked up by a tube, called a trailing suction hopper, equipped with a pump. The sucked-in sediment fills the ship's hold and is then deposited in the deposit area, either by opening the valves located under the hold or by pumping
- Cutter Suction Dredgers (CSD). These are equipped with a rotating cutter head that breaks up hard bottoms (limestone, gravel, etc.). The fragments are then sucked up by means of dredging pumps while the dredger is anchored. The collected sediments are then deposited onto a deposit area or deposited on special barges.
- Excavator dredgers or backhoe dredgers (BHD for Backhoe Dredger). This is a pontoon dredger equipped with a mechanical or hydraulic excavator. The positioning of the pontoon is ensured by 3 piles. A second vessel may be present to act as a tugboat or to transport the sediments collected.
- Mechanical clamshell dredgers (GD for Grab Dredger). The principle of operation is the same as for the excavator dredger, but the tool used for digging is a skip placed on the bottom in open position, and which removes the sediment upon closing. The collected sediment is often deposited on a tender barge.

The noise generated by dredgers differs according to the type of dredger, the type of sediment dredged and according to the operational phases: dredging phase, transit phase (empty or loaded transit) and depositing phase.

The dredging phase is usually the noisiest. During this phase, the noise is mainly related to the removal mechanisms (impact of the spout or shovel on the bottom, suction pumps, closing of the skip, passage of the sediment into the pipe, raising of the skip, etc.). Table 4 shows the noise levels generated by the different types of dredgers during this dredging phase.

The noise generated during dredging is broad-band (30 Hz-20 kHz) omni-directional noise with maximum energy in low frequency (< 500 Hz). This noise can propagate over long distances and be audible above ambient noise up to 25 km in the case of the noisiest ships [158].

In the transit phase, a suction dredger in operation generates a noise whose $L_{p,\mathrm{rms}}$ level is comparable to that of a merchant cargo ship sailing at medium speed (8-16 kn), i.e. **about 170 dB re 1 µPa/√Hz @ 1 m** [95, 161]. The noise emitted in light (empty) or loaded transit is equivalent because a loaded dredger generally has a lower speed. During this transit phase the noise generated is mainly from the propulsion machinery.

The depositing phase is less noisy than the dredging phase, with **$L_{p,\mathrm{rms}}$ levels between 154 and 175 dB re 1 µPa/√Hz @ 1 m, and a maximum of energy in frequencies below 500 Hz** [95].

It should also be noted that the barges and tugboats accompanying the dredgers can generate significant noise levels, sometimes higher than those of the dredger itself [158].

Table 4: Frequency range and noise levels related to dredging sediments according to the type of dredger used.

Dredger type	Noise generated	Level $L_{p,rms}$ (dB re 1 µPa/√Hz @ 1 m)	Maximum energy frequencies	Bibliographical ref.
TSHD	Continuous omnidirectional	150-190	100-500 Hz	29, 95, 118, 156
CSD	Continuous omnidirectional	170-185	100-500 Hz	29, 161
BHD	Transient and repetitive	160-180	20-300 Hz	155
GD	Transient and repetitive	150-165	< 300 Hz	118, 158

V. Coastal works and development

Coastal works and development (port development, construction of dykes or bridges, well digging, etc.) involve many activities likely to generate underwater noise. Among the main activities are drilling, pile driving, pile driving or vibratory driving of sheet piles, excavation and riprapping. As the first two activities have been described in the previous sections (Part 1 - I - Oil and Gas Industry and 1 - II - Marine Renewable Energy), the focus here is on sheet pile driving, excavation and riprapping.

1) Sheet pile driving

Sheet piles are profiled, flattened piles used to reinforce riverbanks or to build dykes, breakwaters or pontoons. They have lateral ribs that allow them to interlock with each other. The sheet piles are driven into the seabed either with a hammer (driving) or with a vibrator or diesel hammer (vibrodriving).

Sheet pile driving generates broadband impulse noise (10 Hz - 100 kHz) of lower intensity than that generated by pile driving because it requires less energy (approximately 4 times less [51]). Emission levels (L_S) in the order **of 200-210 dB re 1 µPa @ 1 m with a maximum of low-frequency energy, between 50 and 1,000 Hz.** However, as with pile driving, the noise level depends on the nature of the substrate and the depth.

Vibratory driving generates continuous noise (which, however, includes impulses related to vibrator oscillations) and at a much lower level. However, it is difficult to make a direct comparison between continuous and impulsive noise. Studies carried out in the context of port development show noise levels in the order of **165 to 185 dB re 1 µPa/√Hz @ 1 m, with maximum energy between 25 and 2,000 Hz** [193].

2) Excavation

Excavating consists in fragmenting and then clearing the debris from a rocky substrate. It can be carried out using explosives, a hydraulic rock breaker (HRB), or a ripping tooth (Figure 21).

Figure 19: Ripper tooth on dipper pontoon (photo courtesy: NEREIS Environnement).

Explosive blasting is by far the noisiest method. Underwater explosions are one of the most impacting sources of anthropogenic noise and the noise generated can propagate over very large distances (up to several thousand kilometres). In simplified terms, the explosion generates two types of waves: shock waves and sound waves, both of high intensity. First, following the explosion, a shock wave is generated. Sudden pressure fluctuations appear, caused by the gas bubbles produced by the explosion. The shock wave is then caught by an acoustic wave formed by these pressure fluctuations. An impulse-like noise is generated [158].

Estimating the noise level caused by this type of operation is complex because it depends on many factors, including the explosive charge, the number of explosions, whether the explosives are buried or not[14] (and burial depth if applicable) and the nature of the rock to be broken.

All underwater explosions generate very high pressure peaks. **Explosive charges of less than 1 kg TNT equivalent can generate emission levels ($L_{p,pk}$) above 260 dB re 1 µPa @ 1 m** [158], **while explosive charges of several thousand kg of TNT equivalent may generate levels in excess of 300 dB re 1 µPa @ 1 m.** This is low-frequency (2 Hz to 1 kHz) omnidirectional and impulse noise with maximum energy in frequencies below 500 Hz [79, 174] and impulse duration in the millisecond range.

Currently, there are no published studies on the noise level generated by hydraulic excavation. However, the noise level would be similar to that generated by driving a small-diameter pile (about 50 cm) with a hydraulic hammer, since the energy supplied and the driving rate of the two types of machine are almost identical [12]. This level would therefore be in the order of 200 dB re 1 µPa @ 1 m.

Similarly, the noise level generated by a ripper tooth (Figure 21) could be assimilated to that generated by a CSD type dredger [12], i.e. about 170 dB re 1 µPa/√Hz @ 1m.

3) Riprapping

Riprapping consists in depositing material on the seabed from a ship equipped with a metal tube. The length of the tube adapts to the height of water in order to control the location of the deposits.

The main source of noise during riprap operations would be the propulsion of the

[14] Burial of explosives can lead to a reduction in the energy released by the explosion of around 20%, but this may require the implementation of noisy operations (e.g.: drilling) [50].

ship carrying out the operation (and in particular the dynamic positioning system), while the noise of the material depositing would be masked [128]. A study comparing the noise level generated by a riprap deposition vessel during the deposition phase and during the positioning phase (without deposition) has also shown that the deposition of rocks on the bottom does not contribute to the noise generated [129].

VI. Marine Aggregate Extraction

The extraction of marine aggregates consists in taking sediment from the sea, using a sand carrier vessel, and bringing it back to shore, where it will be processed for use in works or the treatment of soil or water.

The extraction of aggregates at sea generates underwater noise during the prospecting and deposit search phase and then during extraction. During the prospecting phase, the active acoustics techniques used are those described in Part 1 - I - Oil and Gas Industry.

During the extraction phase, the activity is similar to that of dredging navigation channels, except that the sediments are brought back to land and not deposited at sea. This activity is described in Part 1 - IV - Port Activities.

VII. Cable and Pipeline Laying

Underwater cables provide electrical and telecommunication connections between countries around the globe. The installation of cables on the seabed generates noise before (during the prospecting phase) and during the laying process. The laying of underwater pipelines generally follows the same process and therefore generates the same type of noise.

1) Prospecting phase

The prospecting phase consists in defining the route of the cable or pipeline according to environmental constraints. A certain number of techniques used during this phase are likely to generate noise:

- echosounders which evaluate the bathymetry and define the bottom topography. In the majority of cases these are multibeam echosounders;
- side-scan sonars, which provide an accurate representation of the background, similar to a photograph;
- seismics (generally in a light, high-resolution version) which allows the nature and thickness of sedimentary layers to be determined.

All of these techniques are described in detail in Part 1 - I - Oil and Gas Industry.

2) Installation phase

The laying of cables or pipeline is carried out from a cable vessel or pipeline-laying vessel. Underwater cables are either buried in sediment or laid on the seabed and, if necessary, covered with a protective device (riprap, concrete "mattress", steel protection, etc.). Similarly, pipelines are laid on the seabed and buried as they approach coastal areas.

The cable or pipe can be laid using a cable plough, which allows simultaneous laying and trenching, by *water-jetting* (a pressurised water jet is used to dig a trench), by trenching, dredging or directional drilling.

There are few studies that report on the noise levels generated by the laying of cables or pipes at sea. The acoustic impact study of the North Hoyle wind farm connection, for which a trencher was used, reported broadband noise with maximum energy between 100 and 600 Hz. The noise level was **in the order of 178 dB re 1 µPa/√Hz @ 1 m** [129]. This noise appears to be highly variable, due in particular to the nature of the rock in which the trench is dug.

The use of jetting would lead to noise levels of the same order, but at higher frequencies, between 1 and 15 kHz [71]. When using a cable plough, ship noise appears to be predominant, particularly due to the use of dynamic positioning systems (intensive use of the propulsion system to maintain a position). The noise generated by this type of vessel is in the order of 170-185 dB re 1 µPa/√Hz @ 1 m [194].

The noise generated during drilling and dredging operations is described in the previous sections (Part 1 - I - Oil and Gas Industry and IV - Port Activities).

The use of directional drilling may be necessary for the landing of underwater cables (arrival of the cable on land) or the passage of rocky canyons. Directional drilling requires the installation of a drilling platform, and therefore sometimes the installation of piles by pile driving. The noise generated by this activity is described in Part 1 - II - Renewable marine energy.

When trenching is not possible (or not necessary), the cable or pipe can simply be laid on the seabed and possibly covered with riprap or concrete mats. The noise generated by the installation of this type of protection is described in Part 1 - V - Coastal works and development.

Table 5 shows the noise levels generated by the different methods or equipment used during this phase of cable or pipe installation.

3) Maintenance and dismantling phase

The maintenance and removal of underwater cables and pipelines involves the same type of vessel and processes as those used for installation. The noise levels generated are therefore of the same order as those mentioned above, i.e. 170-185 dB re 1 µPa/√Hz @ 1 m.

Table 5: Frequency range and noise levels related to the laying of cables and pipes according to the type of method or equipment used.

Method/equipment	Substrate type	Level $L_{p,rms}$ (dB re 1 µPa/√Hz @ 1 m)	Max. energy frequencies	Bibliographical ref.
Cable plough	Movable (mud, sand)	170-185 (vessel noise)	< 1 kHz	158
Water-jetting	Movable (mud, sand)	~ 170-180	1-15 kHz	71
Trenching	Rocks	~ 180	100 et 600 Hz	129
Dredging	Movable (mud, sand, gravel)	From 150 to 190 depending on the type of dredger	20-500 Hz	29, 95, 118, 156, 158, 161
Directional drilling	Rocks	120-130 dB	< 1 kHz	158, 194

VIII. Maritime traffic (merchant vessels and passenger transport)

Global maritime traffic contributes permanently to ambient far-field noise. Each individual vessel also contributes to near-field ambient noise on a one-off basis. These are two quite distinct approaches that we will deal with separately.

1) Contribution to ambient far-field noise

Vessel transport contributes significantly to ambient underwater noise. At low frequencies (5-500 Hz), motorised navigation is the main source of anthropogenic noise in the oceans [4].

Numerous studies show a correlation between the increase in ambient underwater noise in certain regions (up to +3 dB per decade, which corresponds to a doubling of sound intensity every 10 years) and the increase in the number of merchant vessels in these regions [8, 116, 169].

Between 1965 and 2003, the average size of merchant vessels doubled and their gross tonnage quadrupled. Worldwide, more than 100,000 merchant vessels are in service at any given time[15], of which more than 10% are large vessels (super-tankers, container ships, etc.), considered to be the noisiest. At present, the number of merchant vessels, their size and power (and thus their speed) is increasing [111, 117].

It is difficult to quantify the contribution of maritime traffic to overall ambient underwater noise because it is a large-scale contribution with high spatial variability. Long-term monitoring is necessary to understand the impact of noise generated by maritime traffic on the environment and marine wildlife. This parameter is monitored in the framework of the Marine Strategy Framework Directive (MSFD) by measure D11a.2 (continuous low-frequency sound).

2) Individual vessel signatures in the near field

The noise generated by merchant vessels depends on many parameters, the main ones being size and navigation speed[16]. Each vessel has its own acoustic signature, which will change according to its speed. This signature is a combination of broadband noise and strong tonal components (peaks of energy at specific frequencies).

The noise generated by motorised vessels is mainly due to the ship's propulsion system (engine + propeller). A substantial amount of this noise comes from cavitation phenomena around the propeller. This is generally the dominant source of noise. Cavitation produces wideband noise which affects the signature at all frequencies (up to 100 kHz). The other components of the propulsion system (engine, gearbox, etc.) also generate noise that is transmitted to the marine environment through the hull. Other sources, such as auxiliary equipment (pumps, generators, etc.) also contribute to the acoustic signature. These last two sources can lead to the formation of strong tonal components that characterise the

[15] Not counting over 2 million fishing vessels.

[16] Other factors such as the mode of propulsion and motorisation, and the age and potential degradation of rotating machinery also have a significant influence on the noise generated.

acoustic signature of ships [158].

The size of the vessel has a significant impact on the noise generated. Medium sized vessels (50 to 100 m) are generally equipped with twin-screw diesel propulsion. They are also often equipped with bow thrusters which have an occasional impact on the acoustic signature (during port manoeuvres). **These medium-sized vessels represent a continuous noise source with levels in the order of 165-180 dB re 1 µPa/√Hz @ 1 m, with maximum energy emitted at low frequencies (< 1 kHz) and strong tonal components up to 50 Hz** [142, 158].

Larger vessels (> 100 m: supertankers, container ships, cruise ships, etc.) have more powerful engines and larger propellers with lower rotational speed. This generates higher noise levels with maximum energy at low or very low frequencies (< 500 Hz). Due to their size, they also have a larger exchange surface, which enhances noise transmittance from machines to the marine environment via the hull. **These large vessels represent a continuous noise source with levels in the order of 180-190 dB re 1 µPa/√Hz @ 1 m, with maximum energy at very low frequencies, below 500 Hz.** For example, a 340 m long supertanker represents a broadband noise source with a level of 190 dB re 1 µPa/√Hz @ 1 m, with maximum energy between 40 and 70 Hz and strong tonal components with a fundamental of 6.8 Hz audible at almost 500 km [117, 142, 158].

IX. Recreational activities

Like merchant ships, recreational motorised boats have a characteristic acoustic signature that varies greatly depending on several parameters, the main ones being size and speed. Generally, boats with outboard engines are also noisier [142].

As with merchant ships, the noise generated by pleasure crafts is mainly related to the propelling apparatus and cavitation phenomena around the propeller. Pleasure crafts are mainly small vessels, equipped with small propellers with a high rotational speed. This leads to a lower and more acute noise level (energy shifted towards high frequencies) compared to the vessels described in the previous paragraph. **Generally speaking, pleasure crafts are a continuous sound source with levels of around 150-175 dB re 1 µPa/√Hz @ 1 m, with maximum energy between 100 and 1,000 Hz.** Some examples of noise levels generated by recreational boats are shown in Table 6 below.

The underwater noise emitted by personal watercrafts (jet skis and water scooters) comes mainly from the bubbles generated by the water jet propulsion system and from the rotation of the turbine blades. It is a continuous broadband noise, the frequency and level of which varies greatly with speed. Studies show that **emissions between 100 Hz and 10 kHz and levels between 120 and 190 dB re 1 µPa/√Hz @ 1 m** [58, 119], with significant variations because personal watercrafts regularly change speed and direction.

Table 6: Example of noise levels generated by recreational motorised watercraft

Machine type	Size	Engine	Speed	Level $L_{p,rms}$ (in dB re 1 µPa/√Hz @ 1 m)	Max. energy frequencies	Bibliographical ref.
Zodiac	5 m	25 CV	-	152	100 and 1,000 Hz	158
Zodiac	-	2 x 175 CV	30 knots	169	100 and 1,000 Hz	57
Zodiac	-	2 x 175 CV	5 knots	147	100 and 1,000 Hz	57
Speed boat	7 m	2 x 80 CV	-	156	100 and 1,000 Hz	158
Jet ski	-	1 235 cm^3	35 knots	185	< 2,000 Hz	119

X. Research/Scientific Activity

Scientific activities at sea use active acoustics to carry out bathymetric surveys, seabed mapping, characterise sediment nature, study the physical parameters of water bodies and evaluate the fishery resource. The use of motorised underwater machines (ROVs, AUVs and underwater drones) to explore the seabed also generates noise. Finally, oceanographic vessels are also by themselves a source of noise.

The use of echosounders, sonars and seismics for the study of the seabed is detailed in the previous sections (Part 1 - I - Oil and gas industry and 1 - III - Fishing activities). Table 7 presents some characteristics of echsounders, sonars and seismic systems used by the French IFREMER oceanographic fleet.

The properties of sound propagation in seawater have been exploited by scientists in order to evaluate the physical parameters of water bodies. The study of the propagation time of acoustic waves makes it possible to identify local temperature and salinity anomalies or a current. Tomography thus uses the emission of low-frequency sounds, between 20 and 200 Hz, to study the propagation of sound waves and assess the salinity and temperature of water bodies at mesoscale (several tens of kilometres). Sound emissions (L_S) are high, in the order of 165 to 220 dB re 1 µPa @ 1 m. However, this technology is rarely used nowadays.

ADCPs (*Acoustic Doppler Current Profiler*) use the Doppler effect to evaluate the speed of movement of suspended particles, and therefore the speed of currents. A sound impulse is emitted with a frequency f_1; upon encountering a moving particle, its frequency is altered, so the reflected wave will arrive at the receiver with a frequency f_2. The difference between f_1 and f_2 is used to calculate the particle's speed of movement and thus the speed of the current. ADCPs generate high-frequency impulse signals. The ADCPs fitted on IFREMER vessels, for example, transmit at 38, 75, 150 and 300 kHz. ADCP emission levels are between 220 and 225 dB re 1 µPa @ 1 m (IFREMER measurements).

Table 7: Characteristics of some of the echosounders, sonars and seismic systems used by IFREMER for oceanographic research (from: Y. Le Gall, personal communication, 2019).

Source		Max. energy frequencies (Hz)	Level L_S (dB re 1 µPa @ 1 m)	Impulse duration (ms)	Time (s)	Directionality
Seismics	Seismic reflection 2 570 in³ (14 airguns)	45	251 (L_S peak)	20	20	-
	Seismic refraction 4 990 in³ (16 airguns)	27	254,5 (L_S peak)	20	60	-
	Rapid seismicity 300 in³ (2 airguns)	40	236 (L_S peak)	20	12	-
	High-resolution seismicity (1 airgun)	100	224 (L_S peak)	4	6	-
Echosounder	Sediment echosounder	1 500-6 500	209-212	50	1	45-20°
	Multi-beam echosounder	13 000	237	2-20	1-20	2° x 150°
	Multi-beam echosounder	95 000	226	0.2-2	0.1-1	3° x 150°
	Single-beam echosounder	12 000	223	1-16		16°
	Single-beam echosounder	200 000	228	0.06-1	> 0.05	7°
Sonar	Panoramic fishing sonar	24 000	223	100	> 0.5	12° x 360°
	Side-scan sonar	100 000 400 000	220	0.1-1	0.1 1	2° x 170° 1° x 170°

XI. Summary

Table 8 below summarises, for each activity presented above, the levels of noise generated and the emission frequencies.

Table 8: Summary of noise source levels and associated frequencies of the main anthropogenic noise sources.

Signal type	Source	Emission level[17] (dB re 1 µPa @ 1 m)	Frequency band	Maximum energy frequencies	Duration	Directionality	Description (Part 1)	Summary sheet (Part 4)
Impulsive noise	Blasting/mining	250-300	2 Hz-1 kHz	< 50 Hz	A few ms to 100 s	Omnidirectional	p. 67 - 68	p. 159
	Seismic (airguns)	225-260	5 Hz-15 kHz	10-300 Hz (max<100 Hz)	10-100 ms	Low (vertical)	p. 51 - 52	p. 153 and 155
	Seismic (boomer and sparker)	200-230	500 Hz-12 kHz	Variable	< 1 ms	Low	p. 52	-
	Pile driving	200-250	10 Hz-20 kHz	100-1,000 Hz	A few ms	Omnidirectional	p. 56 to 58	p. 157
	Single-beam echosounders	210-240	1-500 kHz	Variable	< 2 ms	Yes, vertical	p. 49 to 51	p. 147
	Multiple-beam echosounders	210-240	10-500 kHz	Variable	A few ms	Yes, vertical	p. 49 - 51	p.149
	ADCP	220-225	38-300 kHz	Variable	A few ms	20°	p. 74	-
	Civilian sonars	200-240	> 10 kHz	Variable	< 1 s	Variable	p. 49 - 51	-
	Pingers	130-200	5-160 kHz	Variable	< 2 s	Variable	p. 63 - 64	p. 161
Signal type	**Source**	**Emission level[17] (dB re 1 µPa @ 1 m)**	**Frequency band**	**Maximum energy frequencies**	**Duration**	**Directionality**	**Description (Part 1)**	**Summary sheet (Part 4)**
Continuous noise	Supertanker	~ 190	1-10 kHz	40-70 Hz	-	Omnidirectional	p. 71 - 72	p. 177
	Dredging	150-190	30 Hz-20 kHz	100-500 Hz	-	Omnidirectional	p. 64 - 66	p. 171
	Drilling	120-190	10 Hz-10 kHz	10-1 000 Hz	-	Omnidirectional	p. 53 - 54	p. 163
	Fishing vessel (12 m long, at 7 knots)	~ 150	10 Hz-20 kHz	100-2,000 Hz	-	Omnidirectional	p. 62	p. 173
	Small speed boat (7 m long)	~ 156	10 Hz-20 kHz	100-1,000 Hz	-	Omnidirectional	p. 73	p. 181

[17] Levels represented per 1 m by calculation, not measured at 1 m.

Part 2

Impact of noise-generating activities on marine wildlife

I. The Hearing of Marine Species

Measuring hearing sensitivity in marine animals

There is relatively little information about the hearing sensitivity of marine animals, and this information is not always robust. Testing an animal's hearing under experimental conditions generates stress that can affect the results. Measuring sound in a confined environment (tank, aquarium) can also be problematic. The small number of individuals tested (often one or two) also raises questions due to inter-individual variability.

The values quoted here (hearing levels and frequencies) must therefore be considered with caution and are only intended to give an idea of the relative sensitivities of a group of species to perceive underwater sounds.

1) Marine Mammals

Marine mammals, especially cetaceans, are particularly dependent on acoustics since they use sound in all aspects of their lives: during reproduction, to hunt, feed, avoid predators, communicate or orientate themselves. In the marine environment, visibility is only a few tens of metres at most, whereas sound can propagate over hundreds or even thousands of kilometres [184]. For cetaceans, the emission and reception of sound signals makes it possible to characterise the environment and communicate over several tens or even hundreds of kilometres [178].

Two types of hearing systems exist in marine mammals: an exclusively aquatic auditory system for species that are dependent on the marine environment (cetaceans, sirenians) and an amphibian auditory system for those that live partially on land (pinnipeds).

With the exception of some pinnipeds, marine mammals lack an external ear. The auditory system therefore consists of a middle ear containing the eardrum and ossicles, which directs sound to the inner ear, comprising the cochlea and basilar membrane. Fatty tissues, especially those of the lower jaw, play a role in hearing by transmitting sound to the middle ear [123].

In water, marine mammals perceive sounds between 10 Hz and 200 kHz, with minimum sensitivity thresholds of around 50 dB re 1 µPa for the most sensitive species.

Depending on their hearing sensitivity, six groups can be distinguished [136, 168]:

- **low-frequency cetaceans:** this group includes all Mysticetes (baleen whales). It is questionable because the species in this group have never been the subject of direct assessment of their hearing sensitivity. However, the study of their vocalisations, their behavioural reactions to sound stimuli and their auditory components tend to show that low-frequency cetaceans are capable of perceiving sounds from 10 Hz to 30 kHz, with maximum sensitivity between 1 and 8 kHz. In this frequency range, their auditory threshold is estimated to be around 60 dB re 1 µPa;
- **high-frequency cetaceans:** this group contains most of the Delphinidae (dolphins, killer whales and pilot whales), beaked whales (Ziphiidae), Beluga and Narwhal (Monodontidae) and sperm whales. Direct assessments of hearing sensitivity (behavioural or neurophysiological measurements) have been carried out on about 1/3 of the species in this group. These are capable of perceiving sounds between 100 Hz and 180 kHz, with maximum sensitivity between 10 and 100 kHz. In this frequency range their hearing threshold is less than 60 dB re 1 µPa.
- **very high-frequency cetaceans**: this group includes porpoises, some small Delphinidae, most freshwater dolphins and Dwarf and Pygmy Sperm Whales (Kogiidae). In species of this group, the audible frequency range is equivalent to that of high-frequency cetaceans, but maximum sensitivity is around 100 kHz, with hearing thresholds below 50 dB re 1 µPa. In these species, the signals emitted (especially echolocation clicks) are also higher in frequency than in other cetaceans.
- **sirenians:** this group contains the Manatees (Trichechidae) and the Dugong (*Dugong dugon*). Their auditory sensitivities are close to those of high-frequency cetaceans, but their anatomical differences and the particularities of their sound emissions distinguish them. Measurements carried out on Manatees show that they are capable of perceiving sounds between 250 Hz and 60 kHz, with maximum sensitivity between 10 and 20 kHz and hearing thresholds of 60 dB re 1 µPa on average at these frequencies.
- **phocid carnivores:** this group includes true seals and elephant seals. Their hearing apparatus is amphibious, as they can hear in air as well as in water. Here only the hearing sensitivity of phocids in water will be discussed. In water, phocids are able to perceive sounds between 100 Hz and 100 kHz, with maximum sensitivity between 2 and 30 kHz. At these frequencies the hearing threshold is below 60 dB re 1 µPa;
- **other carnivores:** This group includes other pinnipeds which are not phocids (otariid seals : sea lions and fur seals, walruses), sea otters and the polar bear (*Ursus maritimus*). Here only the hearing abilities of other carnivores in the water will be discussed. The species in this group differ from the phocids in terms of the anatomy of their hearing apparatus (presence of an outer ear in particular, except in the walrus) and their hearing sensitivity. Indeed, if the hearing range (100 Hz-60 kHz) and maximum sensitivity (2-30 kHz) are close, the hearing threshold of these species is higher, with a minimum of 70 dB re 1 µPa on average.

Figure 22 shows an estimated audiogram (representation of the perceptible noise level as a function of frequency) for each of these groups.

From these audiograms, noise thresholds were calculated from which marine mammals are likely to suffer hearing loss. These thresholds are presented in Table 9 and Table 10.

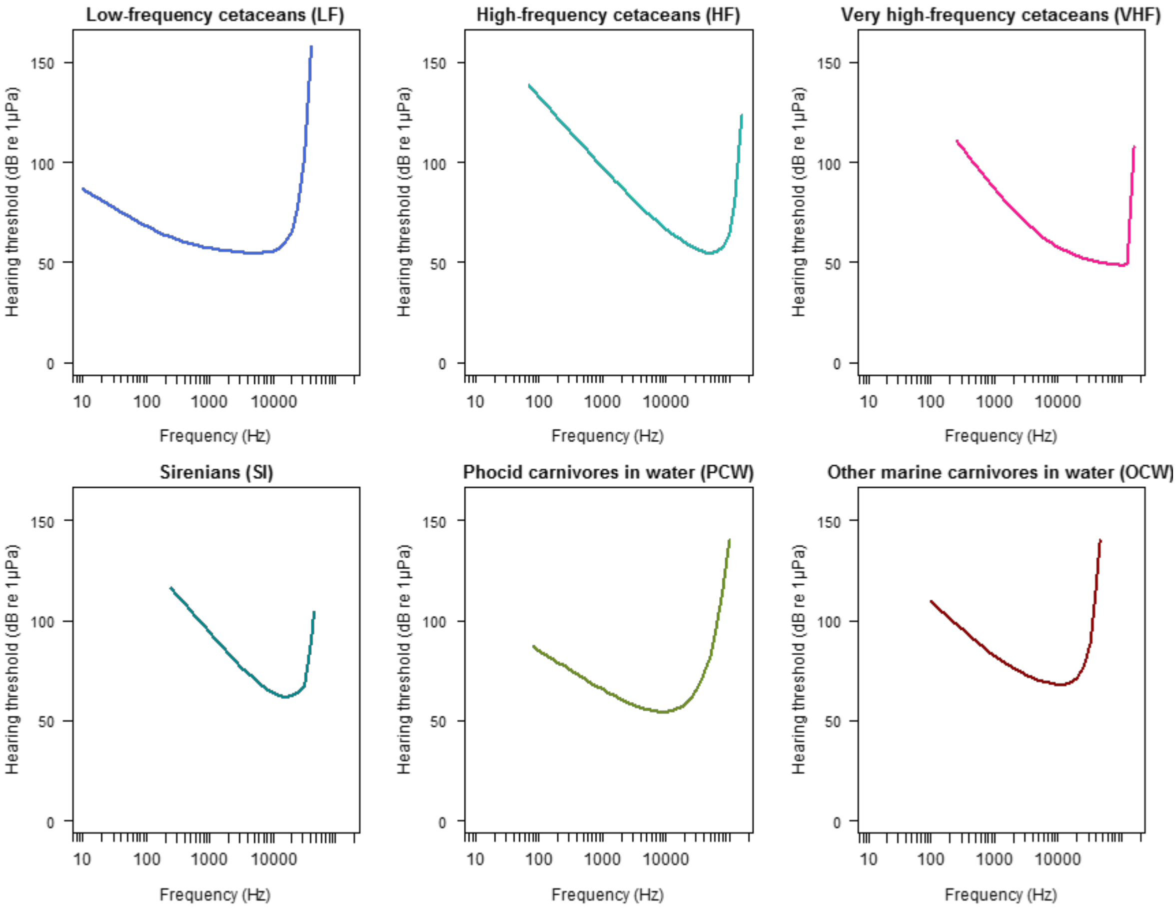


Figure 20: Estimated group audiograms for low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, sirenians, phocids in water and other carnivores in water (according to [136] and [168]).

Hearing in marine mammals, in brief

- In marine mammals, the use of sound is essential to ensure certain vital functions (reproduction, feeding, orientation, etc.).
- Hearing is conditioned by the morphology of the auditory system whose study, coupled with that of the perception of underwater sounds, has made it possible to establish 6 distinct groups: low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, sirenians, phocids and other carnivores.
- Each group is characterised by significantly different hearing sensitivities, with a characteristic hearing range (in Hz) and minimum hearing threshold (in dB re 1µPa). Audiograms have been estimated for each of these 6 groups.
- Generally speaking, marine mammals perceive underwater sounds between 10 Hz and 200 kHz, with minimum sensitivity thresholds close to 60 dB re 1 µPa on average (but this value varies from one group to another).

2) Sea turtles

Sea turtles have a developed hearing system, comprising a middle ear (with an eardrum) and an inner ear [180]. The middle ear conducts sound via the columella (a small bone equivalent to the stirrup in mammals), while the inner ear receives it and detects position and acceleration [195].

Although its functioning is still poorly understood, studies suggest that sea turtle hearing apparatus are suitable for the detection of airborne and underwater sounds. The eardrum is reinforced by a thick layer of fat, which is specific to aquatic reptiles. Sea turtles are capable of picking up acoustic stimuli, but also vibrations via the animal's skeleton (head bones and spinal column in particular) and carapace, which act as receivers of sound waves both on land and at sea [45, 180]. However, this process of vibration perception is not yet very well known. The presence of a middle ear (air-filled cavity) suggests that sea turtles are also capable of perceiving pressure variations.

Marine turtles are believed to be capable of perceiving low-frequency underwater sounds, between 30 and 2000 Hz, with maximum sensitivity between 200 and 600 Hz (Figure 23). However, this maximum sensitivity varies from one species to another and from one individual to another, particularly according to age [98, 134, 152]. The hearing apparatus of sea turtles is also involved in movement and balance.

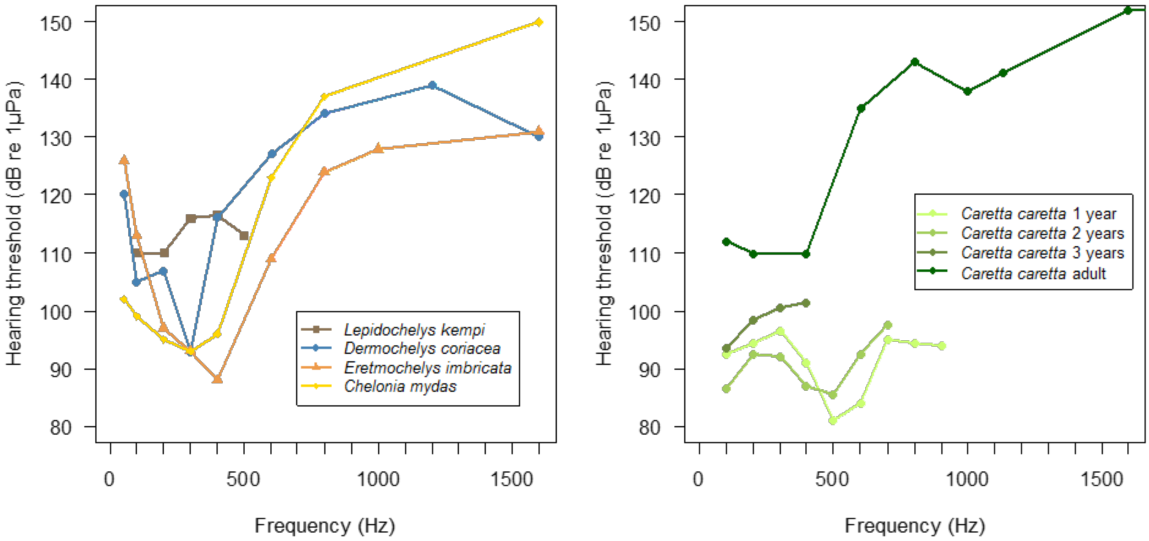


Figure 21: On the left, audiograms of four species of sea turtles: Kemp's ridley sea turtle Lepidochelys kempii*, leatherback sea turtle* Dermochelys coriacea*, hawksbill sea turtle* Eretmochelys imbricata *and the green sea turtle* Chelonia mydas*. On the right, audiogram of the loggerhead sea turtle* (Caretta caretta*) at different life cycle stages (according to [98] and [44]).*

Hearing in sea turtles, in brief

- Sea turtles have a developed auditory system, typical of aquatic reptiles, enabling them to perceive underwater and airborne sounds. Their skeleton and carapace also enable them to perceive vibrations.
- Although the hearing range is equivalent in the different species of marine turtles (30 to 2,000 Hz), their maximum sensitivity varies from one species to another and even from one individual to another depending on their age.

3) Fish

Here, the term "fish" refers to all species of bony fish (Osteichthyes), cartilaginous fish (Chondrichthyes) and agnathans. Although this term no longer has any taxonomic meaning today, it is used here for ease of reading.

All fish are *a priori* capable of perceiving sounds. However, the detection of sound waves in fish differs from one species to another. Detection is done via different "receptors" [76, 152]:

Otolith organs

- In the inner ear, **bony fish** (as opposed to cartilaginous fish such as rays and sharks) have three cavities lined with sensory hair cells, filled with fluid and in which small calcareous accretions called otoliths are located (figure 24). Each individual therefore has three otoliths on each side, making a total of six otoliths. During movement, the inertia of these calcareous accretions, that are very dense in relation to the fluid surrounding them, is perceived by the sensory hair cells, which transmit information to the brain in the form of electrical impulses via the nerves. The otolithic organs therefore detect the movement of particles induced by a sound wave, in the manner of an accelerometer.
- In **cartilaginous fish** and **lampreys**, the otoliths are replaced by calcareous crystals, called otoconies. Cartilaginous fish also have a fourth receptor in the inner ear, the macula neglecta, which contains no calcareous accretions but only sensory cells. This receptor is also believed to play a role in the perception of sound.

The lateral line

In bony and cartilaginous fish, the lateral line is made up of hundreds of sensory hair cells (neuromasts) distributed along the length of the body. These cells are sensitive to the movement of particles and therefore are able to perceive sound waves. However, the sensory receptors in the lateral line only detect movement in the near field and only function close to the sound source.

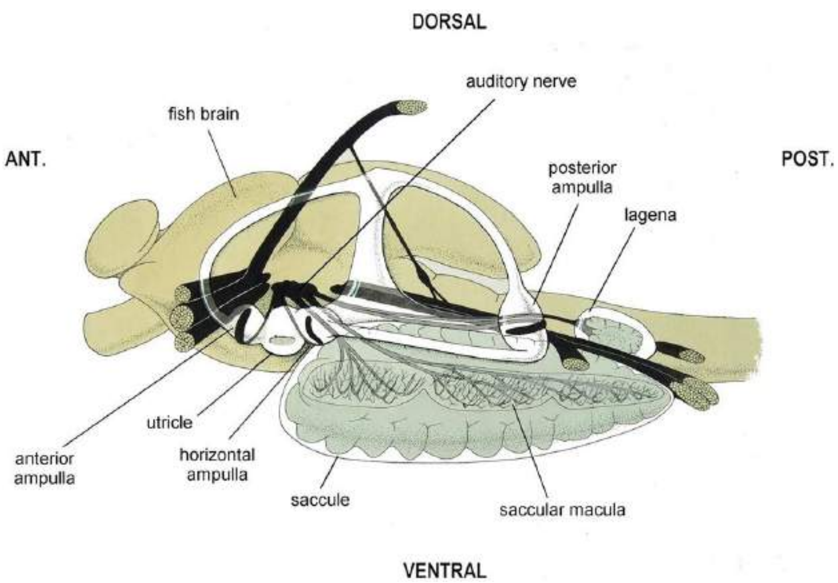


Figure 22: Diagram of the left inner ear and the otolithic organs of a bony fish, with the three otoliths: saccule, utricule and lagena (from [76]).

The swim bladder and other gaseous cavities

Some bony fish have a gas-filled organ called the swim bladder. This organ plays a role in controlling the buoyancy of fish. It is therefore sensitive to changes in pressure. In contact with a sound wave, the volume of gas in the swim bladder will vary, causing a movement of particles that can be transmitted to the otolith organs. The proximity between the swim bladder, when present, and the inner ear therefore has a strong influence on the ability to perceive sounds. In some species the swim bladder is connected to the inner ear via bony connections or via other gaseous cavities (air bubbles behind the inner ear). For these species, hearing ability is all the more important: the range of audible frequencies is wider and/or the perception threshold is lower.

Thus, while all fish have the ability to perceive sounds, hearing sensitivity varies greatly from one species to another, depending on the physiological particularities of each species (lateral line sensitivity, presence or not of a swim bladder, its proximity and connection with the inner ear, etc.). Generally speaking, three categories of fish are considered:

- fish lacking a gaseous cavity. These fish only detect the particle motion component of the sound wave, not the pressure variation component. Examples of such fish are cartilaginous and flatfish;
- fish with a swim bladder not connected to the inner ear. These fish are able to perceive pressure variations but their perception of sound is based solely on the detection of particle motion. These fish are susceptible to barotrauma if exposed to loud sounds. The Atlantic Salmon (*Salmo salar*), for example, belongs to this category;
- fish with a swim bladder connected, via bones or gas cavities, to the inner ear. In these fish, hearing sensitivity is more related to the perception of pressure variations, although they are also able to detect particle motion. They are also at risk of barotrauma when exposed to loud sounds. This category includes, for example, Atlantic Cod (*Gadus morhua*), some clupeids (herring, prat, shad, etc.) or carp.

Figure 25 below shows the audiograms of a few species of fish belonging to these three categories: the nurse shark *Ginglymos-toma cirratum*, which does not have a swim bladder, the Atlantic salmon *Salmo salar*, whose swim bladder is not connected to the inner ear, and the herring *Clupea harengus*, whose swim bladder is connected to the inner ear by a canal.

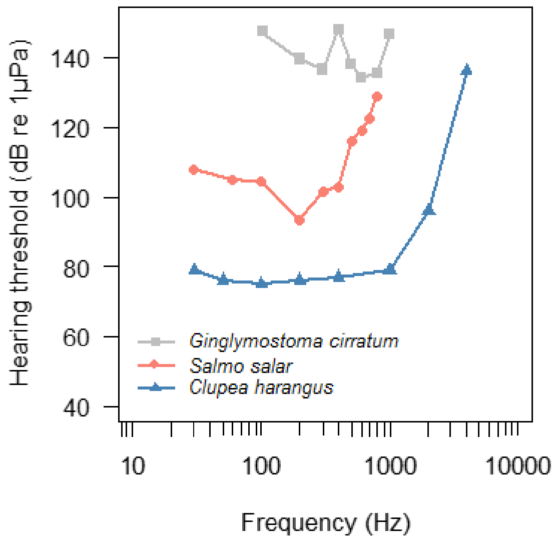


Figure 23: Audiograms of nurse shark Ginglymostoma cirratum*, Atlantic salmon* Salmo salar *and Atlantic herring* Clupea harengus *(according to [26], [55] and [72]).*

It is generally accepted that the vast majority of fish perceive sounds between 50 and 300 Hz at levels below 100 dB re 1 μPa. In fish with a swim bladder connected to the inner ear, sound perception extends to several thousand Hz [76, 152].

Hearing in fish, in brief

- All fish (bony, cartilaginous and agnathic fish) are able to perceive the "particle motion" component of underwater sound due to their otoliths and lateral line.
- However, the hearing abilities of fish vary greatly from one species to another according to their physiology. Some species have a swim bladder that can also pick up the "pressure variation" component of acoustic waves. When the swim bladder is connected to the inner ear (otoliths), the species has better hearing sensitivity (lower hearing threshold and/or wider hearing range).
- Species with a swim bladder may also experience barotrauma when exposed to loud sounds.
- In general, most fish are able to perceive sounds below 100 dB re 1 μPa between 50 and 300 Hz. For some species (Clupeidae, Cyprinidae) this perception extends to several thousand Hz.

4) Crustaceans and molluscs

It is generally accepted that crustaceans are capable of actively emitting sounds (e.g. [52]). However, there is very little information on their ability to perceive and react to sound emissions. Like cartilaginous fish, crustaceans and molluscs lack gas cavities and are therefore unable to detect the "pressure variation" component of sound waves. However, some of them, like fish, have sensory organs and cells that enable them to detect the movement of particles. They have statocysts, a set of sensory hair cells on which one or more mineral parts (statoliths) are found, acting like an accelerometer, like otoliths in bony fish. Statocysts in cephalopod molluscs (cuttlefish, squid and octopus) are very similar to the otolith organs of bony fish.

Studies in cephalopods have demonstrated their ability to detect low-frequency sound emissions (50 to 1500 Hz) due to their statocysts [82, 97, 121, 122]. The thresholds are relatively high, in the order of 125-130 dB re 1 µPa for the range of best sensitivity (around 600 Hz). These molluscs are also capable of sensing the movement of particles in the near field using epidermal sensory receptors, comparable to the lateral lines in fish. The acoustic sensitivity of cephalopods is thought to be related mainly to prey-predator interactions (defence mechanism), but could also be related to migratory movements. Like some fish, cephalopods could use infrasound to locate themselves in space [97].

In crustaceans, the presence of statocysts also makes it possible to perceive sounds. Crustaceans also have sensory hair cells in their antennae and legs which are able to detect the movement of particles. Crustaceans would use acoustics mainly as an indicator of the presence of predators. Low-frequency sounds would also be used by certain larval stages as an indicator for orientation (e.g. the sound of backwash in coastal areas [86]). Studies carried out on certain crustaceans show that they are capable of perceiving low-frequency sounds, from 50 to a few hundred Hertz [52]. Some shrimps are said to be capable of perceiving sounds between 100 and 3,000 Hz, with a maximum sensitivity of less than 110 dB re 1 µPa between 100 and 300 Hz [108].

Hearing in crustaceans and molluscs, in brief

- Crustaceans and molluscs are not sensitive to pressure variations but are able to perceive the motion of particles due to sensory hair cells called statocysts, similar to otoliths in bony fish.
- In crustaceans, statocysts are supplemented by other sensory cells on legs and antennae.
- Molluscs, on the other hand, have epidermal sensory receptors comparable to the lateral line of fish.
- These two groups seem to be able to detect sound emissions in the low frequencies (< 3,000 Hz), but at relatively high levels (> 100 dB re 1 µPa).

5) Diving birds

While the hearing sensitivity of airborne birds is fairly well documented, there is very little information on the underwater hearing sensitivity of diving birds. However, some birds, such as the emperor penguin, can stay submerged for more than 30 minutes and dive to depths of more than 500 m [5].

Some studies carried out on the great cormorant *Phalacrocorax carbo sinensis* in particular, however, tend to show that diving birds are capable of detecting sounds in the air as well as in water. Underwater, sound could be used to locate prey, avoid predators and for orientation [92]. The great cormorant has also developed auditory system adaptations to the marine environment. These adaptations are much less significant than those observed in marine mammals, but are similar to those observed in reptiles (turtles, crocodiles).

In this species, the hearing range would be from 1.5 to 6 kHz, with maximum sensitivity at 2 kHz. At this frequency, the hearing threshold would be less than 80 dB re 1 µPa [5, 92]. However, given these results are based on preliminary studies carried out on a very limited number of individuals (one individual per species in most cases), they remain questionable.

Hearing in diving birds, in brief

- The great cormorant is the only diving bird that has been studied for its ability to perceive underwater sound.
- For this species, an adaptation of the auditory system, close to that of aquatic reptiles, has been observed.
- The great cormorant would be capable of perceiving underwater sounds in medium and high frequencies (1.5 to 6 kHz), with a maximum sensitivity around 2 kHz (threshold below 80 dB re 1 µPa), but these preliminary results remain to be confirmed.

II. Noise emission impacts on marine wildlife

The reactions of marine organisms to noise emissions vary and depend on the species concerned, the intensity of the noise and the duration of the emission. Several levels of disturbance can be distinguished (Figure 26 [158]):

- **tolerance**: animals perceive the noise but do not react to the sound emission (zone of audibility);
- **behavioural responses**: avoidance or flight reactions, interruption of activity underway, changes in dive profile and/or breathing rhythm (zone of responsiveness);
- **masking**: emissions needed by individuals for their communication or perception of the environment are masked by anthropogenic noise;
- **hearing loss**: the hearing sensitivity of the animals' decreases. This decrease may be temporary (TTS: *Temporary Threshold Shift*) or permanent (PTS: *Permanent Threshold Shift*);
- **lethal injury**: the power of the noise emitted causes lesions that are often fatal for animals. They mainly concern the hearing organs, but can also affect other organs (lungs, swim bladder, etc.).

Impacts can be divided into two categories: short-term impacts and long-term impacts.

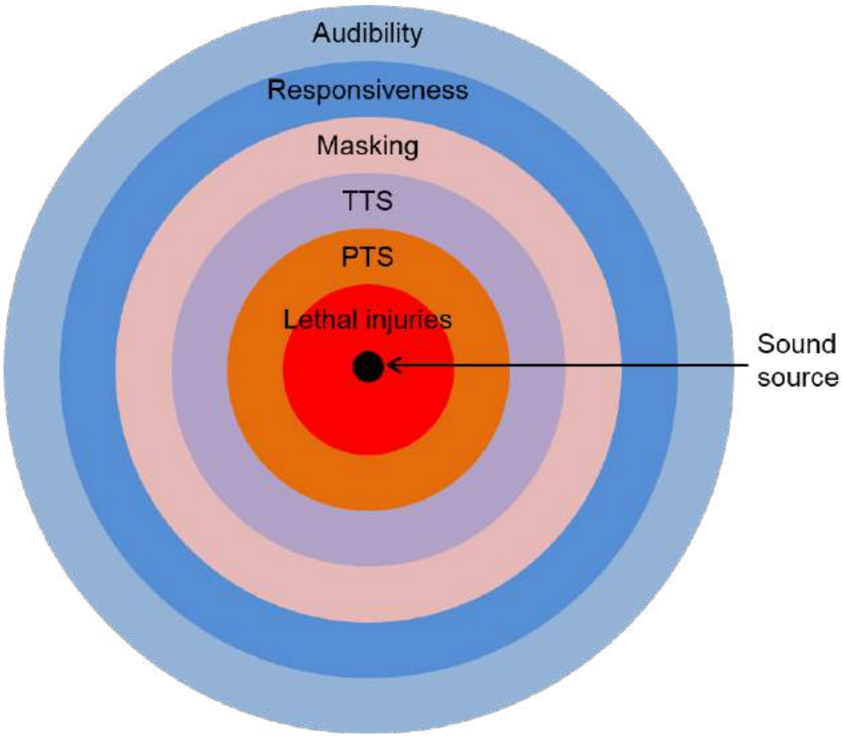


Figure 24: Diagram of the potential impacts of noise emissions according to their degree of severity (according to [158]).

1) Short-term impacts

a) Behavioural changes, flight, migration changes

Behavioural responses can be defined as the remarkable change in an animal's current activity in response to a sound. Examples of behavioural effects include abandon of an important activity such as feeding or fleeing the area [141]. These behavioural responses are however very difficult to link to a particular cause.

- Examples of changes in distribution or abundance in response to noisy activities have been studied on **marine mammals** on various worksites. Wind farms in Northern Europe in particular have been the subject of numerous follow-ups. During the pile-driving episodes, a drastic decrease in the presence of porpoises and seals near the sites was observed, but an increase in abundance was observed at a distance of 20 to 50 km from the parks. This indicates that the animals fled the noisy areas but nevertheless remained in the vicinity [19, 37, 75, 176].

  While flight reactions are relatively easy to observe, disturbed behavioural responses that do not necessarily involve the animals fleeing are more difficult to detect [67]. However, studies on whales and rorqual whales have shown that their reactions to maritime traffic and seismic surveys can be manifested by changes in diving behaviour and feeding activities [18].

  Different groups of cetaceans may show different responses to noise disturbance: small, faster cetaceans tend to swim very quickly away from the source, while large cetaceans tend to swim back to the surface [141, 158, 172].

- In **sea turtles,** behavioural responses to noise disturbances have been very little studied. However, studies have shown that turtles do surface when exposed to low frequencies, as well as increasing their swimming speed in response to airgun emissions [134]. Another study reports cessation of activity and diving in response to low $L_{p,\mathrm{pk}}$ frequency levels [134] received in the order of 191 dB re 1 µPa also generated by air guns [40].

- In **bony fish,** behavioural changes in response to noise have also been observed, particularly following exposure to seismic emissions. These reactions are manifested by changes in position in the water column, changes in swimming speed or variations in the structure of schools of fish [24].

- In **crustaceans and molluscs,** behavioural responses have been observed in correlation with acoustic disturbances (e.g. valve movements in mussels, antennae in hermit crabs). These responses occur when the induced vibrations are in the order of those generated by pile driving or the use of explosives [159]. In crustaceans, numerous examples of behavioural responses to acoustic stimuli have been observed, such as cessation of feeding in lobsters and green crabs and burial and limited movement in langoustines [52].

- The behaviour of **seabirds** can also be affected by noise, but few studies have yet looked into this issue. Studies have shown a change in the feeding area of Cape penguins during a seismic survey in South Africa, about 100 km from the colony [149]. Although it is difficult to define whether the effect was direct or indirect (flight of prey or predators?), this work is a first investigation into the potential impacts of noise emissions on diving birds.

Movement of individuals is the most widely observed behavioural change in response to noise [140]. While these effects appear to be less severe than direct mortality from injuries, accidental catching or collisions, they actually affect a larger number of individuals and a wider spatial and temporal scale. The indirect effects of these movements (habitat loss, increase in energy expenditure, etc.) are currently little studied, and are virtually absent from existing mitigation measures because they are not quantified [69].

b) Acoustic masking

Acoustic masking occurs when an external sound covers a bioacoustic signal or makes it more difficult to detect. The signal in question may relate to communication between individuals, orientation, prey or predator detection (Nowacek *et al*., 2007; Clark *et al*., 2009). Low-frequency waves (low-pitched sounds) travel greater distances. Animals, especially whales, use them to communicate with each other, sometimes over large distances. The masking of low-frequency emissions (e.g. by maritime traffic) has *a priori* more impact than the masking of high-frequency emissions.

Masking has been demonstrated in cetaceans, but it is very difficult to determine at what level this masking is likely to occur. Evidence of masking is based on behavioural or vocal adaptations.

Studies on humpback whales have shown that they tend to use surface signals (jumps, fin strikes) rather than speech to communicate when the sound level increases [48]. Other species such as right whales (*Eubalaena australis* and *E. glacialis*) change the frequency range of their vocalisations: they emit sounds at higher frequencies and for longer periods in areas with higher ambient noise [145]; some communities of killer whales (*Orcinus orca*) increase the amplitude of their communication signals in the presence of vessel noise [81]. It has also been shown that the Blue Whale (*Balaenoptera musculus*) tends to produce more vocalisations in response to the noise generated during seismic surveys by sparkers[18] [41].

These behavioural changes are generally known as the Lombard effect and aim to maintain a certain threshold of detectability of communication signals within individuals in a population [48]. However, understanding of the phenomenon and, above all, the predictability of masking levels for different species are still in early days [61].

c) Non-lethal, permanent or temporary physiological injury

Non-lethal physiological injury can occur at several levels:

- at the organ/tissue related to hearing level. This damage may manifest itself as temporary or permanent hearing loss;
- at the level of organs/tissues not related to hearing. The pressure variations generated by a sound wave can cause lethal or non-lethal injuries in certain organs (kidneys, liver, gonads, etc.).
- on a metabolic level. The disturbance linked to noise exposure leads to an increase in stress hormone levels, respiratory rhythm or heart rate. These different physiological responses often

[18] See Part 1 - I - 1) Prospecting and searching for deposits

result in long-term impacts (weakening, slower growth, etc.). - see Part 2 - II - 2 - Long-term impacts).

Temporary hearing loss (TTS) or permanent hearing loss (PTS) is an alteration in an animal's hearing sensitivity, at a given frequency or over its entire hearing range, as a result of exposure to noise [141].

The frequency at which noise is emitted affects its potential to generate TTS or PTS, but so does the nature of the signal: impulsive noise is more likely to cause hearing loss than continuous noise [64]. Multiple and/or long exposures are also more likely to impact animals than a single short exposure, but there are still few simple exposure models that can accurately predict the potential effects of such exposures. After a TTS, the return to the previous hearing threshold will vary in time, depending on the intensity of the sound, its duration of emission and the physiological condition of the animal.

In the context of offshore projects, TTS or PTS perimeter estimates are thus regularly carried out, based on weighted hearing thresholds, sound levels generated and noise propagation. Modelling is thus carried out upstream to estimate the size of physiological impact zones (permanent or temporary) for marine species.

- In **marine mammals**, thresholds for temporary hearing loss have been measured directly in captive animals (mainly in Delphinidae and harbour porpoise); estimates of thresholds for permanent hearing loss are made by derivation of TTS or extrapolating measurements. The extent of hearing loss (increase in the threshold of perception of a sound) and its duration also depend on the intensity of the perceived noise and its duration.

  At the metabolic level, studies have shown that noise exposure in cetaceans has an influence on the secretion of hormones (adrenaline, glucocorticoids) and on cardiovascular functions [162, 167].
- In **sea turtles**, TTS and PTS thresholds are still poorly known. Temporary hearing loss has been observed in a loggerhead turtle exposed to airgun fire at $L_{E,p}$ exposure levels above 175 dB re 1µPa².s (Lenhardt, 2002). However, this observation is not sufficient for extrapolation to all sea turtles, or even to all individuals of the *Caretta caretta* species.
- In **fish**, TTS are caused by damage to the sensory cells or nerves that transmit sensory signals. Experiments have shown that seismic emissions can cause damage to the cilia of the inner ear sensory cells of some fish species [24]. However, the cells renew themselves regularly, so that damaged sensory cells can be replaced, leading to a return to the previous level of sensitivity [152]. Depending on the intensity of the noise and the duration of exposure, it may take several months for an individual to fully recover from a TTS [166]. There are currently no documented cases of PTS in fish.

  Bony fish with a swim bladder (or other gaseous cavity) are more exposed to the risk of physiological injury, on the one hand because their hearing threshold is generally lower (especially if the swim bladder is connected to the inner ear) and they are therefore more prone to TTS, and on the other hand because the presence of gaseous cavities induces a risk of damage to the walls of this cavity following pressure variations generated by a sound wave (barotrauma). However, fish without gaseous cavities are also susceptible, to a lesser extent, to physiological injury, particularly to organs such as the liver, spleen, intestines and gonads. However, the lack of studies makes it difficult to assess the potential physiological effects of noise exposure on these species.

- Basin experiments have also shown that exposure to seismic noise sources leads to the secretion of stress hormones in Atlantic salmon (*Salmo salar*) and European sea bass (*Dicentrarchus labrax*), as well as an increase in respiratory rate. Exposure to continuous noise sources, however, did not lead to such changes [24]. Other fish species, however, showed a significant increase in blood cortisol levels when exposed to noise equivalent to that of maritime traffic [186].
- In **crustaceans**, no observations of TTS or PTS have been reported to date, but one study has documented hepatopancreatic and ovarian damage in snow crab (*Chionoecetes opilo*) related to seismic prospection [52]. However, a study carried out under similar conditions on the same species did not result in the observation of any damage. Crustaceans appear to be relatively unlikely to suffer physiological injury from sound waves, probably because they do not have a gas cavity and are only sensitive to particle motion. However, since these organisms use acoustics as an indicator for predator presence, noise can be a source of stress that can affect their metabolism. For example, an increase in respiratory rate, slower growth and reproduction rate has been observed in the brown shrimp (*Crangon crangon*) exposed to high intensity sound waves [154]. In green crab (*Carcinus maenas*) exposed to continuous noise (equivalent to that of maritime traffic) an increase in respiratory rate was also observed [182].
- Exposure to noise can also have an effect on the development of **eggs and larvae.** Indeed, it seems that, in bony fish at least, the perception of sound by larvae is equivalent to that of adults. Moreover, in some species, the swim bladder appears in the early larval stages. These are therefore potentially susceptible to barotrauma. Fish larvae exposed to high noise levels also show delays in development and eggs show a higher mortality rate [186].

  For molluscs, exposure of New Zealand scallop larvae (*Pecten novaezelandiae*) in close proximity (5-10 cm) to noise emissions identical to those produced by seismic surveys leads to developmental delays and malformations in adults [3]. The same type of noise can delay egg hatch in snow crabs. The impact of noise on larval development has also been observed in many crustacean species [52].

Similar to behavioural reactions, physiological injury also has indirect effects. Temporary or permanent hearing loss, like any other physiological injury, will affect an individual's chances of survival (see Part 2 - II - 2 - Long-term impacts). Hearing loss will affect communication between individuals, as well as the ability to detect predators and prey and to assess the environment. Physiological injury therefore has consequences with varying extents on the different populations concerned.

d) Lethal injuries

Impulsive noise of very high intensity is capable of causing lethal injury to marine organisms.

- The direct implications of noisy anthropogenic activities on the mortality of **marine mammals** are difficult to decipher. The activities most often questioned concern military operations and the use of low- and mid-frequency sonar. However, the concomitance of events is not sufficient to demonstrate a causal link [68, 88, 137, 147]. Necropsies, which would make it possible to establish a link between strandings and high-intensity noise, are not systematically carried out, or not within a period of time that would allow reliable conclusions to be drawn.
- However, observations made during mass strandings often show animals in good physical condition, some of which had just fed, with temporal lobe and cochlea haemorrhage, lung and kidney haemorrhage, jaw haemorrhage and cardiovascular injuries [35, 62, 88]. The presence of air bubbles in the cerebral parenchyma, the lungs, kidneys and liver suggest that the animals' death may have been caused by gas embolism due to rising too quickly [35, 88].
- While mass strandings have occurred in different parts of the world, correlations with human activities often remain ambiguous. Filadelfo *et al.* [63] therefore undertook in 2009 an inventory of mass stranding events of beaked whales and military activities in 3 areas and determined whether the correlations were statistically significant. The response was positive for events in the Mediterranean (14 mass stranding events between 1992 and 2004) and the Caribbean Sea (7 mass stranding events between 1991 and 2000), but negative for Japan (18 mass stranding events between 1978 and 1999) where other factors can explain these strandings.
- In bony fish, barotrauma can lead to death, immediately after exposure to a strong pressure variation or up to several days later. Fish without a swim bladder are unlikely to suffer lethal injury. In fish with a swim bladder, injury occurs directly to the swim bladder or adjacent organs (liver, kidneys, spleen, gonads [36]). Studies carried out on different species of fish exposed to pile-driving noise have shown that this type of noise can cause lethal injury to fish in close proximity [56, 150], at a variable level depending on the species.
- André *et al*, in 2011 [7], exposed four species of **cephalopod molluscs** (two species of squid, cuttlefish *Sepia officinalis* and octopus *Octopus vulgaris*) to sounds with a received $L_{p,\mathrm{pk}}$ level of 175 dB re 1 µPa in a frequency band between 50 and 400 Hz. All exposed individuals showed severe cellular damage and neuronal degeneration not allowing survival of the animal. These results were subsequently confirmed by other studies [186]. The authors stress the importance of the physiological injury observed at emission levels considered to be low and confirm the need for further research on these species.

  In the early 2000s, several mass strandings of giant squid took place in Spain. These individuals all showed significant internal damage, in statocysts and certain internal organs. These strandings took place while seismic surveys (airguns) were being carried out in the vicinity, and it is likely that the lesions found on these molluscs were related to exposure to high intensity sound waves [70].
- High-intensity sound waves can also have a lethal impact on the **eggs and larvae** of many species. For example, snow crab eggs exposed in close proximity (2 m) to a

sound equivalent to that generated during seismic surveys significantly increases mortality rate [52]. Another study also shows that airguns can double or even triple the mortality rate of zooplankton over a perimeter of more than one kilometre around the source, depending on the taxa. Krill larvae seem to be particularly sensitive to this type of emission [115].

Mortality due to exposure to sound waves can be direct, as a result of a lethal injury, but also indirect when a minor injury or disturbance affects an organism's ability to survive. Thus, even a low-intensity TTS can lead to disorientation and death of an animal. Similarly, a sudden reaction, such as an overly rapid rise to the surface, can cause a gas embolism with fatal consequences.

Short-term impacts, in brief

- Short-term impacts correspond to effects observed in direct response to noise exposure. They include behavioural reactions, acoustic masking, physiological injury, lethal or not, which may be of a permanent or temporary nature.
- The most commonly observed behavioural reactions correspond to escape (moving, burial) and, depending on the species, to changes in water column positioning, swimming speed or feeding. However, the consequences (indirect effects) of these reactions are studied little.
- Knowledge about masking phenomena is still in early days. The understanding and predictability of masking levels is still emerging and further research is needed. However, there are some studies demonstrating that cetaceans (the most studied group) have developed a vocal behavioural adaptation, also known as the "Lombard effect", in response to acoustic masking. Indeed, as acoustics are essential to ensure communication between individuals of the same population, cetaceans must maintain a certain threshold of signal detectability.
- Non-lethal physiological injury, whether permanent or temporary, influence the chances of survival of individuals and consequences with varying extents on the populations concerned, both for the different larval stages (delayed hatching and development, malformations) and for adults (barotrauma, organ injury, metabolic stress, impaired communication). Depending on the species, this type of injury depends on the sound intensity, the duration of exposure and the physiological state of the animal.
- Lethal injuries can be caused by even brief exposure to very loud impulsive noise. The death of individuals can be immediate (haemorrhage, injury to vital organs) or indirect (stranding, predation).

2) Long-term impacts

a) Habituation, adaptation, moving

The prior exposure of animals to noise and their habituation or not may explain why they react differently to disturbances. Studies conducted in the 1980s showed that resident Arctic whale populations were much more sensitive than others to noise from icebreakers. These non-migrating populations had little or no exposure to noise (so-called 'naïve' populations) and showed flight behaviour at distances of more than 50 km from the vessel and behavioural disturbance at distances of more than 80 km [125].

At the same time, other populations are adapting to these changes in their environment. In various anthropized areas around the world, studies have shown a lasting modification of the signals emitted by several cetacean species. As explained above, with the increase in background noise in certain regions, some species have 'adapted' their communication by modifying the frequency of their emissions, their intensity or by reducing the interval between each signal [31, 145].

However, apparent tolerance to disturbance may have population-wide effects that are more difficult to assess, particularly for animals with a high propensity for site fidelity [13, 14]. Some areas have an important role in the survival of an animal population (reproduction, feeding, etc.), and leaving them due to disturbance can have significant consequences on the fitness of the population (reproductive success, increased risk of predation, exposure to other pressures, etc.). Some populations will therefore prefer to remain in the area despite the risk of impact rather than leave it [162]. The lack of response can then be interpreted as an absence of impact, whereas it is rather a lack of alternative in the face of constraints [13].

Potential habituation to repetitive signals has been demonstrated in some fish. During repeated exposures to seismic emissions, rockfish (*Sebastes*) showed a return to their pre-exposure behaviour during shooting, suggesting habituation. Reef fish showed a decrease in the intensity of their response to noise as they were exposed to the same source. This type of learned behaviour has also been observed in squid, crabs and cuttlefish [24].

b) Energy and demographic-related consequences

For some organisations such as the *National Marine Fisheries Service* (NMFS)[19], Behavioural disturbances are not considered as damage. However, if they do not cause harm in the strict sense of the word, they can have important consequences for individuals and the population in the longer term, for example, because of the risks associated with difficulties in accessing resources, reduced reproduction rates or reduced survival rates of the young. However, it is very complex to directly relate individual disturbance to the effect on the population.

[19] *A U.S. federal agency that is part of the National Oceanic and Atmospheric Administration (NOAA), itself part of the U.S. Department of Commerce.*

Some studies have shown that repeated noise emissions, depending on their intensity and frequency, can cause chronic stress in marine mammals, and more specifically beaked whales. This state of stress is thought to have effects on the feeding and reproduction of the animals [190].

Behavioural change or chronic stress may lead to the abandonment of an important activity (feeding, breeding or rearing young) or an ecologically important site in response to the noise emitted. Repeated or prolonged abandonment of vital activities could lead to harmful consequences for the affected animal [141] and ultimately for the population [74]. The inability to access a functional area, such as food or breeding area, can affect an animal's energy reserves and consequently its survival or fertility [135].

Long-term impacts, in brief

- Long-term impacts can cause behavioural disturbances and influence species demographics.
- Some species do not adapt to the noise emissions that affect them and flee them. Their behaviour can be altered, even far from the sound source. Stress, sometimes chronic, can occur, even to the point of stopping an activity that is essential for the survival of the population (feeding, reproduction, rearing young).
- Other species habituate to noise emissions, sometimes with a return to previous behaviour, or develop adaptations. This absence of flee does not in any way express an absence of impact on the population, but may indicate a lack of alternatives in the face of constraints. Long-term impacts, especially if they are prolonged or repeated, can have significant consequences on the population's maintenance and demography.

3) Cumulative impacts

Anthropogenic activities generate various pressures on individuals, populations and ecosystems. The pressures interact with each other and can change the magnitude of an effect by increasing it (synergy) or decreasing it (antagonism). Assessing the effects of these pressures requires access to physiological, demographic and behavioural experimental and field data on a very broad spatiotemporal scale, from the individual to the ecosystem. In the marine environment, such data are virtually non-existent [32].

The question concerning the cumulative impacts of noise arises at different levels. Noise is a pressure that is cumulative with others (habitat destruction, accidental catching, collision, fishing, but also ocean acidification, climate change, etc.). A single anthropogenic activity alone generates pressures of different kinds. Assessing the cumulative pressures relating to noise is a challenge, and represents only a partial assessment of the cumulative impacts of all anthropogenic activities. In particular, it is necessary to take into account:

- **The cumulative impact of the same project over its entire duration.** The methods used to calculate the perimeters and levels of impact for marine mammals are often based on durations that are much shorter than the total duration of works. It is difficult to predict the behaviour of highly mobile species such as mammals, fish or turtles in the face of noise pollution. Predicting the cumulative impacts generated by works over their entire duration implies knowing the behaviour (at a distance or not) of the animals, which is impossible. However, in the presence of very noisy activities, such as seismic or pile-driving, it is very unlikely that animals will remain close to the noise source without reacting [65, 168].
- **The spatial accumulation of the impacts of several noisy worksites or activities.** Predicting the acoustic impact of several nearby worksites requires access to information on the noise generated by each of the activities, which can be complicated in the context of industrial projects for reasons of confidentiality. The use of robust models to define the propagation and exposure levels of several simultaneous worksites is essential in these cases. The sound barrier effect is often mentioned as a likely impact of spatially close worksites, especially if the works are concomitant. This must be confirmed by modelling.
- **The cumulative impact over time of several worksites or noisy activities.** Even if they do not take place at the same time, repeated exposure of marine organisms to the nuisance generated by nearby worksites or routine activities (in particular maritime traffic) can have impacts and in particular create a state of chronic stress [190]. The impact of this stressful situation on the fitness of individuals, and ultimately on the population, is difficult to estimate with current methods. It is therefore a research theme that needs to be developed.

Cumulative impacts, in brief

- The cumulative impacts of noise-generating anthropogenic activities require the acquisition of robust knowledge at different geographical and seasonal scales, both on existing noise pressures and on the populations present and potentially impacted. The assessment of cumulative impacts therefore requires going beyond a simple impact study for a given project.
- Fundamental research work on this issue should be encouraged, as well as the bringing together of the various actors involved (scientists, industrialists, public services, etc.).

III. Assessing the impacts of a project on marine wildlife

1) Assessing the noise level and the propagation of acoustic waves

To assess the impacts of a project on marine wildlife, the first step consists in quantifying the expected noise level and modelling the propagation of acoustic waves, depending on the characteristics of the noise and the study area.

a) Assessing noise level

In order to obtain a reliable representation of the sound impact of a project, it is first of all necessary to evaluate as accurately as possible the spectral characteristics of the noise whose propagation is being modelled. These acoustic characteristics will then be integrated into the sound wave propagation model in the form of a source spectrum model (representation of emission levels as a function of frequency) representative of the sound source under study.

This source spectrum model must be representative of the emission conditions under assessment. For example, in the case of pile driving, the model must be established for the same pile diameter, the same material, the same driving repeats, the same method of driving, etc.

In the absence of data collected *in situ*, bibliography must be searched for data that is as representative as possible of the noise being assessed. If there is no data on the noise source to be characterised, it is possible to use a model of a source with similar characteristics. For example, the sound impacts of a hydraulic rock breaker, for which no acoustic data is currently available, can be assimilated to that generated by driving a pile of 50 cm in diameter, provided that the driving rate is similar to that of the breaker, that the diameter of the pile corresponds to that of the hammer and that the energy transmitted by the motor is of the same order for both machines [12].

In order to check the relevance of the source spectrum model, the propagation model can be recalibrated *a posteriori* with data measured *in situ* in order to verify the consistency of the model's predictions.

b) Assessing the propagation of acoustic waves

Acoustic wave propagation is a complex phenomenon, and its assessment sometimes requires the use of specific modelling software. The modelling of acoustic wave propagation is essential to assess the sound impact of a project, particularly in shallow water where reflection/refraction phenomena are particularly prominent and where the propagation of low-frequency waves is strongly attenuated.

Before modelling the noise footprint of a noise source, it is necessary to produce a map of the pre-existing noise environment, i.e. to model the ambient noise in the study area without the noise source whose impact is being assessed. This estimate of the ambient noise must be representative of the environmental conditions expected at the time the noise source is introduced into the environment (same temperature, sea state, etc.).

The modelling software must take into account the ambient noise in the study area. If the ambient noise is not taken into account in the model, the emergence will be greater and the inherent noise of the emitting source being assessed will therefore be overestimated.

The accuracy of model predictions depends on the choice of algorithms which must be adapted to the situation being modelled, but also on the quality of the input data supplied to the model. Since sound propagation is dependent on the characteristics of the environment, acoustic wave propagation modelling software must take into account the environmental parameters of the study area and at least:

- **the bathymetry**. Bathymetry has a strong influence on the propagation of acoustic waves. Shallow-water propagation is very different from deep-sea propagation, in particular due to reflection phenomena, and some algorithms (such as those based on the ray theory) are not adapted to it [158];
- **the nature of the seabed**. Sediment composition has a strong influence on the behaviour of acoustic waves: sand tends to favour the reflection of waves, mud favours absorption phenomena and rocky substrates favour diffusion phenomena. The nature of the seabed must therefore be taken into account in order to integrate the geoacoustic properties of the study area into the model;
- **the bathycelerimetric profile**, based on depth-dependent temperature and salinity profiles (CTD profiles), so that the model can calculate the speed of the acoustic waves and integrate the possible stratification of the water column. This profile must be representative of the environmental conditions in the study area at the time when the sound emissions will be generated (same place, same season).

The software must also integrate a propagation loss model adapted to the study area in order to take into account the signal attenuation between the source and the receiver. This model can be established using *in situ* measurements. This option is to be preferred in order to guarantee a model representative of the environmental conditions of the study area and thus a more accurate estimation of the losses. Alternatively, a theoretical model can be used.

There are several theoretical propagation loss models; the simplest is the spherical propagation model, which considers that the acoustic wave propagates in the same way in all directions. The losses are then calculated as follows:

$$\text{Loss (in dB)} = 20 \log_{10} X + \alpha X/1000$$

Where X is the distance (in m) between the source and the receiver, and α is the damping attenuation coefficient (in dB/km).

This spherical propagation model gives a very simplified representation of propagation loss phenomena and its use must not be systematic.

Finally, the acoustic wave propagation model must integrate, in the form of a source spectrum model detailing the levels by frequency, the noise generated by the emitting source which will have been assessed beforehand.

Assessing and modelling sound wave propagation, in brief

- The acoustic impact study of a project must assess *a priori* the expected noise level within the study area and anticipate the propagation of sound waves. This assessment is carried out when the context requires it using modelling software.
- The model must be calibrated with input data representative of the study area and time period. This data includes at least the bathymetry, the seabed nature and the bathycelerimetric profile of the water column. The model must also integrate the sound wave loss during their propagation in the environment, as well as the ambient noise in the area under consideration.
- The noise whose impact is being assessed is integrated into the model in the form of a source spectrum model (representation of emission levels as a function of frequency) which must be representative of the emission conditions.
- Although the calibration of the model can be based on bibliographical sources, *in situ* measurements are to be favoured in order to approach real conditions and ensure the robustness of the predictions.

2) Knowing the species present

a) Distribution, seasonality, presence

In order to assess the potential impacts of anthropogenic activity, basic knowledge of the marine populations in the area is necessary. It is therefore necessary to provide at least the following information:

- Species diversity: what are the species present or potentially present on the study site?
- Spatial and temporal distribution: what are the most frequented areas? Which species are present in these areas? Do they have a seasonality of presence?
- Visitation and use of the site: are the species resident or transient on the site? What is the importance of the site in relation to the surrounding area? Is the area known for a particular use (feeding, breeding, rearing the young)?
- The sensitivity of the species present: is the species particularly sensitive to noise? What is its conservation status? Is the species subject to other pressures within the study area (fishing, pollution, depletion of resources, etc.)?

All this information makes it possible to define the issues at stake and assess the potential effects of the project on marine communities.

There is a substantial amount of data for mainland France and overseas territories, but it is rarely sufficient to assess the impacts of a project. While it provides valuable data on the general functioning of a sector (on the scale of a maritime facade), existing public data are generally acquired on a spatial and temporal scale that is not compatible with a detailed study of the frequentation and use of the area by marine species. Dedicated data acquisition, by *in situ* monitoring, is therefore necessary in most cases.

For all environmental monitoring, it is necessary to clearly identify the question to be answered, in line with the extent and level of impact expected from the worksite. The types of monitoring and the adapted spatial-temporal scales vary according to the objectives sought: identifying a change in distribution or abundance in the context of a wind project is not the same as identifying a change in behaviour during a seismic survey.

b) Hearing sensitivity

The first step is to identify the sensitive species potentially present in the study area and assess their hearing sensitivity based on available data. A prior bibliographical study is essential in order to obtain an audiogram for each species (or group of species) or, failing that, that of a taxonomically close species.

Marine mammals can be divided into 6 hearing groups according to their use of acoustics [167, 168] (see Part 2 - I - 1 - Marine mammals for more details):

- low-frequency cetaceans, including great whales;
- high-frequency cetaceans, such as deep-sea divers and most delphinids;
- very high-frequency cetaceans, such as certain delphinids and porpoises;
- sirenians;
- phocids;
- other carnivores.

For each group, the hearing sensitivity is different according to the hearing range frequencies.

Similarly, in fish, hearing sensitivity can be very different from one species to another (see Part 2 - I - Hearing in marine species).

Some regulations, mitigation measures and good practice guidelines recommend considering only acoustic emissions within the hearing range of the species concerned as having an impact. While this measure seems logical, it is not unanimous because of the interspecific and inter-individual variability that can be observed.

Knowing the species present, in brief

- The project leader must list the species present in the worksite, find out about their protection status, their spatial and temporal use of the site and their sensitivity to pressures, particularly noise. Indeed, depending on the taxa, hearing sensitivity and sensitivity to noise differ from one taxa to another.
- These elements will enable the project leader to understand the stakes and potential effects of the project on the species present and to formulate the right questions to adapt the impact study to the sensitivity of the study area.

3) Setting tolerance thresholds and defining exclusion limits

In order to limit the noise impact of a project, some countries have defined tolerance thresholds in the form of a maximum level not to be exceeded at a given distance from the source. Germany has, since 2013, set this threshold at 160 dB re 1 µPa².s ($L_{E,p}$) and 190 dB re 1 µPa ($L_{p,\mathrm{pk}}$) 750 m away from the noise source during pile-driving operations; Belgium has also set a $L_{p,\mathrm{pk}}$ threshold of 185 dB re 1 µPa to 750 m.

In France, there are no regulatory criteria concerning exposure thresholds for underwater noise. The ministerial order of 9 September 2019 relating to the definition of the good ecological status of marine waters and methodological standards for assessment (NOR: TREL1923380A) sets the criteria for assessing the ecological status and pressures on the marine environment at the scale of marine sub-regions. It does not set a regulatory threshold not to be exceeded in the context of offshore projects, but work in this direction is nevertheless under way at national and European levels.

The work by Southall *et al.* in 2007 [167], which defined TTS and PTS thresholds for marine mammals, has been used as a reference for more than 10 years and has become the threshold to be respected. However, since 2007, knowledge in the field of bioacoustics has progressed [59, 64, 66, 168]. The National Oceanic and Atmospheric Administration (NOAA - U.S. Department of Commerce) updates the calculations of hearing weights and thresholds on the basis of scientific advances, while trying to ensure statistical robustness in the light of rare data and peer reviews. The proposed new thresholds incorporate new knowledge on the auditory sensitivities of marine mammals and the characteristics of different noise sources. New weighting functions have been developed (see Annex 1), particularly in the context of the work of the U.S. Navy [65]. These new thresholds and weighting functions were the subject of a recent publication [168].

We will consider these results as our most advanced and operational state of knowledge in the field to date. As described above, six groups of marine mammals are distinguished: low-frequency cetaceans (great whales), high-frequency cetaceans (most of the Delphinidae, sperm whales and beaked whales in particular), very high-frequency cetaceans (porpoises, Kogiidae, freshwater dolphins), sirenians, phocids and other carnivores (Otariidae, Ursidae and Mustelidae).

Two types of noise are considered: impulsive noise and non-impulsive or continuous noise. Exposure to impulsive noise can result in a higher risk of mechanical fatigue of the inner ear than exposure to non-impulsive noise [77]. The duration of sound exposure is therefore not the only criterion that can lead to physiological injury. In this case, the sound exposure level ($L_{E,p}$) is not the most appropriate metric to describe the effects of impulsive sounds. A dual approach is therefore proposed by expressing the TTS and PTS thresholds in both sound exposure levels ($L_{E,p}$) and sound pressure levels ($L_{p,\mathrm{pk}}$) for each hearing group.

New TTS thresholds were thus determined, which were then extrapolated to PTS. Different thresholds were established for impulsive (Table 9) and continuous (Table 10) noise. The thresholds for impulsive noise are available in two versions: weighted $L_{E,p}$ thresholds (including species group weighting functions), i.e. based on the frequencies to which the different groups are most sensitive, and unweighted $L_{p,\mathrm{pk}}$ thresholds (thresholds of received levels independent of the hearing sensitivity of the receiver).

Table 9: TTS and PTS thresholds for the different categories of marine mammals exposed to impulsive noise. The cumulative sound exposure levels over 24 hours ($L_{E,p,24h}$) are expressed in dB re 1 µPa².s. The sound pressure levels ($L_{p,pk}$) are expressed in dB re 1 µPa (according to [136] and [168]).

Impulsive noise	**TTS**		**PTS**	
	$L_{E,p,24h}$ **(weighted)**	$L_{p,\mathrm{pk}}$ **(unweighted)**	$L_{E,p,24h}$ **(weighted)**	$L_{p,\mathrm{pk}}$ **(unweighted)**
Low-frequency cetaceans	168	213	183	219
High-frequency cetaceans	170	224	185	230
Very high-frequency cetaceans	140	196	155	202
Sirenians	175	220	190	226
Phocids in water	170	212	185	218
Other carnivores in water	188	226	203	232

Table 10: TTS and PTS thresholds for the different categories of marine mammals exposed to continuous noise. 24-hour cumulative sound exposure levels ($L_{E,p,24h}$) are expressed in dB re1µPa².s (according to [136] and [168]).

Continuous noise	**TTS** $L_{E,p,24h}$ **(weighted)**	**PTS** $L_{E,p,24h}$ **(weighted)**
Low-frequency cetaceans	179	199
High-frequency cetaceans	178	198
Very high-frequency cetaceans	153	173
Sirenians	186	206
Phocids in water	181	201
Other carnivores in water	199	219

There are currently no defined avoidance response thresholds for the different species groups. Some values from underwater experiments or extrapolation exist and are sometimes used. However, only the values for TTS and PTS are the subject of relative consensus.

For sea turtles and fish, work by Popper *et al*. in 2014 [152] also established TTS and PTS thresholds for different sources of impulsive sound. As for marine mammals, thresholds are proposed in terms of sound exposure levels or sound pressure levels. There is currently no consensus in the scientific community on behavioural responses. This work is still in progress and should be updated soon. The values given in Table 11 are therefore subject to change.

Table 11: TTS and PTS thresholds for the different categories of fish and sea turtles for a pile-driving impulsive noise type. Sound exposure levels ($L_{E,p}$) are expressed in dB re1µPa².s.
Sound pressure levels ($L_{p,pk}$) are exprssed in dB re 1µPa (according to [152]).

Group	**TTS**	**PTS**	
	$L_{E,p}$	$L_{E,p}$	$L_{p,pk}$
Sea turtles	Not available	210	207
Fish (lacking swim bladders)	186	219	213
Fish (swim bladder not connected to internal ear)	186	210	207
Fish (swim bladder connected to internal ear)	186	207	207
Eggs and larvae	Not available	210	207

Tolerance thresholds, in brief

- Some countries have set noise levels not to be exceeded at a certain distance for underwater works (e.g. pile driving). Currently, in France no threshold has been set.
- However, recent literature (2019) proposes threshold limits, above which hearing loss (TTS or PTS) can be observed. These thresholds are currently the reference values to be taken into account in the context of acoustic impact studies.
- There is currently no scientific consensus on the thresholds for behavioural reactions.

4) Current biological impact prediction models

The potential impacts of noise on wildlife can be understood on two distinct scales:

- At the individual level, the impacts apply to the individual's ability to communicate with other individuals, hunt and detect predators, and ultimately to their survival;
- At the population level, impacts apply to the ability of individuals to reproduce, survival rates and mortality.

Existing methods for noise modelling and impact estimation based on acoustic thresholds and weighting functions for different species groups can be used to statistically define the number of animals impacted at the time of the noisy activity. However, this does not consider medium- or long-term consequences on the animals. Models predicting long-term consequences are therefore being developed. These models are highly dependent on input data and are often based, at least partly, on expert opinion. The uncertainty surrounding the results they produce is therefore significant. Nevertheless, they offer new approaches by taking into account demographic and energy aspects. As research progresses, these models are likely to evolve rapidly, or even be replaced by new tools. These models are:

- **The SAFESIMM** model (*Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna*) Based on the noise levels generated by the activity and the levels received by the agents, the probability of undergoing a PTS, TTS or behavioural response is estimated for each agent based on a dose-response relationship. The results are then integrated over the entire period of works in the form of a history of injury numbers (permanent or temporary injuries) and/or disturbances suffered by each of the agents.

  The modelling of different scenarios using this tool makes it possible to quantify the impacts of different construction methods or different sources of noise and is thus a decision-making tool for the project leader.
- **Interim PCoD** (IPCoD) was developed by the *Sea Mammal Research Unit* (SMRU) at St Andrews University in 2014 in order to produce a first quantitative estimate of the potential effects on marine mammal populations of the construction and operation of all types of marine renewable energy systems in British waters [73, 99]. It is a simplified version of the PCoD, which could not be applied to the species at stake in the region due to the lack of empirical information for many of the parameters. The objective of this model is to predict over varying time periods the potential demographic impacts of wind farm works on a given marine mammal population. While this type of model depends heavily on input data and expert opinion, and despite all the uncertainties associated with each of the input parameters, it is nonetheless an interim tool to begin quantifying the long-term impacts of acoustic nuisance.
- **The DEPONS model** aims to predict the long-term impacts of noise on marine mammals [126]. It uses existing models of movement and energy balance (energy input/output) based on the fact that vital areas and population dynamics are based on food competition. The DEPONS model is similar to the IPCoD but differs in terms of the basic information and the treatment of demographic aspects. While IPCoD uses average survival rates for the

species considered, the DEPONS model is more energy-oriented and considers survival through the ability of individuals to find food. This model therefore requires knowledge on the availability of prey. It can be used to simulate the effects on populations according to different scenarios, distances to the source and over varying lengths of time. Today, the DEPONS model only applies to the harbour porpoise.

Table 12 below summarises existing biological impact prediction models.

Biological impact prediction models, in brief

- Various models have been developed to predict the long-term consequences of marine mammal disturbances.
- In all cases, these models are based on hypotheses, be it on sound propagation, demographic parameters, thresholds or behaviours.
- Although their results are still to be put into perspective, these tools nevertheless provide the first quantification of the impacts of noise on marine fauna. Most of them are currently available for only a few species, due to a lack of sufficient data, but these models offer promising prospects for assessing impacts and simulating different solutions. They are therefore destined to become decision-making tools for offshore worksites.

Table 12: Summary table of the different current prediction models.

Tool	Input elements	Developed for	Suitable for	Less suitable for
SAFESIMM	- Noise level generated by the activity - Received noise level by the agents (individuals) - Duration of works - Number of individuals concerned	Impact of sonar emissions on marine mammals, since extended to other activities	- Define the number of PTS, TTS or behavioural disturbances suffered by marine mammals when exposed to high noise levels. - Explore scheduling scenarios	- Define the effects on fitness or make long-term projections
IPCoD	- Number of individuals affected per day - Demographic parameters of the population concerned - Number of days of disturbance	Impact of acoustic disturbance on marine mammal populations	- Predict the population developmental paths (impacted vs. non-impacted) in response to the works. - Exploring scenarios, including cumulative impact scenarios	- Working on species for which few data exist - Working in areas with large seasonal variations in density
DEPONS	- Demographic parameters of the population - Prey availability map - Population movement - Noise reaction distance	Impact on North Sea harbour porpoises	- Assessing cumulative impacts on porpoises - Exploring spatio-temporal work scenarios	- Working on species other than the harbour porpoise

5) Limitations and further developments

Noise acts at different levels on marine species and can therefore generate impacts of different kinds. While the direct impacts are already difficult to understand and quantify and are far from unanimous in the scientific community, the indirect impacts are very minimally identified and/or documented. Current knowledge of marine wildlife remains incomplete. Our ability to detect a decline before it reaches dramatic proportions raises questions [184, 192]. The improvement of fundamental knowledge on distribution, life cycles and migration patterns remains an essential point for understanding impacts and defining effective mitigation measures.

The evaluation of the sound impact of a project on the environment is based on the robustness of sound wave propagation modelling software. The choice of algorithms is therefore critical and these must be adapted to the environmental conditions of the study area, and in particular to the bathymetry. Modelling in shallow waters is particularly complex and requires adaptations, particularly in relation to cut-off frequencies. Model calibration also appears to be a determining factor for the quality of the predictions. The quality and reliability of the input data are therefore of utmost importance. The use of data collected *in situ*, particularly for the evaluation of propagation loss, should be favoured as far as possible in order to limit bias in estimations.

The primary aim of the mitigation methods conventionally implemented to reduce direct impacts (soft-start/ramp-up, stopping activities when animals are observed nearby, etc.) is based on the assumption that animals are able to flee in order not to avoid an impact. It also assumes that the moving of animals has less harmful effects than direct impacts. This may not be true for some species, particularly those in restricted or resident areas. Moving may then have consequences for the survival of individuals and hence the population [67] (Figure 27). The population's ability to find suitable alternative areas must therefore be taken into account in impact assessment.

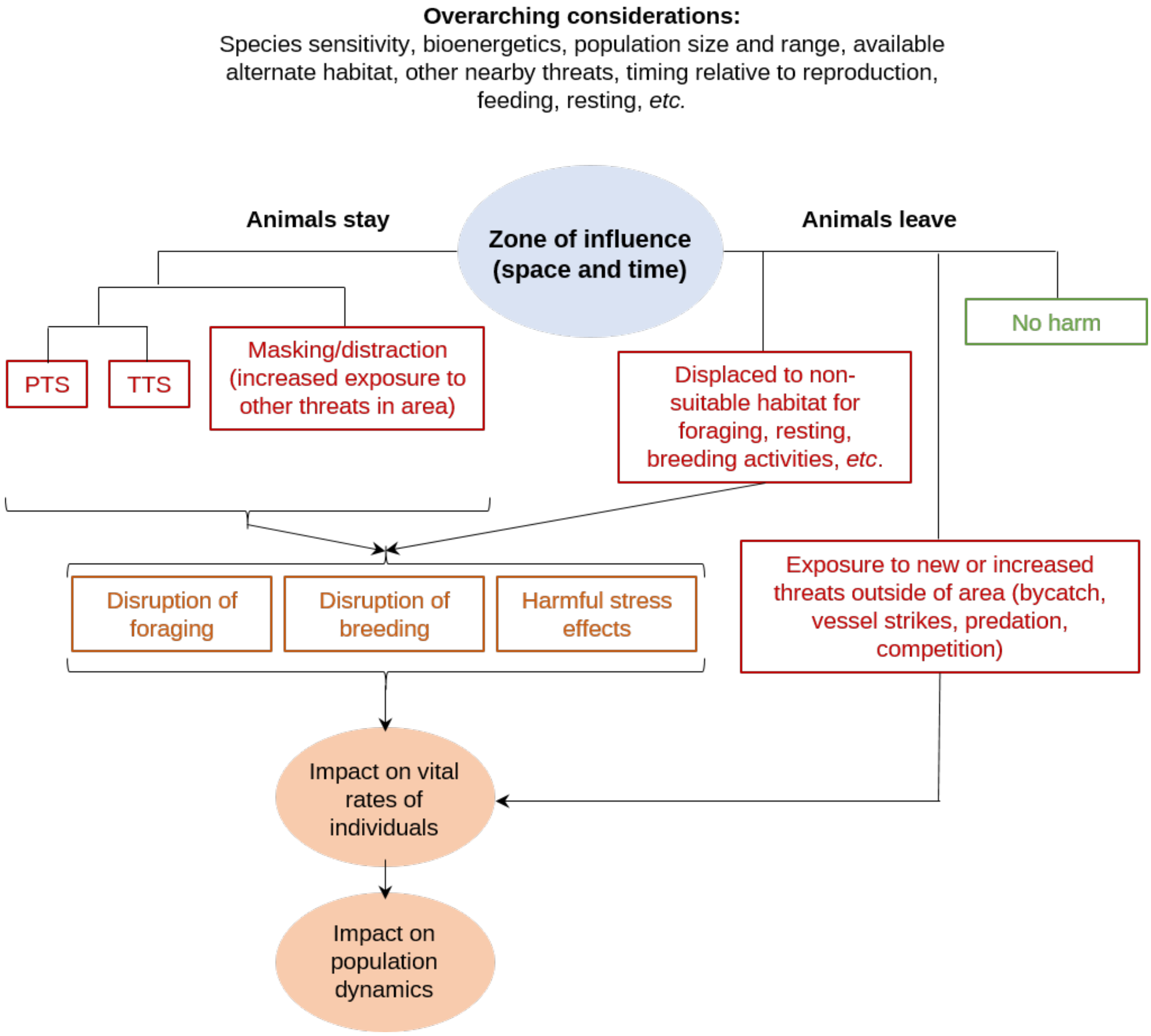


Figure 25: Suggested flowchart for assessing the impacts of human activities on marine mammals. For populations with high-site fidelity, moving can have significant consequences and lead to the same consequences as direct damage (from [67]).

The extrapolation of individual impacts at the population level is a line of research development that should be encouraged in order to reduce the uncertainties and margins of error, which are still numerous. Studies on the noise responses of taxa other than marine mammals are even more limited, which limits our understanding of the phenomenon.

The indirect responses of animals, energy-related consequences and long-term impacts, as well as the mechanism of accumulation of new and existing pressures, also appear to be essential lines of research to be developed so that mitigation measures become truly adapted to impacts and spatio-temporal scales and no longer governed solely by a precautionary principle.

Finally, the determination of thresholds above which the implementation of impact distance assessments and, where appropriate, mitigation measures is mandatory is to be encouraged. Although this presupposes in-depth work on existing knowledge and requires the development of measures and adapted methodologies, it would allow standardisation in the treatment of impacts and harmonisation of practices.

Limitations and further developments, in brief

- Thorough knowledge on the potentially impacted species, their biology and hearing sensitivity, as well as a well-calibrated noise propagation model are essential to assess the impacts and propose appropriate mitigation measures.
- In the event of disturbance, some species resident to or dependent on an area are seriously affected in their ability to survive, while others have the capacity to flee. In this case, it is necessary to assess their capacity to find suitable alternative areas.
- Proposals for impact mitigation measures must be drawn up on appropriate spatial and temporal scales in order to avoid the precautionary principle.
- Determination of regulatory thresholds is encouraged.

Photo courtesy: Cohabys

Part 3

Procedures and technologies to avoid, reduce or compensate the impacts of sound emissions on marine wildlife

I. Avoid

An avoidance measure is defined as a measure that modifies a project in order to eliminate a negative impact that it may have on the environment. This implies, for a species or group of species, that the avoidance measure ensures that there is absolutely no impact, whether direct or indirect, on any of the individuals making up the population nor on the physical and biological components required for its complete life cycle [124].

The same measure, in function of its efficacy, can be considered as either avoidance or reduction: avoidance indicates that the chosen solution ensures complete elimination of a given impact. If the measure does not ensure complete elimination, it becomes a reduction measure [124]. Some measures described in this chapter will therefore also be mentioned in the Reduce chapter.

1) Spatial and temporal planning

Most of the best-practice guides and international recommendations agree about the usefulness of defining **sensitive areas and/or periods for marine species, in which noisy activities should be forbidden.** But only a few countries have clearly defined - on the basis of their ecological importance - closed areas and/or periods for activities such as seismic surveys (in particular Brazil, Australia, Russia and ACCOBAMS signatory countries). These areas and/or periods concern breeding, feeding, raising young or migration.

This measure seems a simple and effective mitigation solution to ensure sensitive species are not harmed during the periods when they are most vulnerable [146, 185, 187, 191]. To achieve this, two prerequisites are required: (i) having sufficient knowledge about ecologically important areas for sensitive species, and about their distribution, abundance, movements, seasonality and sensitivity to noise; (ii) having official regulations that fix these closed periods and/or areas.

It would therefore be desirable that more countries adopt this measure once there is sufficient knowledge or when propitious areas have already been identified.

Other aspects to be encouraged are the sharing of distribution data and the utilisation of modelling or extrapolation techniques for existing data in order to provide information about areas where knowledge is limited or even non-existent.

Buffer zones around these protected areas, closed to noisy activities, can also ensure that risks and injuries to animals are minimised [42, 187, 192].

The case of large diving cetaceans in

general, and beaked whales in particular, deserves special attention because these species are difficult to detect visually due to their discreet behaviour and very long dives. It is important to bear in mind that they are species that live constantly at the limits of their physiological capacities (extended breath-holding, high pressures, etc.) and are therefore all the more sensitive to stress, whether chronic or resulting from accumulated impacts [192]. **Areas known to be preferential habitats for beaked whales (heads of submarine canyons, the slope of the continental shelf) are therefore to be avoided or monitored very carefully, in particular when these areas are not far from the coasts** [42, 190]. For instance, the map below (Figure 28) shows the areas defined as being of special interest for Cuvier's beaked whale (*Ziphius cavirostris*). Inside these areas, it is recommended to avoid high-intensity impulsive sound emissions [2].

Avoiding areas with a concentration of prey (and in particular spawning grounds) is also advised in order to avoid impacting their availability to marine mammals [42].

Areas of ecological importance (spawning grounds, nurseries) may vary in function of the taxa concerned. The heritage value of species and their sensitivity to sound emissions need to be taken into account. **In a case when a measure that would avoid an impact on a sensitive taxon would cause major impacts to other taxa, a compromise solution must be found, and that solution redefined as a reduction measure.**

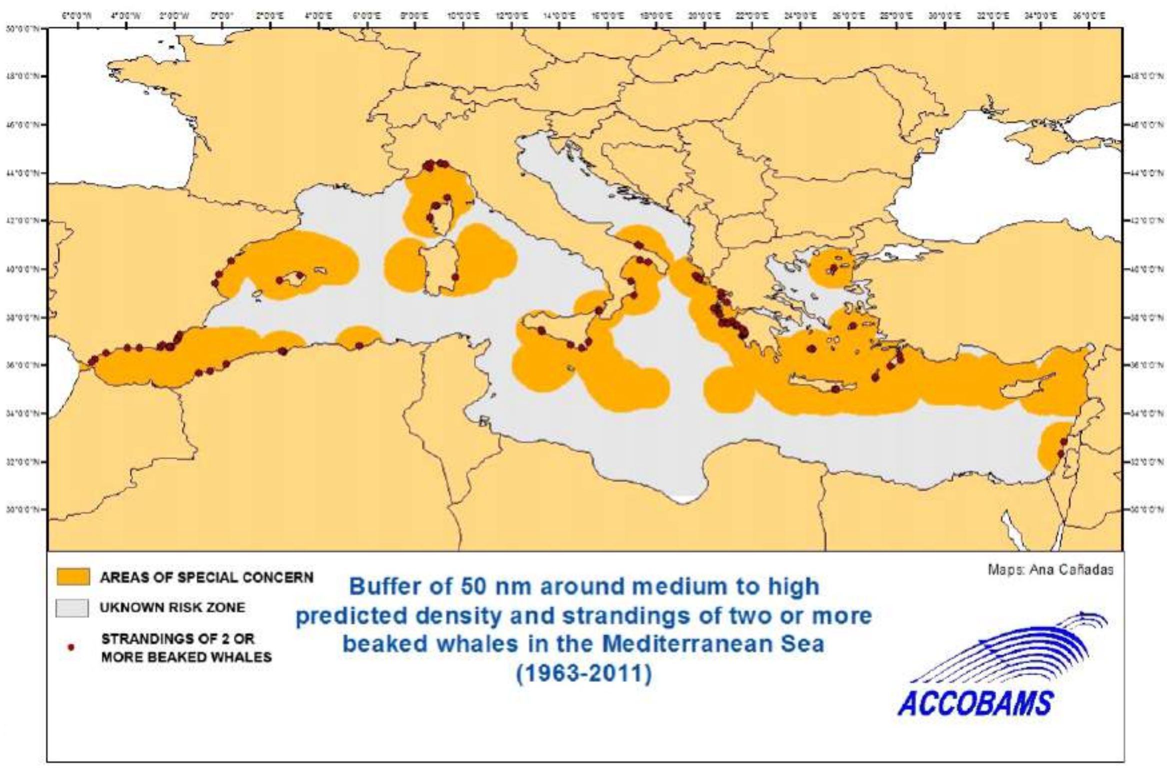


Figure 26: Location of areas of special concern for Cuvier's beaked whale in the ACCOBAMS Agreement Area (according to [2]).

2) Project scale/characteristics

Adapting the project with regard to environmental issues can be a solution for avoiding impacts identified in advance. This adaptation may concern the **scale of the project, its location or the techniques to be used to carry it out.**

An assessment must be systematically carried out for each project to analyse potential impacts in function of the project outline, intended routes, number and types of foundations, types of moorings, and sound sources used. Analysis of alternative methods and/or areas together with an assessment of potential gains in terms of noise reduction must also be taken into account. This involves having thorough knowledge of the noise levels generated by each considered scenario and of the impacts on the species present.

Orientation towards less noisy practices and lower-impact areas is to be encouraged.

3) Suspension of works during ecologically important periods

In areas where special periods in biological cycles have been identified, the suspension of noisy works can be envisaged. This may concern spawning, breeding or birthing grounds where noise pollution during those periods could interfere with, and cause long-term effects on, the balance and sustainability of populations. When these areas and periods are known, works need to be adjusted to take them into account.

The seasonality of the activity does not prevent the project being carried out, but the schedule needs to take these periods into consideration in order to avoid them.

4) Utilisation of zero-impact exploitation/operation techniques

One possible impact avoidance measure is the utilisation of techniques emitting frequencies with rates and/or durations that do not impact the species present. If the measure does not completely exclude the probability of impact for the species concerned, it then becomes a reduction rather than avoidance measure.

Table 13 summarises the main impact avoidance measures that can be implemented for works at sea.

Table 13: Recapitulative table of impact avoidance measures (in green: measures to be implemented beforehand, in orange: measures to be implemented during the works, exploitation and/or dismantling phase).

Measure	Activity concerned	Implementation	Efficacy	Limitations
Spatial and temporal planning	All	Forbid noisy activities in areas or periods recognised as sensitive for marine species (e.g. beaked whale habitat, breeding or birthing grounds for humpback whale, spawning grounds for fish)	Good	Knowledge of these areas/periods often lacking
Adapting the scale or characteristics of the project	All	Define the area, the routes taken, construction methods and/or scale of the project in order to choose the least-impact scenarios	Good	Thorough knowledge required about the noise levels generated by each considered scenario
Suspension of works during ecologically important periods	All	Adjust the works schedule to take into consideration species' biological cycles by avoiding the most sensitive periods (breeding, birthing, etc.)	Good	Thorough knowledge required of species' biological cycles
Use of zero-impact techniques	Sonars, single- or multi-beam echo sounders, acoustic deterrents	As far as possible, choose techniques that avoid impacting a species group by adjusting frequencies, rates and durations	Variable in function of technique	Not applicable to all species-groups at the same time

Avoidance measures, in brief

There are various avoidance measures for eliminating a project's negative impacts linked to underwater noise. To achieve this, the project developer may:

- Adapt the spatial dimensions of the project and/or the works schedule, avoiding high-risk areas/periods, scaling the project as well as possible and/or stopping works when marine mammals/turtles are observed;
- Adapt the project (in terms of both dimensions and characteristics) to the environmental issues involved;
- Suspend works during ecologically important periods;
- Use zero-impact techniques (frequencies and/or emission levels outside the hearing ranges of potentially impacted species).

A compromise needs to be found if these measures impact other taxa. The project developer can also precisely define the needs of the project to fine-tune the location of the works or the techniques used. Orientation towards the utilisation of the least noisy techniques is highly encouraged.

II. Reduce

Reduction measures are those aimed at decreasing a project's permanent or temporary negative impacts on the environment, during the works, exploitation or dismantling phase. They can act by reducing the duration of the project, adjusting its seasonal consequences, or reducing the intensity or spatial consequences of the impact [124].

The setting up of reduction measures is not systematic. It follows on from an impact assessment and is defined on a case-by-case basis. The measures need to be proportionate with the impact, itself directly linked to the species present, the ecological importance of the area and the expected consequences of the activity.

The thresholds above which reduction measures need to be set up have not yet been defined. Concerning seismic airgun surveys, some initiatives have defined source volumes in cubic inches (in^3) above which reduction measures need to be set up. In New Zealand, on this basis, the Department of Conservation has defined 3 categories of seismic surveys in function of the volumes concerned (< 150 in^3, between 151 and 426 in^3 and > 427 in^3). Below 150 in^3, no reduction measure is required. For higher volumes, measures are required but they vary in function of the category [39]. In France, IFREMER self-regulates regarding this question and has carried out internal work also aimed at defining a threshold volume. For surveys using sources of less than 500 in^3, no reduction measure is implemented. For any survey above 500 in^3, a mitigation protocol is applied [46].

It is crucially important to extend this work to other noise sources. Defining seismic source volumes or the diameter of piles above which reduction measures need to be set up is beyond the scope of this guide. Nonetheless, it is an essential prerequisite for the setting up of effective reduction measures scaled to the project. The development of this work to define thresholds is therefore strongly encouraged.

1) Planning

As with avoidance solutions, the first solution for reducing impacts is to **adjust the works schedule in function of periods propitious for marine species.** While the use of habitats by certain species is difficult to comprehend, some areas are known to be breeding or feeding grounds for marine mammals, turtles, pelagic fish, etc. During their seasonal presence in these areas, they are particularly vulnerable to noise pollution. Minimising disturbance during these periods decreases the probability of impacting these species.

During the impact assessment it is also important to consider the **presence of alternative areas** where potentially impacted species could take refuge, and to include consideration of individuals' ability to reach these areas.

In addition, it is necessary to **envisage before the start of the project the methods or technologies that could limit the noise impact.** To do so, the choice of techniques and construction materials is of major importance.

Consideration of already existing activities and projects already underway in the area can also enable **schedules to be adjusted** in order to reduce disturbance. In function of the project and intensity, this can take various forms: it may be advantageous to carry out a relatively low-noise or small-scale project at the same time as a bigger/noisier project if the latter could mask the noise footprint of the former; two similar-scale projects could either be carried out one after the other or simultaneously in function of the cumulated impact predictions modelled in advance.

For MRE projects, **the farm should be set up in such a way as to avoid creating any barrier effect** generated by the various facilities. This involves, for example, ensuring that bays or narrow passages are not "closed", leaving enough space between two wind or tidal power turbines, and not placing two farms next to each other.

2) Reducing noise at its source

a) Using less noisy techniques

There are several solutions for limiting the noise generated by works or activities at sea. They consist in using less noisy techniques that can be grouped in three categories:

Measures to adjust or modify the techniques or tools used

- It is possible **to increase the strike duration** used to drive in piles. Lengthening the strike duration when pile driving reduces the mechanical stress amplitude in the pile. This modifies the noise spectrum emitted, shifting it to lower frequencies [54]. However it can also potentially increase the sound exposure level ($L_{E,p}$). This measure is currently limited to small-diameter piles (less than 2 m) and therefore needs to be analysed on a case-by-case basis when proposed for a project.
- **The use of a material other than steel** is sometimes proposed for activities such as pile driving. By using an alternative material such as composite fibres, it is possible to reduce sound radiation from lateral surfaces and therefore reduce noise. A reduction in the order of 20 dB ($L_{p,\mathrm{pk}}$) has been announced by some authors [157] but the economic viability of such solutions is questionable.
- For seismic or sounding surveys, the main recommendation consists in **restricting emissions to study areas,** i.e. switching off sound sources when measurements are not required (changing action, transit within areas, etc.). Concerning seismology, it is also recommended to use the lowest-volume sources (airguns) needed to achieve the objectives of the survey and to reduce as much as possible the proportion of energy that propagates horizontally [42, 185].
- Reducing the noise levels generated by marine vessels involves **adapting the design of the vessel**, in particular the profiles of the hull and propeller. This measure needs to be taken before construction, so existing vessels are minimally concerned. Adaptations could nevertheless be applied, provided they are economically viable. It is therefore recommended that States and shipowners should review their merchant fleets in order to define which vessels would most benefit from adjustments to effectively reduce their noise levels [84]. Tools exist to do this, such as the EEDI (Energy Efficiency Design Index) developed by the International Maritime Organisation (IMO).

According to a study in 2014 [102], making the noisiest vessels quieter is the best way to reduce the noise linked to maritime traffic. **Cavitation is the major source of radiated noise.** The excessive cavitation generated by these vessels is often due to poor design of the underwater parts. Solutions for readjusting already constructed vessels exist or are under development[20]. Propellers need to be designed so as to reduce cavitation phenomena. The design of the hull, by streaming the water towards the propeller, also plays a role in reducing cavitation.

- The choice of machinery and optimisation of its position in the hull can also contribute to reducing radiated noise. **Diesel-electric propulsion** has been identified as an advantageous configuration for reducing noise and vibrations, and should be encouraged where possible. *In situ* measures need to be taken in parallel to evaluate the gains obtained by new designs of hull, propeller and propulsion systems [102].
- In addition to their specific design, regular maintenance of certain parts such as the propellers and hull can also reduce noise. Removing biofouling and rough patches on these surfaces limits the water resistance and friction that contribute to cavitation phenomena.
- Finally, **reducing speed** to below that at which cavitation phenomena are created can also decrease noise levels and is a simple and widely applicable measure [9, 85]. Recent works have shown that a 10% reduction in the speed of the world fleet would decrease by 40 % the acoustic energy produced by maritime traffic worldwide [101]. These gains are all the more significant because this measure would also reduce greenhouse gas emissions and the risk of collision with large cetaceans. **Reducing the speed of vessels thus seems an appropriate, easily applied and effective measure whose large-scale implementation is highly recommended.**

Standard ISO 17208-1:2016

The development of standards and norms for measuring the noise radiated by vessels and reducing their sound emissions is to be encouraged in order to provide a reference base and harmonise practices. To this end, Standard ISO 17208-1:2016 describes the procedures to be set up and the quantities to be used for measuring the underwater noise generated by vessels, particularly in deep waters.

[20] See Leaper *et al.*, 2014 [102] for further information.

Measures to choose other techniques than those traditionally used to reduce sound emissions

- The **vibratory pile driving** technique consists in driving the piles by combined oscillation and hammering. To do this, the pile is subjected to an oscillatory movement at a frequency of 20 Hz by means of rotating weights. These vibratory movements drive the pile into the substrate. Hammering is therefore only used to finish driving the pile into its final position. This technique thus reduces the hammering time and therefore the sound exposure level. The gains from using this technique are in the order of 15 to 20 dB $L_{E,p}$. However, the noise generated by vibratory pile driving is continuous, difficult to compare directly with the impulsive noise of conventional pile driving [100]. The utilisation of **drilling to replace or complement pile driving** is also an avenue developed by several companies providing technologies suited to different types of pile and sediment. Drilling is already used for a certain number of substrates where driving is difficult (for example hard rock or limestone).
- For wind turbines, the choice of **gravity foundations** rather than monopiles can also be a solution for reducing noise. This consists in placing concrete structures either directly on the seabed or on a levelling layer, then filling them with ballast. It therefore requires neither drilling nor pile driving, and thus in principle leads to much lower noise levels. However, gravity foundations require preparation of the seabed (flattening, levelling, etc.), which may also lead to noise pollution [25] linked to the techniques used (dredging in particular).
- For seismic surveys, there is an emerging trend towards the utilisation of **alternative technologies** such as Marine Vibroseis [47]. This technique uses lower frequencies and modulated signals, reducing the sound pressure level ($L_{p,\mathrm{pk}}$) compared with a conventional source for an equivalent sound exposure level ($L_{E,p}$). However, the utilisation of very low-frequency and much longer-duration impulsive signals compared to a conventional source may lead to more serious impacts for marine wildlife. The seismic source then becomes comparable to a very low-frequency military sonar system. Studies need to be encouraged to assess the impacts of these new methods.

Measures to set up incentives for action

These measures are not in themselves a solution for reducing noise, but they encourage industrial companies to seek and adopt such solutions. The initiative of the Port of Vancouver in Canada (ECHO programme, aimed at better understanding and managing the impacts of maritime traffic on marine mammals) is an example of a transdisciplinary, collaborative project to reduce the noise generated by vessels. A number of certification companies have developed voluntary-basis performance indicators for ports, shipowners or terminals including noise reduction (Green Marine in the USA). Such initiatives, voluntary but recommended and economically attractive (bonuses, reduced fuel consumption, etc.), appear to be a good method for involving the various stakeholders, aside from strict regulation.

Generally speaking, analysis of the various techniques that can be used and the noise levels that they generate needs to be carried out for each project. The choice of method should be made in function of expected impacts. **The choice of the least noisy practice is to be recommended, on condition that it does not have greater impacts in other ways (destruction of seabeds, pollution, etc.).**

The noise reduction measures linked to adaptation or modification of techniques are summarised in Table 14 below.

Table 14: Recapitulative table of reduction measures linked to adaptation or modification of techniques (in green: measures to be implemented beforehand, in orange: measures to be implemented during the works, exploitation and/or dismantling phase).

Measure	Activity concerned	Implementation	Efficacy	Limits
Increase strike duration	Pile driving	Increase the duration of the strike when driving in the piles	Unknown	Lowers the frequency of emissions, and potentially increases $L_{E,p}$
Change material	Pile driving	Use a material other than steel (composite fibres)	Unknown	Economic viability and medium/long-term strength of the alternative material
Restrict emissions	Seismic surveys	Restrict emissions to study areas, use the smallest source required for the survey	Good	Restart procedure for each new action
Design of vessels and propulsion system	Maritime traffic	Design hulls and propellers to reduce cavitation, choice of propulsion system	Good	Minimally applied to vessels already built
Maintenance of vessels	Maritime traffic	Maintain hulls and propellers to reduce friction	Unknown	-
Reduction of vessel speeds	Maritime traffic	Reduce the speed of vessels below the cavitation speed	Good	Longer scheduling
Vibratory pile driving, drilling	Pile driving	Use vibratory pile driving or drilling techniques to complement or replace conventional pile driving	Good	Lack of knowledge about continuous noise
Gravity foundations	Pile driving	Choose gravity base instead of monopile foundations	Good	Impact of seabed preparation
Marine Vibroseis	Seismic surveys	Use the alternative Marine Vibroseis technology instead of conventional airguns	Unknown	Very low-frequency sound comparable to military sonar signals
Norms, standards	All	Establish standards for measuring noise	Good	Requires scientific consensus; application framework
Incentives	All	Create incentives for companies to develop or adopt noise reduction measures	Good	Financial compensation

b) Techniques to insulate/confine the source of noise

Bubble curtains are the most widely used source noise reduction method for fixed sound sources (principally conventional and vibratory pile driving, drilling and the use of explosives). The principle is simple: compressed air is injected into perforated tubes, the ejected air forms a cloud of bubbles. The contrast in acoustic impedance caused by the air/water interface leads to the diffusion of the sound waves through the air bubbles, and the reflection of the waves by the curtain reduces the noise generated [100].

There are several technologies, some of which are already commercialised. Globally speaking, two families can be distinguished: large bubble curtains set up around a worksite and small bubble curtains set up around a precise point (a pile to be driven for example). The system is sometimes doubled, even tripled, to increase the noise reduction.

The use of bubble curtains has been widely tested on various worksites. While the technique is now mature and the reductions obtained are significant (up to 18 dB), the principal constraint remains the tidal current. The efficacy of the method is dependent on environmental conditions (bathymetry, sea state, current, etc.).

The **Hydro Sound Damper (HSD)** system is a variant of the bubble curtain in which a net with air-filled balloons and various polymer elements is set up around the source of noise. The aim of this system is to avoid the bubbles drifting with the tidal current. Moreover, the maximum absorption frequency can be modified by changing the size and composition of the balloons. The system nonetheless remains dependent on the weather conditions, and cannot be set up in the presence of a strong current or heavy swell.

There are other variants, such as the **confined bubble curtain** in which the bubble curtain is enclosed in a cylindrical casing. These systems are close to the concept of isolation casings (see below).

Isolation casings confine the source of noise (a pile to be driven in most cases) in a cylindrical steel or plastic casing coated with insulating materials to reduce noise. Some technologies include a bubble curtain inside the casing.

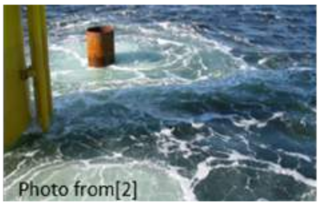
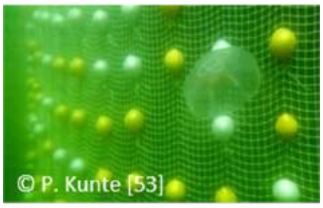
Cofferdams are isolation casings aimed at creating a waterless space around the pile. The pile is placed inside a steel shell wider in diameter than the pile, and pumps are used to remove the water between the two structures. The sound waves then remain confined in the shell due to the difference in impedance between air and water.

These techniques have been deployed in several marine wind farms in the North Sea (Riffgat and Aarhus Bight for example) and show considerable noise reductions (up to 23 dB $L_{E,p}$ [100]).

The last two techniques (isolation casings and cofferdams), more recent and less widely used than bubble curtains, have the advantage of being less influenced by the current than bubble curtains, and could therefore be interesting alternatives.

The characteristics of all these techniques are summarised in Table 15.

Table 15: Recapitulative table of the principal existing bubble curtain and isolation casings technologies (according to [2]).

Technology	Noise reduction capacity	Possible applications	Maturity	Bibliographical references
Large bubble curtain  	Single bubble curtain: 10 to 15 dB $L_{E,p}$ Double curtain: 15 to 18 dB $L_{E,p}$	Pile driving Drilling Dredging Blasting	Commercialised, highly used worldwide	15, 100
Small bubble curtain  	4 to 14 dB $L_{E,p}$	Pile driving Drilling	Proven technology on various worksites	15, 100
Hydro Sound Damper  	4 to13 dB $L_{E,p}$	Pile driving Drilling Dredging Blasting	Technology tested on several wind farms	15, 100
Isolation casings  	Without bubble curtain: 10 to 14 dB $L_{E,p}$ With curtain: 17 to 23 dB $L_{E,p}$	Pile driving Drilling	Commercialised, tested on various wind farms	15, 100
Cofferdam  	10 to 23 dB $L_{E,p}$	Pile driving Drilling	Proven technology on some worksites	15, 100

3) Presence monitoring and exclusion procedures

Standardised national or international procedures have been initiated by a certain number of countries around the world to propose mitigation measures for noisy activities. These guidelines are either general or focussed on one particular activity (seismic surveys, wind farms, sonar, etc.)

In 1995, the United Kingdom's JNCC Guidelines were the first national guide to determine guidelines and mitigation measures to be implemented for seismic surveys. While there are considerable variations between the guidelines subsequently published in other regions and for other activities, most measures are inspired by these original guidelines. Many measures have therefore been borrowed from these "pioneering" guidelines without necessarily being applicable or appropriate to other areas [146, 187, 191]. Moreover, as "pioneering" guidelines, they are essentially based on common-sense measures rather than an established scientific basis [146]. They nevertheless set down the groundwork for most procedures currently used throughout the world.

a) Definition and calculation of an exclusion zone

An exclusion zone is an area of predefined radius around the noise source. It is the zone considered to be dangerous for the marine species concerned.

Many guidelines recommend a fixed exclusion zone with a radius of 500 m around the sound source. While this area may be sufficient to avoid injuries (even more than sufficient depending on the source implemented), behavioural disturbance and acoustic masking may occur over a wider area [158]. Studies report significant reactions observed outside the arbitrarily defined 500 m zone [11, 27, 69, 172].

Some guidelines/recommendations therefore propose calculating the exclusion zone from the hearing thresholds for behavioural disturbance, which appears much more protective. However, it poses two major problems: on the one hand, it implies that these threshold values exist and are reliable; on the other hand, the thus-defined mitigation zones will be larger than those defined using injury thresholds, posing the question of how to ensure visual monitoring of an area several km in diameter [34].

Other organisational approaches then need to be considered such as placing observers on other vessels or using aerial monitoring to locate the animals at a larger scale [94, 140, 146]. Aerial monitoring is particularly used in certain regions (Hawaii, California, Australia) during naval exercises involving the sonar use [42].

In conclusion, it is too early, in the current state of knowledge and techniques, to define exclusion zones based on behavioural impacts. For projects likely to cause permanent or temporary damage to marine species, it is therefore recommended that an exclusion zone be applied that is appropriate to the issues and characteristics of the site and project, corresponding at least to the area where there is a risk of physiological injury (PTS zone) to the species present, combined with a precaution factor to be defined in function of environmental conditions (zones, periods, ecological role, etc.), **on condition that the minimum radius is 500 m.**

The initiative taken by New Zealand to increase the size of the exclusion zone in the presence of young animals would seem to be pertinent in view of their higher sensitivity [34]. It is therefore recommended that the precaution factor should be increased in areas/periods favourable to the presence of young individuals and to define a buffer zone. An alert zone can also be defined around the exclusion zone, serving as an area in which any animal spotted is likely to enter the exclusion zone (Figure 29).

b) Pre-watch

Pre-watch, or pre-works monitoring, is **meticulous monitoring of the area around the worksite aimed at ensuring that no species potentially impacted by noise (in general marine mammals and/or turtles)** is present before the start of sound emissions. It consists of 360° visual and/or acoustic monitoring carried out by Marine Mammal Observers (MMOs) and/or Passive Acoustic Monitoring (PAM) operators. This measure is proposed by all the best-practice guidelines. The area to be watched can correspond the above-defined exclusion zone or be enlarged to include an additional "alert zone". The pre-watch generally lasts between 30 min (depth < 200 m) and 60 min (depth > 200 m) and works will not start if there is any observation/detection during this time. In areas where large diving cetaceans (Sperm Whale, beaked whales) may potentially be encountered, a duration of 60 min is strongly advised by most recommendations (even 120 min for ACCOBAMS). In the event of animals being present during this time, the start of the sound emissions is postponed.

Pre-watch requires that the weather

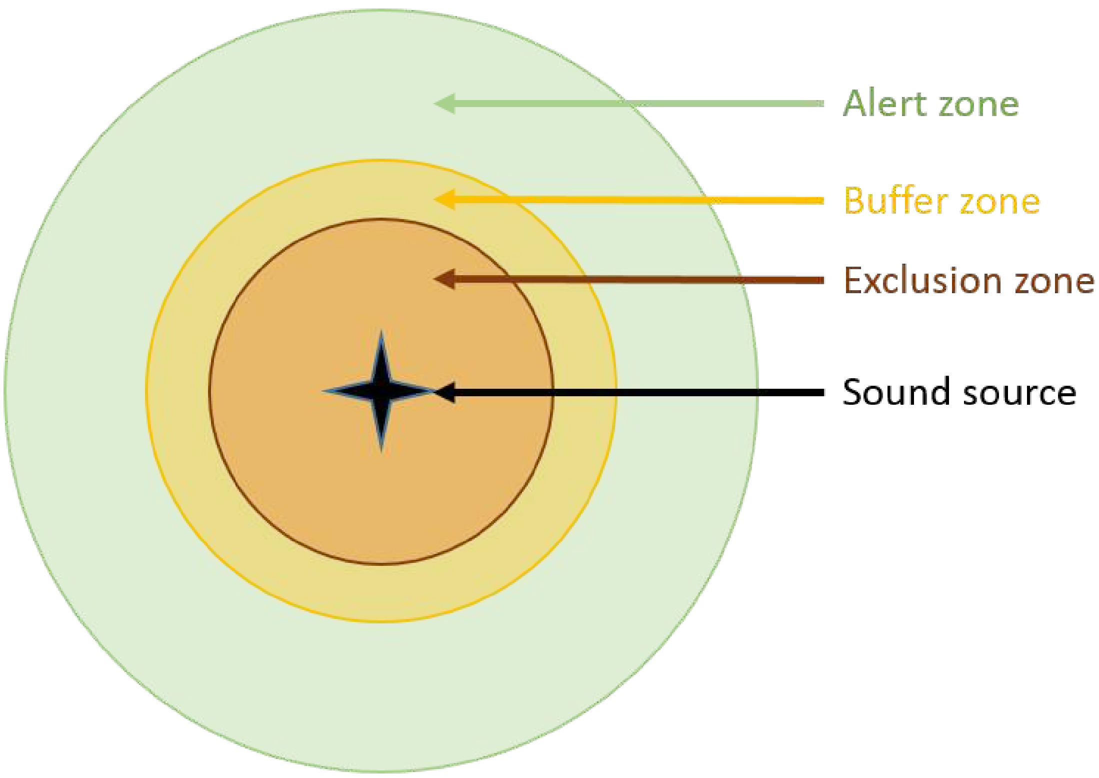


Figure 27: Zones defined around the sound source.

conditions enable visual monitoring of the exclusion zone and its surroundings. This means that the MMOs must be high enough, have a clear view and be able to observe within a radius of at least 1 km around the observation platform. Similarly, the range of the hydrophone(s) should be checked to ensure that it covers the monitoring area.

It is therefore recommended to set up visual and/or acoustic pre-watch for noisy activities[21] lasting about 60 min for areas deeper than 200 m and/or likely to harbour large diving cetaceans and about 30 min for areas less than 200 m deep.

c) Soft-start and ramp-up

Soft-start and ramp-up are **procedures for progressively increasing the noise level to repel marine species** in the vicinity of the emission sources so as to avoid any risk of physiological harm. Soft-start consists in progressively starting the activity (for example the gradual starting-up of airguns in the case of seismic surveys, or a progressive increase in rotor speed for drilling or in strike rate for pile driving) until the maximum emission level is reached. When that is not possible (in the case of the use of explosives or machines whose intensity cannot be regulated), the ramp-up technique is used: noise is emitted into the area using a different sound source, whose emission level is increased until it reaches the expected sound level. Only then, once that level has been reached, is the original sound source implemented.

The duration of the procedure needs to be long enough to drive animals a significant distance away, but not long enough for them to start getting used to the noise (habituation). While there is debate concerning the efficacy, duration and setting up of these procedures [48, 191], they nevertheless remain a standard measure in most worksites and are recommended by all the best-practice guidelines or recommendations. The recommended duration of progressive increase in noise level is generally between 20 and 40 minutes. To obtain the desired repellent effect, some guidelines recommend an increase in 6 dB steps until the expected maximum power is reached [28].

The setting up of a soft-start or ramp-up procedure lasting from 20 to 40 min is recommended if it is technically possible to set it up.

d) Visual monitoring during the emissions

Visual monitoring is the most common attenuation method, found in all the guidelines, recommendations or protocols generally applied in the case of noisy activities (Figure 30). However, its implementation varies considerably concerning both the number of observers

Figure 28: Marine mammal observer on watch (photo courtesy: Cohabys).

[21] The threshold above which a noisy activity requires the setting up of mitigation measures is not defined here. As a reminder, for seismic airgun surveys, IFREMER has defined the threshold of 500 in^3 as the volume of air above which measures should be implemented.

and whether or not the monitoring is continuous.

While its efficacy is highly dependent on the observers' skills and the weather conditions, visual monitoring remains a pertinent measure. It is generally considered that above 4 on the Beaufort scale (windspeed higher than 16 knots), the conditions no longer enable effective monitoring to be carried out. The height of the swell and the visibility are also factors to be taken into account. Moreover, visual observation can only be performed by day. A complementary system of passive acoustic monitoring can partly compensate for these limitations.

The use of thermal or infra-red imaging can prolong the monitoring after nightfall. While this technology is currently only effective for large animals and in polar or subpolar regions, it will probably become a promising tool in the near future.

The use of experienced and independent observers is crucial for ensuring high-quality monitoring and impartial, effective and rapid decision-making [144, 187]. It is therefore important to be vigilant concerning observers' skills and experience. Some regions impose obligatory certification to be able to work in waters under their jurisdiction in order to ensure the quality of the observers. The United Kingdom imposes JNCC MMO certification for working in in its waters; in the Gulf of Mexico, BOEM PSO training is required. New Zealand imposes training by the NZ Department of Conservation and certain Mediterranean countries require the MMO training dispensed under the aegis of ACCOBAMS.

To ensure attentive monitoring, the observers need to have time to take breaks. It is therefore recommended to use at least three observers. In this way, two observers can be on watch at the same time and the work can be organised in shifts.

It is therefore recommended that three observers should be used to carry out the monitoring of marine wildlife during noisy operations[22]. Standardisation of the protocols produced by the work of the major organisations (JNCC, ACCOBAMS, etc.) is encouraged. The use of qualified, experienced, even certified observers is also essential.

In addition to their mitigation role, visual observations can also play an important role in monitoring the impacts of the worksite. Although not sufficient to be considered as a full monitoring operation, they may provide information concerning frequentation by marine megafauna in the immediate proximity of the worksite.

[22] The threshold above which a noisy activity requires the setting up of mitigation measures is not defined here. As a reminder, for airgun seismic surveys, IFREMER has defined the threshold of 500 in^3 as the volume of air above which measures should be implemented

e) Acoustic monitoring

Real-time acoustic monitoring needs to be considered as a complementary tool in combination with visual observations, in that in enables the detection of marine mammals when observation conditions are poor for the observers (by night or under inclement weather conditions). There are various systems, ranging from PAM systems dragged behind seismic vessels to networks of buoys equipped with autonomous recorders. PAM systems enable real-time detection of signals emitted by cetaceans in the vicinity of the hydrophones by means of automated detection algorithms and/or listening by a PAM operator. Detections can be displayed using software such as PAMGuard, Ishmael or the proprietary programmes of the various solution providers.

However, the method still has its limits. It is difficult to discriminate between certain species entirely on the basis of their signals and also to precisely locate the position of the animal detected. While some species emit short-range signals (less than 200 m in the case of porpoises for example), others such as baleen or sperm whales can be audible kilometres away. The reliability of the automatic detection and classification algorithms is currently insufficiently robust. It is also important to check that the algorithms used are appropriate to the study area.

Unlike visual observation, there are very few detailed protocols concerning the utilisation of PAM as a monitoring tool in the framework of offshore worksites. Its use is often encouraged (JNCC, ACCOBAMS) without any procedure being really described in detail.

As with visual observations, the level of qualification of the PAM operators is crucial. It is imperative that they should be trained specialists, highly experienced in the utilisation of such systems.

For continuous monitoring of an exclusion zone, it is essential that the number of PAM operators and the number of hydrophones should correspond with the task to be accomplished and the number of MMOs present onboard.

There are currently numerous technological innovations in the field regarding both the localisation of animals and the automatic detection of bio-acoustic signals. The tool is therefore set to develop very quickly.

As with visual observation, acoustic monitoring can help monitor worksite impacts by providing information on frequentation by cetaceans in the immediate proximity of the worksite and on real-time

Visual and acoustic monitoring

Visual monitoring of the study area is commonly recommended for particularly noisy activities (seismic surveys, drilling, pile driving, use of explosives, etc.). It can be effectively completed by acoustic monitoring, by night or in the event of poor weather conditions.

Both types of monitoring need to be carried out by qualified, experienced, even certified monitors (Marine Mammal Observers (MMOs) for visual monitoring and Passive Acoustic Monitoring (PAM) operators for acoustic monitoring). Some organisations such as ACCOBAMS provide certification for these monitors.

emission levels.

The utilisation of a PAM system is recommended for noisy operations[23] to complement visual observation. The use of qualified, experienced, even certified operators is essential.

f) Stoppage of works when animals are present

The best-practice guidelines and procedures are not unanimous concerning the stoppage of works when animals are present in the exclusion zone: (i) some guidelines recommend stopping the works and not starting them again until the animals have left the exclusion zone (after a new pre-watch and soft-start procedure); (ii) others only recommend stoppage if the animals entering the exclusion zone are sensitive species (defined in advance); (iii) finally, others consider that the fact that the animals enter the exclusion zone indicates that the noise generated does not disturb them. No stoppage is therefore necessary [42, 191].

Given that the definition of the exclusion zone is generally based on known tolerance thresholds (physiological injury thresholds plus a precautionary margin), that animals can be disoriented by exposure to noise, and that the efficacy of repellent measures such as soft-start is not known, **it is recommended to stop the works in the event of animals entering the exclusion zone. This implies than an exclusion zone should be defined in advance for the various species designated as sensitive to the noise generated. The detection of the animals is then carried out by visual observations and acoustic monitoring.**

This type of measure may slow down the project and prolong delivery times. But it can reduce the risk of temporary or permanent impact on animals entering a potentially dangerous area. This constraint should therefore be integrated into the project before it starts to be taken into account in its planning and budgeting.

The flow diagram presented in Figure 31 details an example protocol that could be implemented to reduce impacts on marine wildlife in the framework of carrying out works at sea.

g) Acoustic deterrents

Here we only deal with the use of acoustic deterrents as a measure for reducing the risk of noise impacts in the framework of noisy worksites. Their utilisation for fisheries is not covered.

Two main types of acoustic deterrents can be used to drive animals away from potentially dangerous areas: pingers, which generally emit between 2.5 and 100 kHz, and seal scarers, which emit between 8 and 17 kHz. Both types of instruments, initially intended to repel animals from fisheries and reduce accidental bycatch, are additionally used during the construction of marine wind farms [20] or port developments. Seal scarers are frequently recommended as a repellent measure for harbour porpoise because they are considered by some authors to be less detrimental to the species than pingers due to their emission frequencies [20]. While their efficacy has been proven, some authors believe that these devices may repel marine mammals much further away than expected [22] and could contribute to excluding the animals

[23] The threshold above which a noisy activity requires the setting up of mitigation measures is not defined here. As a reminder, for seismic airgun surveys, IFREMER has defined the threshold of 500 in^3 as the volume of air above which measures should be implemented.

from favourable habitats by increasing or even exceeding the impact of the worksite [38, 189].

While acoustic deterrents have proven effective on some worksites, they nonetheless cannot be recommended for all worksites and their utilisation should not be generalised. As with other sound sources, it is important that they do not emit above the levels required. For very high-frequency species in particular, prudence is essential. The carrying out of a soft-start procedure and meticulous monitoring of the worksite area are generally sufficient to drive animals away from potentially impacted areas.

The presence monitoring and deterrent procedures are summarised in Table 16 below.

Noise reduction measures, in brief

For reducing the noise impacts of noisy activities, 3 categories of measures can be distinguished:

- Measures aimed at planning the works outside ecologically critical periods or areas;
- Measures aimed at reducing the noise at its source;
- Measures aimed at repelling sensitive species from areas potentially dangerous for them.

The first two categories should be prioritised. It is more ecological to seek to reduce the noise before it becomes detrimental rather than to drive animals away from areas that are potentially important for their biological cycles. These types of measures are also quantifiable by measuring the sound generated, whereas it is more difficult to evaluate repellent techniques.

These measures should be completed by monitoring for the presence of animals. This monitoring may be visual and acoustic and must be carried out by qualified, experienced, even certified monitors.

The choice of measures to be implemented must be consistent with the expected impacts. The project developer should analyse the various measures available and integrate them in the project schedule and budget.

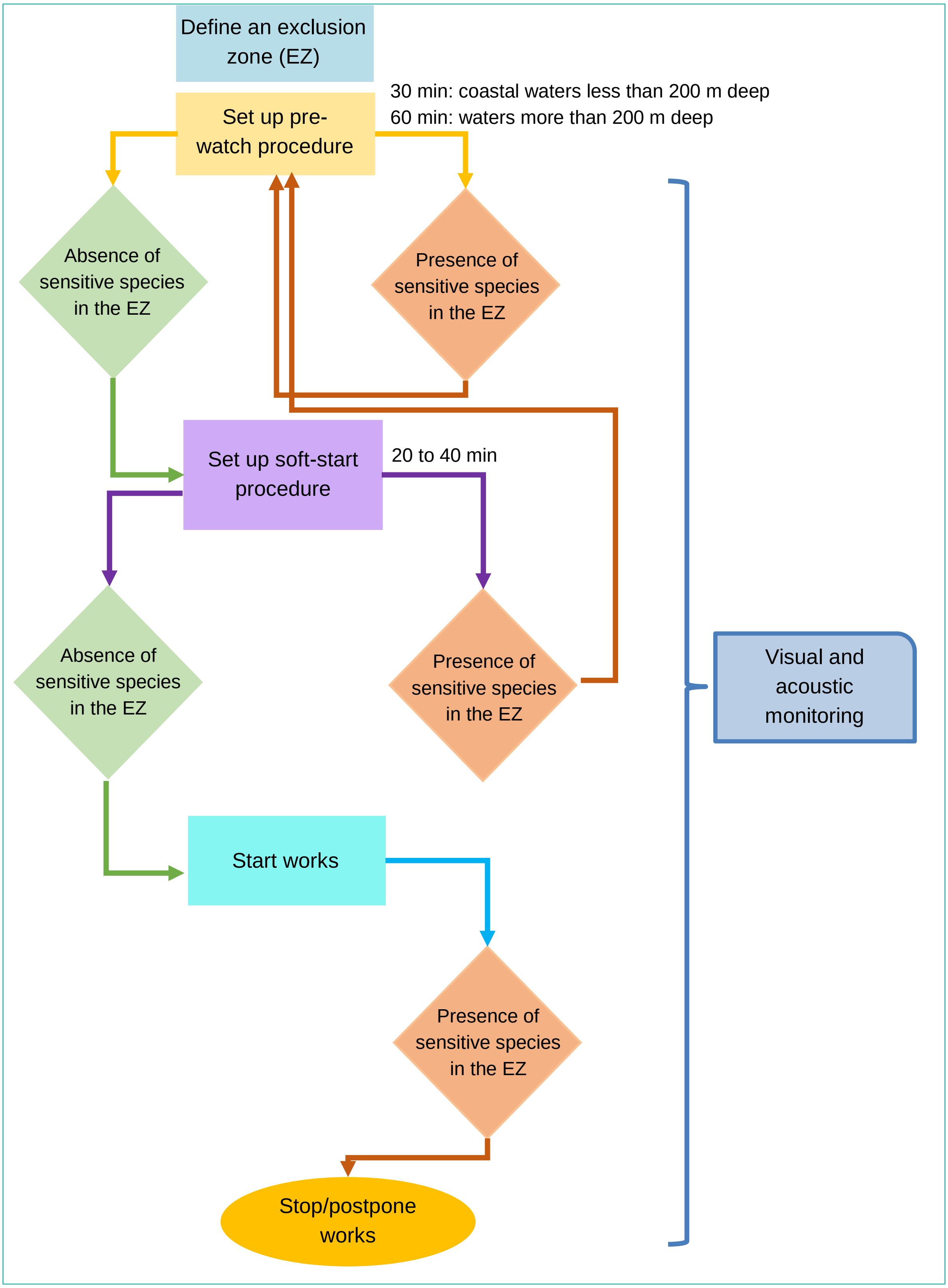


Figure 29: Example protocol that could be implemented to reduce impacts on marine wildlife in the framework of carrying out works at sea.

Table 16: Recapitulative table of presence monitoring and deterrent reduction measures
(in green: measures to be implemented beforehand, in orange: measures to be implemented during the works, exploitation and/or dismantling phase).

Measure	Activities concerned	Implementation	Efficacy	Limitations
Definition of an exclusion zone	Marine worksites, drilling, pile driving, seismic surveys, dredging, blasting	Define a zone in which there should be no sensitive species present (physiological impact zone)	Good	Availability of monitoring measures or tools for zones of more than 1 km
Pre-watch	Marine worksites, drilling, pile driving, seismic surveys, dredging, blasting	Visual/acoustic monitoring of the exclusion zone and its surroundings to check for the absence of sensitive species. Duration 30 to 60 min in function of the zone.	Good	Availability of monitoring measures or tools for zones of more than 1 km
Soft-start/ramp-up	Marine worksites, drilling, pile driving, seismic surveys, dredging, blasting	Progressive increase in sound levels to repel sensitive species. Duration 20 to 40 min.	Unknown	Limited knowledge of the effective increase sequence in function of species/group of species
Visual monitoring	All	Presence of qualified and experienced marine wildlife observers to monitor the exclusion zone and its surroundings. 2 to 3 monitors required	Good	Dependant on observation conditions, impossible at night
Acoustic monitoring	All	Deployment of a passive acoustic system for detecting and localising signals emitted by cetaceans	Good	Identification of particular species complicated, detection distance variable in function of species
Stoppage of works	Marine worksites, drilling, pile driving, seismic surveys, dredging, blasting	Stopping works in progress in the event of sensitive species being present in the exclusion zone, restart once they have left according to a predefined procedure	Good	Economic cost for the worksite, acceptability by the worksite owner
Use of deterrents	Marine worksites, drilling, pile driving, seismic surveys, dredging, blasting	Utilisation of devices such as pingers or seal scarers to drive animals away	Lack of scientific consensus	Repulsion from ecologically important areas, habituation of animals

III. Compensate/Offset

The aim of compensation/offset measures is to compensate for direct or indirect negative effects that could not be avoided or sufficiently reduced. Such measures need to compensate in compliance with ecological equivalence and attain the objective of no net loss of biodiversity [124].

With regard to underwater noise of-anthropic origin, there are currently no compensation/offset measures for marine wildlife. In the absence of such measures, any action laid down in a national Action Plan (for example turtles or marine mammals) contributes to the conservation of the species concerned, and such accompanying actions are therefore to be encouraged.

IV. Follow-up

Any ARC measure needs to be subjected to monitoring, imposed by regulations, in order to justify the setting up of the measures and their efficacy. This monitoring must therefore respond to a precise objective, and enable the results obtained to be evaluated compared to those expected. In other words, the monitoring must reveal the evolution of the habitats and species during the duration of the worksite, and assess whether the planned ARC measures had the desired effect.

The type of monitoring, its frequency, scale and means of implementation, and also the type of analysis carried out depend on the project itself, the species present and the ecological importance of the area.

The monitoring must therefore check whether or not an impact was observed, generally in response to an initial status assessment carried out before the works began. For projects that continue after the works phase, such as MRE farms, this implies monitoring the project once it is in operation and during the lifetime of the energy farm, and monitoring of frequentation by marine species according to methods to be defined in function of the project and the area concerned.

For other projects (seismic surveys, dredging, excavation, blasting), particular attention must be paid to the stranding of animals in the areas concerned via the existing intervention networks. Post-works monitoring can also be envisaged for these projects.

For continuous activities such as maritime traffic, it is difficult set up the monitoring of measures. The ARC measures proposed being essentially based on adapting the design, maintenance and reducing speed, technical measurements of the gains obtained in terms of noise reduction need to be carried out *in situ*. Accompanying measures can be proposed to achieve further gains.

V. Accompany

ARC measures can be combined with accompanying measures. Unlike ARC measures, accompanying measures are not a response to a regulatory obligation but rather a proposition by the project developer to improve knowledge or increase the efficacy of ARC measures. They do not replace ARC measures and are more an expression of commitment to the species or habitats concerned by the project [124].

1) Acquisition and dissemination of further knowledge

One accompanying measure is the acquisition of further knowledge about areas or species concerned by projects or works. This may involve carrying out complementary environmental monitoring on a larger scale (spatially and/or thematically compared to what was required for the initial status assessment), sharing gathered data, enhancing knowledge about impacts or the biology of species, participating in research programmes, etc.

This new knowledge may then help to define ecologically important areas and periods.

The acquisition of knowledge about the noise levels generated by various anthropic activities is also to be encouraged, since the data still remain fragmented or even non-existent for some sources. Improving knowledge about the impacts of sound emissions on marine wildlife also needs to be continued and supported. The dissemination and promotion of data gathered by monitoring operations or in the framework of accompanying measures is also an essential point.

2) Restoration/rehabilitation of habitats

Other accompanying measures include the restoration of degraded habitats or the rehabilitation of areas in order to favour or increase biomass or biodiversity. This implies that these habitats present characteristics propitious to the development of local fauna and flora.

These restoration measures can thus help to improve the ecological status of an area and enable it to develop towards a status more favourable to its ecological functioning or biodiversity.

The creation of marine protected areas is a State prerogative that cannot be a compensation or accompanying measure on the part of the project developer. However, contributing to the improvement of habitats or the restoration of ecosystems can be accompanying measures fully compatible with the objectives of a marine protected area.

3) Awareness-raising actions

The project developer can include awareness-raising actions in the project aimed at users of the area and the general public with regard to key issues. Actions concerning underwater noise and methods for reducing it, and limiting its impacts and consequences for marine wildlife, can therefore be envisaged by project developers. Communication and transparency regarding the methods used on the worksite are also to be encouraged.

Other measures, in brief

- There are no compensation/offset measures for impacts linked to sound emissions.
- However, accompanying measures can be set up. They consist in acquiring complementary knowledge about the impacted areas or species, and about the noise levels generated, setting up habitat restoration programmes, or carrying out awareness-raising actions.

VI. Summary

Table 17 below summarises all the measures available for avoiding and reducing the impacts of noise on marine wildlife.

Table 17: Recapitulative table of measures for avoiding and reducing the impacts of noise on marine wildlife (in green: measures to be implemented beforehand, in orange: measures to be implemented during the works, exploitation and/or dismantling phase).

Type of measure	Activity concerned	Efficacy	Implementation	Stage of development	Cost of implementation	Difficulty
Avoid						
Definition of sensitive areas/periods	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	High	Data analysis, fundamental knowledge	Depends on sector of activity	None, but possible impact on worksite schedule	Knowledge limits
Scaling of project	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	High	Scaling the project with regard to environmental issues	?	Potentially significant, to be considered as far in advance as possible	Economic viability, existing knowledge
Suspension of construction works	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	High	Suspend works during key periods	?	Potentially considerable, to be considered as far in advance as possible	Existing knowledge, economic viability
Reduce						
Adaptation of techniques, less noisy techniques	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	Variable	Adaptation or modification of techniques or schedule	Variable	Potentially significant, to be considered as far in advance as possible	Existing knowledge, economic viability
Definition of an exclusion zone	Pile driving, seismic surveys, drilling, dredging	High	Visual and acoustic monitoring, modelling	Commonly set up	None	Technical limitations
Pre-watch	Pile driving, seismic surveys, drilling, dredging	High	Visual and acoustic monitoring, modelling	Commonly set up	Acoustic observers and monitors (3 to 5 persons, i.e. 1200 to 2200 € exc. VAT/day)	Technical limitations
Soft-start/ramp-up	Pile driving, seismic surveys, drilling, dredging	Unknown	Gradual increase in noise levels	Commonly set up	Acoustic observers and monitors (3 to 5 persons, i.e. 1200 to 2200 € exc. VAT/day)	Knowledge limits

Type of measure	Activity concerned	Efficacy	Implementation	Stage of development	Cost of implementation	Difficulty
Visual surveillance	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	High	Presence of observers on board	Commonly set up	3 marine wildlife observers (approx. 1,200 € exc. VAT/day)	Dependent on weather conditions
Acoustic surveillance	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	High	Acoustic equipment, PAM operator	Commonly set up	2 passive acoustic monitoring operators (approx. 1,000 € exc. VAT/day)	Technical limitations
Stoppage of works if animals present	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	Assumed to be high	Real-time visual /acoustic surveillance	Commonly set up	Potentially considerable, to be considered as far in advance as possible	Acceptability, economic consequences
Acoustic deterrents	Pile driving, seismic surveys, drilling, dredging, blasting, maritime traffic, laying cables	Debated	Setting up of scaring devices	Often used	200 to 500 € unit cost	Loss of habitat
Bubble curtains (air or HSD)	Pile driving, drilling, use of explosives	High	Curtains deployed around worksite or facility	Commercialised	*Between 10,000 and 100,000 € in function of type of worksite*	Dependent on currents
Buffer materials, cofferdams, isolation casings	Pile driving, drilling	High	Deployed around worksite or facility	Commercialised or being tested	?	Less developed than bubble curtains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Part 4

Summary Fact Sheets

The fact sheets presented in this part summarise, for certain sources of noise:

- the levels reached and frequency ranges concerned by the emissions;
- the species potentially exposed;
- the potential impacts;
- the measures to be considered for avoiding or mitigating these impacts, and the possible accompanying measure(s) to be set up.

Each fact sheet also gives a concrete observation case study for each of sources presented, with the broadband levels measured (level calculated for the whole recording frequency band).

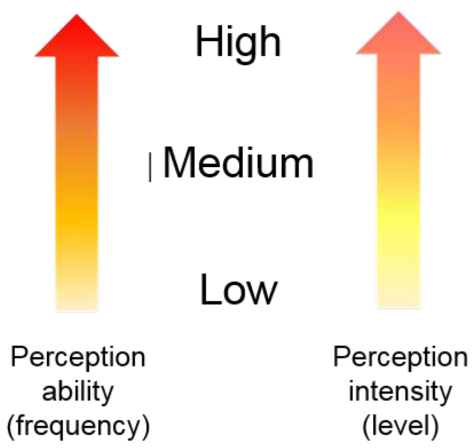
The fact sheets illustrate categories of activities, but there are major differences within each of these categories. The noise levels generated may vary considerably for a single activity in function of project characteristics. Potential impacts also vary in function of the operation (techniques used, duration of emissions, noise levels generated, etc.) and the issues specific to the site (presence of species in the area, ecological importance of the area, recurrence of noisy activities, etc.)

The avoidance, reduction or accompanying measures to be set up should therefore be proportionate with the expected impacts. **In these summary fact sheets, a certain number of measures are proposed for each activity, but that does not mean that they should be implemented systematically.**

Consequently, a case-by-case study is required to establish whether measures should be set up. It is necessary to evaluate the impact distances (the PTS perimeters at least), in particular by modelling the noise propagation and inventorying the species potentially present in order to quantify the level of impact. The avoidance, reduction and accompanying measures should then be adapted in function of this level.

The fact sheets are classified in function of the type of noise generated by the activity presented: impulsive noise (blue fact sheets) or continuous noise (green fact sheets).

On each fact sheet, next to the list of species exposed, there is a colour-coded scale to assess the risk for each species-group **in the event of direct exposure.**



These arrows show the exposure of each species-group to the noise-source concerned in function of their auditory abilities, in particular the frequencies they are capable of perceiving (and the breadth of the frequency-range in question) and noise-level at which they start to hear it.

The colours (red, orange, yellow and beige) therefore show the ability of species to perceive the frequencies emitted (red means that the corresponding species-group is likely to be highly exposed to the noise emitted by the source, because the frequencies emitted correspond to the range of frequencies perceived, whereas beige means that the species-group is little-exposed). The intensity of the colour (bright or pale) reflects the intensity of the noise perceived: the brighter the colour the more the noise-level emitted by the source is likely to be strongly perceived by the species-group concerned.

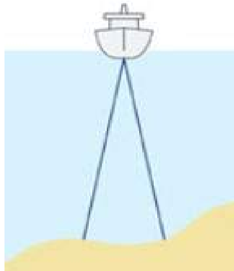
Index of fact sheets:

1. SINGLE-BEAM ECHO SOUNDER

DESCRIPTION

Device emitting sound waves in the marine environment and using their reflection by the seabed to measure water-depth, observe the water column, visualise the morphology of sea floor and characterise the surface nature of the substrate.

Single-beam echo sounders emit one narrow-angled beam vertically below the boat.



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APPLICATIONS

- Oil and Gas Industry
- Marine Renewable Energies
- Laying of cables and pipes
- Fishing
- Scientific/Research activities

GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	12-500 kHz (variable)
Expected L_S level (@ 1 m)	210 to 240 dB re 1 µPa
Duration of impulse	≤ 2 ms
Directionality	Vertical High (a few degrees)

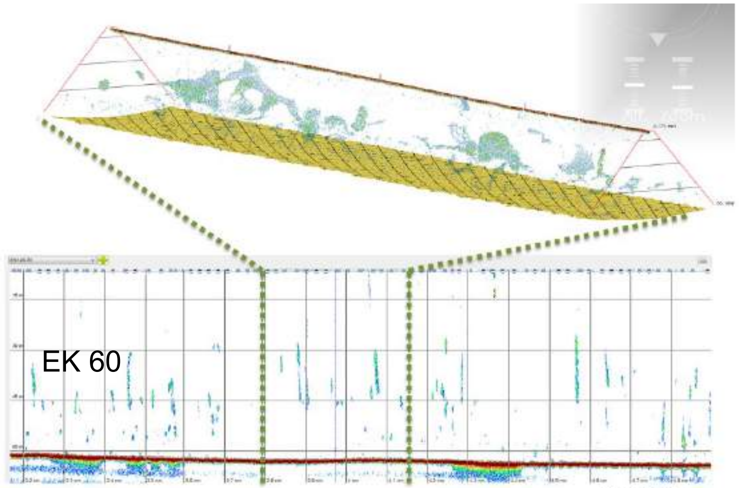
Main influential parameters:

- Maximum-energy frequency (the lower the frequency, the more the sound wave propagates over long distances)
- Directionality

EXAMPLE CASE STUDY

Observation conditions:

Type of sounder	Single-beam echo sounder Fishing **Simrad EK60-38**
Vessel	Oceanographic vessel



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Observations:

Type of emission	Impulsive
Nominal frequency	38 kHz
Maximum emission level (L_S @ 1 m)	231 dB re 1 µPa
Duration of impulse	0.25 – 4 ms
Emission directionality	7°

Source: IFREMER

1. SINGLE-BEAM ECHO SOUNDER

EXPOSED SPECIES

- Very high-frequency Cetaceans
- High-frequency Cetaceans
- Phocids
- Sirenians
- Other Carnivores
- Low-frequency Cetaceans (emissions <30 kHz)

POTENTIAL IMPACTS

Low probability of impact due to the high directionality of the beam emitted and low impulse duration: risks limited to the zone situated vertically below the sounder, close to the antenna.

High-frequency sounders (>100 kHz) are only perceptible to high-frequency and very high-frequency cetaceans. Sounders whose emissions are higher than 180 kHz are inaudible to all marine animals.

ASSESSMENT

No recommendation

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Limit utilisation	Use the device most suited to the objective, restrict spatial and temporal extent of utilisation to studied areas	++	p. 117
Limit emissions	Use the lowest possible power for the intended objective	++	p. 117

Impulsive Noise

2. MULTI-BEAM ECHO SOUNDER

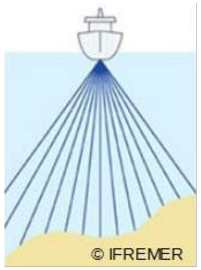
DESCRIPTION

Device emitting sound waves in the marine environment and using their reflection by the seabed to measure water-depth, visualise the morphology of seabeds and characterise the surface nature of the substrate.

Multi-beam echo sounders emit in several directions, with a wide beam spread angle in the transversal plane of the carrying vessel.

APPLICATIONS

- Oil and Gas Industry
- Marine Renewable Energies
- Laying of cables and pipes
- Fishing
- Scientific/Research activities

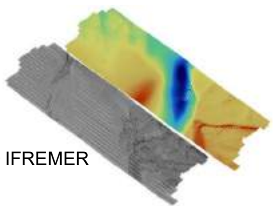


GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	10-500 kHz (variable)
Expected L_S level (@ 1 m)	210 to 240 dB re 1 µPa
Duration of impulse	A few ms
Directionality	High (longitudinal plane of carrying vessel)

Main influential parameters:

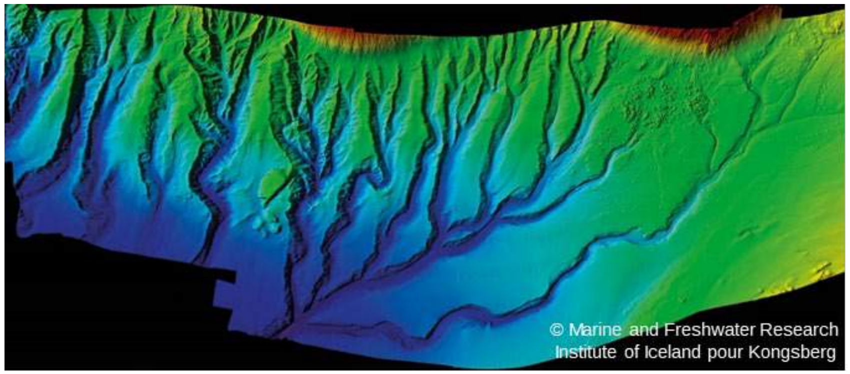
- Maximum-energy frequency (the lower the frequency, the more the sound wave propagates over long distances)
- Directionality



EXAMPLE CASE STUDY

Observation conditions:

Type of sounder	**Kongsberg EM304** multi-beam echo sounder
Vessel	Oceanographic vessel



Observations:

Type of emission	Impulsive
Nominal frequency	30 kHz
Bandwidth	26-34 kHz
Maximum emission level (L_S @ 1 m)	234 dB re 1 µPa
Duration of impulse	A few ms
Emission directionality	0.5° x 140°

Source: IFREMER

Impulsive Noise

2. MULTI-BEAM ECHO SOUNDER

EXPOSED SPECIES

- Very high-frequency Cetaceans
- High-frequency Cetaceans
- Phocids
- Sirenians
- Other Carnivores
- Low-frequency Cetaceans (emissions ≤ 30 kHz)

POTENTIAL IMPACTS

Low probability of impact due to the high directionality of the beam emitted and low impulse duration: risks limited to the zone situated vertically below the sounder, close to the antenna.

High-frequency sounders (> 100 kHz) are only perceptible to high-frequency and very high-frequency cetaceans. Sounders whose emissions are higher than 180 kHz are inaudible to marine animals.

ASSESSMENT

No recommendation

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Limit utilisation	Use the device most suited to the objective, restrict spatial and temporal extent of utilisation to studied areas	++	p. 117
Limit emissions	Use the lowest possible power for the intended objective	++	p. 117

Impulsive Noise

3. SEDIMENT ECHO SOUNDER

DESCRIPTION

Acoustic device emitting sound waves to characterise sediment layers to depths of several tens of metres.

APPLICATIONS

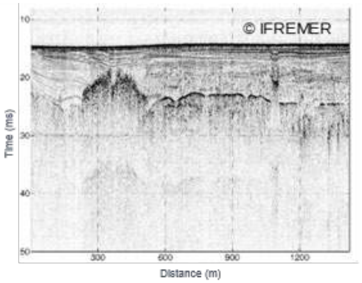
- Oil and Gas Industry
- Marine Renewable Energies
- Laying of cables and pipes
- Scientific/Research activities

GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	1-10 kHz (variable)
Expected L_S level (@ 1 m)	190 to 230 dB re 1 µPa
Duration of impulse	Several tens of ms
Directionality	High (vertical)

Main influential parameters:

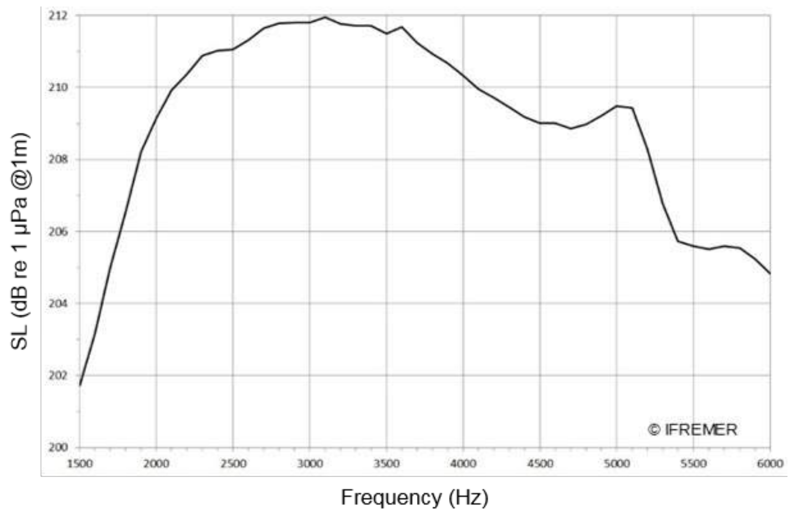
- Maximum-energy frequency (the lower the frequency, the more the sound wave propagates over long distances)
- Directionality



EXAMPLE CASE STUDY

Observation conditions:

Type of sounder	**IxBlue Echoes 3500** sediment echo sounder
Type of vessel	Oceanographic vessel



Observations:

Type of emission	Impulsive
Bandwidth	1.5-6.5 kHz
Max. energy frequency	3.1 kHz
Maximum emission level (L_S @ 1 m)	212 dB re 1 µPa
Duration of impulse	10 - 100 ms
Emission directionality	20 - 50°

Source: IFREMER

3. SEDIMENT ECHO SOUNDER

EXPOSED SPECIES

- Low-frequency Cetaceans
- High-frequency Cetaceans
- Very high-frequency Cetaceans
- Phocids
- Sirenians
- Other Carnivores
- Diving birds (emissions ≤ 6 kHz)
- Fish (emissions ≤ 3 kHz)
- Turtles (emissions ≤ 3 kHz)
- Crustaceans and Molluscs (emissions ≤ 3 kHz)

POTENTIAL IMPACTS

Low probability of impact due to the high directionality of the beam emitted and the low impulse durations: risks limited to the zone situated vertically below the sounder, close to the antenna.

Sediment sounders emitting at more than 3 kHz are only audible to marine mammals and, to a lesser extent, by diving birds (up to 6 kHz).

ASSESSMENT

No recommendation

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Limit utilisation	Use the device most suited to the objective, restrict spatial and temporal extent of utilisation to studied areas	++	p. 117
Limit emissions	Use the lowest possible power for the intended objective	++	p. 117

Impulsive Noise

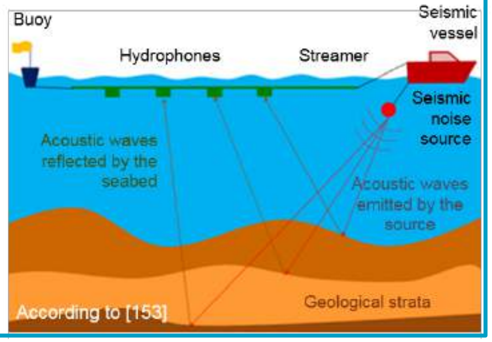
4. SEISMIC AIRGUN SURVEYING

DESCRIPTION

Technique emitting a high-intensity sound wave (using one or more airguns) in order to study its reflection and refraction by the various strata of the seabed to characterise its geological structure.

APPLICATIONS

- Oil and Gas Industry
- Marine Renewable Energies
- Laying of cables and pipes
- Fishing
- Scientific/Research activities



GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	5 Hz-15 kHz (10-100 Hz)
Expected Ls level (@ 1 m)	240 to 260 dB re 1 µPa ($L_{S,pk}$)
Duration of impulse	10-100 ms
Directionality	Low

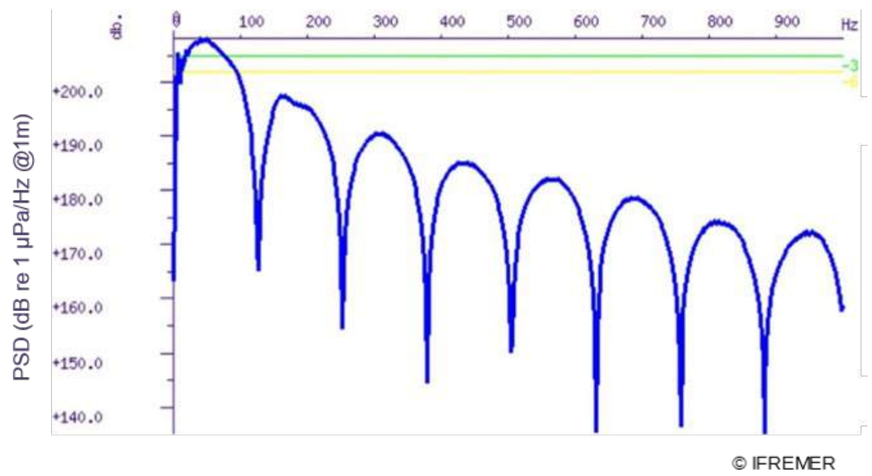
Main influential parameters:

- Volume of air contained in the gun
- Number of airguns
- Pressure exerted on the volume of air

EXAMPLE CASE STUDY (HEAVY SEISMIC SURVEY)

Observation conditions:

Context	IFREMER Multi-trace seismic survey
Type of airgun	GGUN airguns
Volume	2 570 in^3
Number of airguns	14



Observations:

Max. energy frequencies	< 100 Hz
Peak pressure	36.4 bar @ 1 m
Max. levels @ 1 m	$L_{S,pk}$: 251 dB re 1 µPa $L_{E,p}$: 229 dB re 1 µPa^{2}s
Firing interval	20 s

Source: IFREMER

Impulsive Noise

4. SEISMIC AIRGUN SURVEYING

EXPOSED SPECIES

- Low-frequency Cetaceans
- High-frequency and Very high-frequency Cetaceans
- Phocids and Other Carnivores
- Sirenians
- Fish
- Turtles
- Diving birds
- Crustaceans and Molluscs

POTENTIAL IMPACTS

Variable in function of source power

- PTS (tens even hundreds of metres)
- TTS (tens to hundreds of metres)
- Masking (distance unknown)
- Disturbance (several km)
- Indirect effects (fleeing of prey, loss of habitat, *etc.*)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Modelling to evaluate the impact distance for each species-group: **at least** determination of the scope of physiological damage (PTS)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	+++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	+++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
MMO – PAM surveillance + mitigation	Establishment of a safety zone with constant surveillance by MMOs + passive acoustic system = stop in the event of presence in the exclusion zone	++	p.124 to 129
Pre-watch and soft-start procedure	Observation before starting emissions and progressive increase in the sound-level of operations	+	p.125-127
Limit emissions	Use smallest possible source for the intended objective, restrict emissions to the studied area	+	p. 117

ACCOMPANY

Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, *etc.*	p. 134

Impulsive Noise

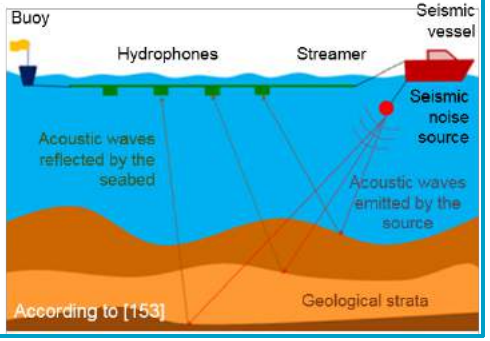
5. HIGH-RESOLUTION SEISMIC SURVEYS

DESCRIPTION

Technique emitting a high-intensity sound wave (using a low number airguns) in order to study its reflection and refraction by the various strata of the seabed to characterise its geological structure.

APPLICATIONS

- Oil and Gas Industry
- Marine Renewable Energies
- Laying of cables and pipes
- Scientific/Research activities



GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	5 Hz-15 kHz (10-100 Hz)
Expected Ls level (@ 1 m)	225 to 240 dB re 1 µPa ($L_{S,pk}$)
Duration of impulse	10-100 ms
Directionality	Low

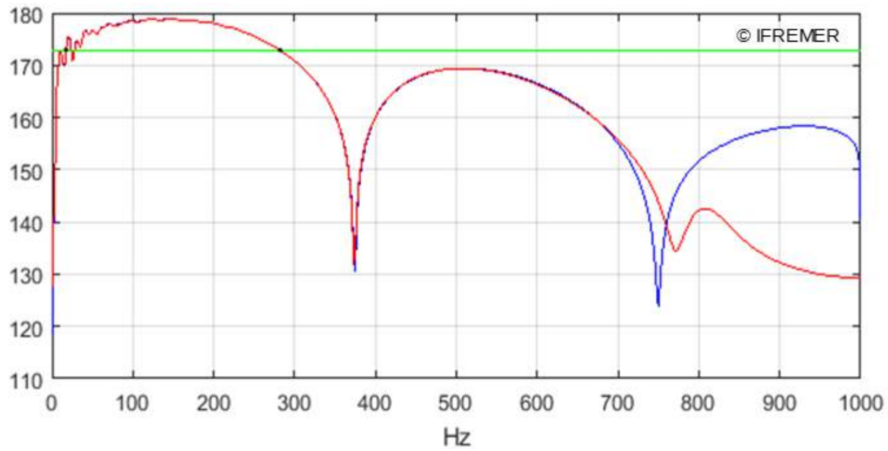
Main influential parameters:

- Volume of air contained in the gun
- Number of airguns
- Pressure exerted on the volume of air

EXAMPLE CASE STUDY (HIGH-RESOLUTION SEISMIC SURVEY)

Observation conditions:

Context	IFREMER HR Seismic Survey
Type of airgun	Mini-GI airguns
Volume	96 in^3
Number of airguns	2



Observations:

Max. energy frequencies	< 100 Hz
Peak pressure	4.3 bar @ 1 m
Max. levels @ 1 m	$L_{S,pk}$: 233 dB re 1 µPa $L_{E,p}$: 206 dB re 1 µPa^{2}s
Firing interval	6 s

Source: IFREMER

5. HIGH-RESOLUTION SEISMIC SURVEYS

EXPOSED SPECIES

- Low-frequency Cetaceans
- High-frequency and Very high-frequency Cetaceans
- Phocids and Other Carnivores
- Sirenians
- Fish
- Turtles
- Diving birds
- Crustaceans and Molluscs

POTENTIAL IMPACTS

Impacts more limited than with heavy seismic surveys and variable in function of source power

- PTS (from a few to several tens of metres)
- TTS (< 50 m)
- Masking (distance unknown)
- Disturbance (several km)
- Indirect effects (fleeing of prey, loss of habitat, *etc.*)
  - Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Modelling to evaluate the impact distance for each species-group: **at least** determination of the scope of physiological damage (PTS)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	+++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	+++	p. 111 to 113

REDUCE

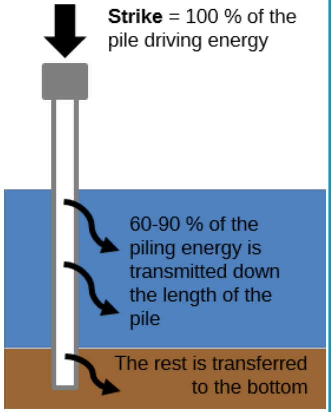
Measure	Description	Efficacy	Page
Limit utilisation	Use the device most suited to the objective, restrict spatial and temporal extent of utilisation to studied areas	+	p. 117
Limit emissions	Use the lowest possible power for the intended objective	++	p. 117

Impulsive Noise

6. HYDRAULIC PILE DRIVING

DESCRIPTION

Process of driving a generally metallic pile into the substrate by means of a single hydraulic hammer.



From [6]

APPLICATIONS

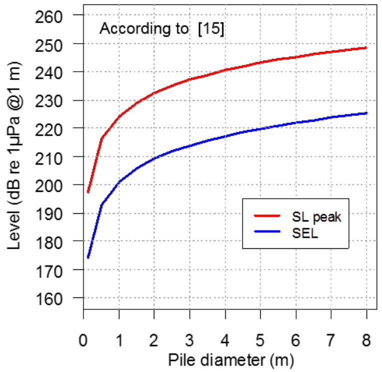
- Oil and Gas Industry
- Marine Renewable Energies
- Coastal works and development
- Laying of cables and pipes (setting up of drilling rigs)

GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	10 Hz-20 kHz (100-1,000 Hz)
Expected Ls level (@ 1 m)	200-250 dB re 1 µPa
Duration of impulse	A few milliseconds
Directionality	Omnidirectional

Main influential parameters:

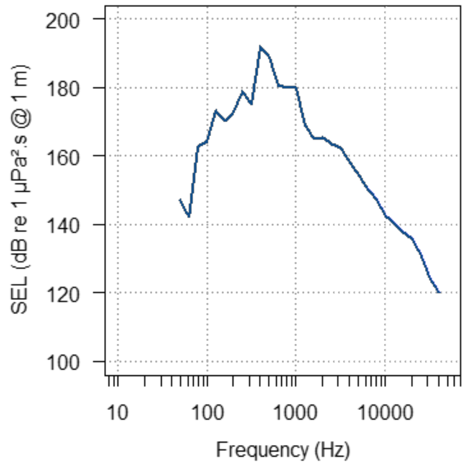
- Pile diameter
- Seabed-type
- Bathymetry
- Driving depth
- Hammer-type and energy transmitted
- Driving rate



EXAMPLE CASE STUDY

Observation conditions:

Pile diameter	1.22 m
Seabed-type	Silt + rock
Bathymetry	10 m on average
Driving depth	6 m
Hammer-type and energy transmitted	IHC-S70 hydraulic hammer Net max. energy / strike: 70 kJ Weight of hammer head: 3.5 t Weight of hammer: 8.3 t
Driving rate	Max. 50 strikes/min



Observations:

Max. energy frequency	400 Hz
Max. levels @ 1 m	$L_{S,pk}$: 207 dB re 1 µPa $L_{E,p}$: 192 dB re 1 µPa².s
Impulse duration observed	80 ms

Impulsive Noise

6. HYDRAULIC PILE DRIVING

EXPOSED SPECIES

Low-frequency Cetaceans
Phocids and Other Carnivores
High-frequency and Very High-frequency Cetaceans
Sirenians
Fish
Turtles
Crustaceans and Molluscs
Diving birds

POTENTIAL IMPACTS

Variable in function of source power

- PTS (tens even hundreds of metres)
- TTS (tens to hundreds of metres)
- Masking (several km)
- Disturbance (several km)
- Indirect effects (fleeing of prey, loss of habitat, *etc.*)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Modelling to evaluate the impact distance for each species-group: **at least** determination of the scope of physiological damage (PTS)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	+++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	+++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Bubble curtains, isolation casings, etc.	Use equipment that reduces source-noise	+++	p. 122 to 123
MMO – PAM surveillance + mitigation	Establishment of a safety zone with constant surveillance by MMOs + passive acoustic system = stop in the event of presence in the exclusion zone	++	p. 124 to 129
Soft-start procedure	Progressive increase in the sound-level of works operations	+	p. 126-127
Alternative methods	Use alternative methods (vibratory pile driving, drilling) Choose other foundations (EMR), reduce pile diameter	/	p. 119

ACCOMPANY

Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p. 134

Impulsive Noise

7. UNDERWATER ROCK BLASTING

DESCRIPTION

Process of fragmenting a rock substrate using explosives, then excavating the debris

APPLICATIONS

- Oil and Gas Industry
- Marine Renewable Energies (dismantlement)
- Coastal works and development

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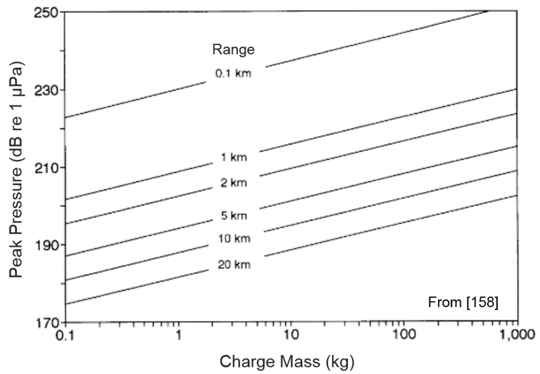
GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	2 Hz-1 kHz (< 500 Hz)
Expected LS level (@ 1 m)	250 to 300+ dB re 1 µPa
Duration of impulse	A few ms
Directionality	Omnidirectional

Main influential parameters:

- Explosive charge
- Number of charges
- Burial of charges/ depth of burial
- Type of rock
- Bathymetry

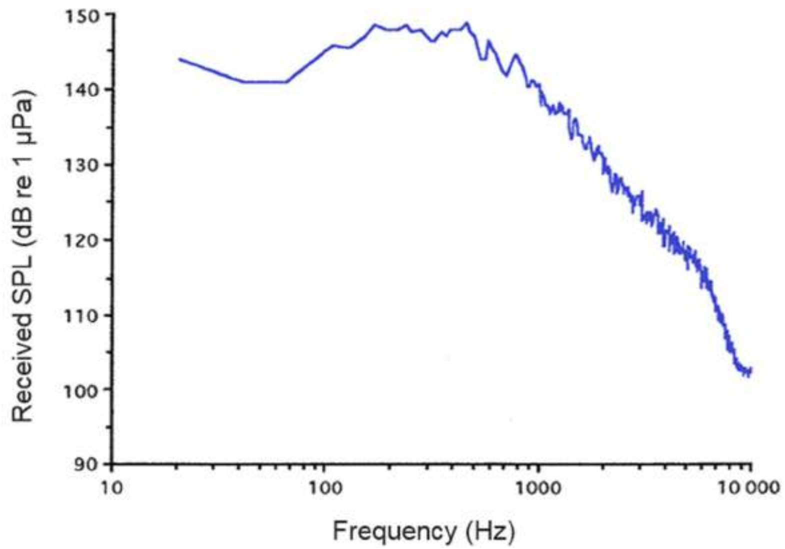


From [158]

EXAMPLE CASE STUDY

Observation conditions:

Type of explosive	Tovex™
Explosive charge	1,510 kg
Type of seabed	Rocky
Charge burial depth	Between 3 and 10 m
Bathymetry	Approximately 15 m



Observations:

Max. energy frequency	456 Hz
Max. level @ 1835 m	$L_{S,pk}$: 149 dB re 1 µPa
Max. level @ 1 m	$L_{S,pk}$: 214 dB re 1 µPa

According to [174]

7 - UNDERWATER ROCK BLASTING

Impulsive Noise

7. UNDERWATER ROCK BLASTING

EXPOSED SPECIES

Low-frequency Cetaceans
Phocids
Other Carnivores
Very high-frequency Cetaceans
High-frequency Cetaceans
Sirenians
Fish
Turtles
Crustaceans and Molluscs
Diving birds

POTENTIAL IMPACTS

Variable in function of expected noise level

- PTS (from tens of metres to several km)
- TTS (from tens of metres to several km)
- Masking (?)
- Disturbance (several km)
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Modelling to evaluate the impact distance for each species-group: **at least** determination of the scope of physiological damage (PTS)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	+++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	+++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Bubble curtains, isolation casings, etc.	Use equipment that reduces source-noise	+++	p. 122-123
MMO – PAM surveillance + mitigation	Establishment of a safety zone with constant surveillance by MMOs + passive acoustic system = stop in the event of presence in the exclusion zone	++	p. 124 to 129
Pre-watch and ramp-up procedure	Observation before starting emissions and progressive increase in the sound-level of operations	+	p. 125 to 127

ACCOMPANY

Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p. 134

Impulsive Noise

8. ACOUSTIC DETERRENT DEVICES (PINGERS)

DESCRIPTION

Acoustic deterrents (pingers) are small devices that emit a high-frequency impulsive signal to keep marine mammals away from fishing boats, fish farms or potentially dangerous activities.

APPLICATIONS

- Fishing
- Marine Renewable Energies
- Oil and Gas Industry
- Coastal works and development
- Scientific/Research activities

GENERAL CASE

Type of emission	Impulsive
Bandwidth (max. energy)	5-160 kHz (variable according to target species)
Expected LS level (@ 1 m)	130 to 200 dB re 1 µPa
Duration of impulse	< 2 s
Directionality	Variable

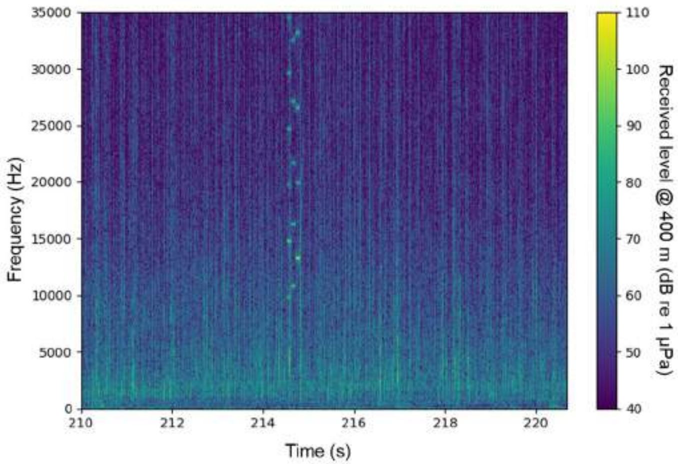
Main influential parameters:

The choice of frequency/ frequencies and emission level depend on the reason for using the deterrent and the species of marine mammals it is intended to repel.

EXAMPLE CASE STUDY

Observation conditions:

Type de deterrent	Dolphin/porpoise deterrent
Brand and model	AQUATEC Aquamark 210
Depth of immersion	2 m
Bathymetry	10 m
Type of emission	Random with variable frequency modulations (5 to 160 kHz) and impulse duration (50-300 ms)



Observations:

Max. energy	Variable
Maximum emission levels @ 1 m	$L_{S,pk}$: 148 dB re 1 µPa $L_{E,p}$: 143 dB re 1 µPa².s
Duration of observed impulse	300 ms

Impulsive Noise

8. ACOUSTIC DETERRENT DEVICES (PINGERS)

EXPOSED SPECIES

Variable in function of target species

High-frequency and Very high-frequency Cetaceans
Phocids
Sirenians
Other Carnivores
Low-frequency Cetaceans
Diving birds

POTENTIAL IMPACTS

- TTS
- Masking
- Disturbance (several km)
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

Since acoustic deterrent devices are deliberately set up to drive away certain species, their utilisation is not generally combined with prior assessment.

In the case where these deterrents are used to secure a zone (in the framework of high-impact works), it is nonetheless important to evaluate their efficacy (modelling of noise footprint, assessment of the number of deterrents required, etc.).

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Restrict utilisation	Use the device most suited to the objective, restrict spatial and temporal extent of utilisation	++	p. 117

ACCOMPANY

Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p. 134

Continuous noise

9. DRILLING

DESCRIPTION

Technique for boring a shaft in the ocean floor, either to access an oil or gas field or to insert a pile.

APPLICATIONS

- Oil and Gas Industry
- Marine Renewable Energies
- Coastal works and development
- Laying of cables and pipes

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	10 Hz - 10 kHz (10-1,000 Hz)
Expected level (@ 1 m)	120 to 190 dB re 1 µPa/√Hz
Directionality	Omnidirectional

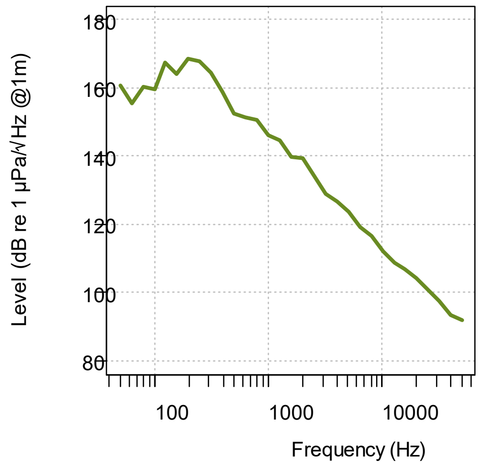
Main influential parameters:

- Type of rig: fixed, floating or mobile platform
- Type of rock
- Diameter of drilling column
- Depth

EXAMPLE CASE STUDY

Observation conditions:

Drilling system	Symmetrix (enables drilling in loose and/or unstable sediments)
Nature du fond	Silt + rock
Type of rig	On-land platform
Diameter of drilling column	0.9 m
Rotation speed	15 rpm on average
Drilling depth	5 m
Bathymetry	13 m



Observations:

Maximum energy frequency	200 Hz
Maximum level @ 1 m	168 dB re 1 µPa/√Hz

Continuous noise

9. DRILLING

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids and Other Carnivores
- High-frequency and Very high-frequency Cetaceans
- Sirenians
- Fish
- Turtles
- Crustaceans and Molluscs
- Diving birds

POTENTIAL IMPACTS

Variable in function of expected noise level

- PTS (a few metres)
- TTS (some tens of metres)
- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Modelling to evaluate the impact distance for each species-group: **at least** determination of the scope of physiological damage (PTS)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Bubble curtains, isolation casings, etc.	Use equipment that reduces source-noise	+++	p. 122-123
MMO – PAM surveillance + mitigation	Establishment of a safety zone with constant surveillance by MMOs + passive acoustic system = stop in the event of presence in the exclusion zone	++	p. 124 to 129
Pre-watch and soft-start procedure	Observation before starting emissions and progressive increase in the sound-level of operations	+	p. 125 to 127

ACCOMPANY

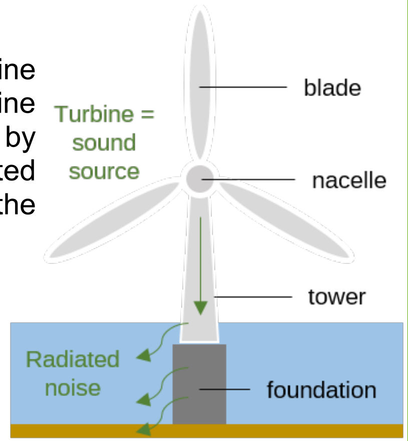
Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p. 134

Continuous noise

10. WORKING (FIXED-FOUNDATION) WIND TURBINE

DESCRIPTION

A (fixed-foundation) offshore wind turbine transmits noise into the marine environment: the vibrations created by the turbine at the nacelle are propagated via the mast and foundations into the water column and sediments.



APPLICATIONS

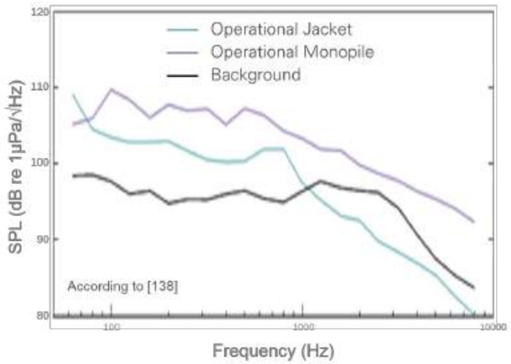
MREs

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	50 Hz - 2 kHz (< 500 Hz)
Expected level (@ 1 m)	120-150 dB re 1 µPa/√Hz
Directionality	Omnidirectional

Main influential parameters:

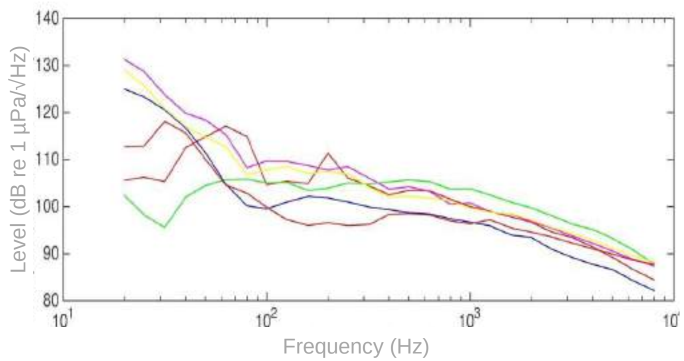
- Type of foundation (gravity base < jacketed < monopile)
- Wind speed
- Unit power of turbines



EXAMPLE CASE STUDY

Observation conditions:

Location	C-Power Parc offshore windfarm (Thorntonbank, Belgium)
Type de foundation	Jacketed (4 piles)
Unit power of turbines	5 and 6 MW
Number of turbines	54 (325 MW in total)
Bathymetry	30 m on average
Wind speed	10 m/s
Sea state	1 to 2-3



Observations (average of 5 recordings):

Maximum energy frequency	20-500 Hz
Maximum level @ 1 m	133 dB re 1 µPa/√Hz

According to [139]

Continuous noise

10. WORKING (FIXED-FOUNDATION) WIND TURBINE

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids
- Other Carnivores
- High-frequency and Very high-frequency Cetaceans
- Sirenians
- Fish
- Turtles
- Crustaceans and Molluscs
- Diving birds

POTENTIAL IMPACTS

Impacts still little-known

- Masking?
- Disturbance?
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Limit vibrations	Choose materials and foundations that reduce vibrations when working	+	p. 116-117 p. 119
Encourage the circulation of animals	Consider how to set up the windfarm in such a way as to avoid creating a barrier effect	/	p. 117

ACCOMPANY

Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p. 134
Encourage colonisation of the foundations (reef effect) and regulate fishing activities in the windfarm area (reserve effect)	p. 134

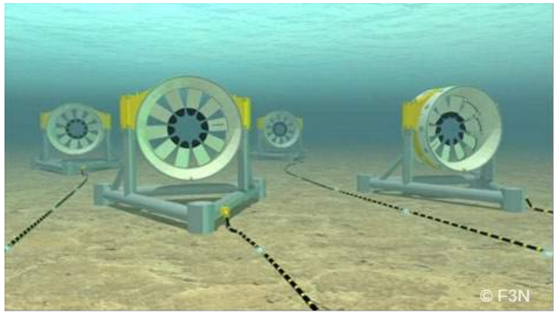
Continuous noise

11. WORKING MARINE CURRENT TURBINE

DESCRIPTION

An immersed turbine that produces electricity from marine currents.

The whole structure therefore emits noise directly into the le marine environment.



APPLICATIONS

- CMREs

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	10 Hz - 3 kHz (< 500 Hz)
Expected level (@ 1 m)	150-165 dB re 1 µPa/√Hz
Directionality	Omnidirectional

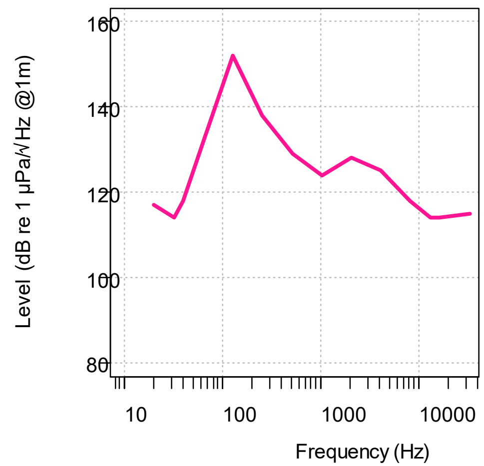
Main influential parameters:

- Current speed
- Unit power of turbines

EXAMPLE CASE STUDY

Observation conditions:

Type of marine current turbine	Arcouest turbine (OpenHydro)
Turbine power	2.2 MW
Bathymetry	From 40 to 50 m
Substrate	Rocky
Weather conditions	Wind: 6 to 8 knots Sea state < 2 Beaufort
Current measured	Between 0.69 and 1.66 m/s



Observations:

Maximum energy frequency	128 Hz
Maximum level @ 1 m	152 dB re 1 µPa/√Hz

According to [107]

Continuous noise

11. WORKING MARINE CURRENT TURBINE

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids
- Other Carnivores
- High-frequency and Very high-frequency Cetaceans
- Sirenians
- Fish
- Turtles
- Crustaceans and Molluscs
- Diving birds

POTENTIAL IMPACTS

Impacts still little-known

- Masking?
- Disturbance?
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technology and maintenance	Reduction of noise generated by the vanes: biofouling, cavitation, rotation speed, etc.	++	p. 118
Encourage the circulation of animals	Consider how to set up the turbines in such a way as to avoid creating a barrier effect	/	p. 117

ACCOMPANY

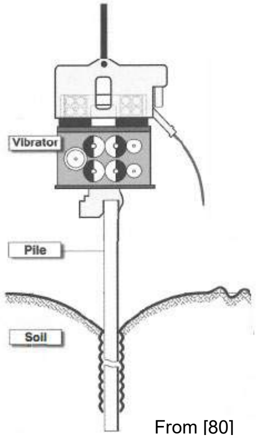
Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p.134

Continuous noise

12. VIBRATORY PILE DRIVING

DESCRIPTION

Technique for driving a pile or sheet pile into the substrate through oscillation transmitted by means of a vibratory hammer.



From [80]

APPLICATIONS

- Coastal works and development
- Oil and Gas Industry
- Marine Renewable Energies
- Laying of cables and pipes

GENERAL CASE

Type of emission	Continuous and impulsive
Bandwidth (max. energy)	10 Hz - 50 kHz (25-2 000 Hz)
Expected level (@ 1 m)	165-185 dB re 1 µPa/√Hz
Duration of impulse	A few tens of ms
Directionality	Omnidirectional

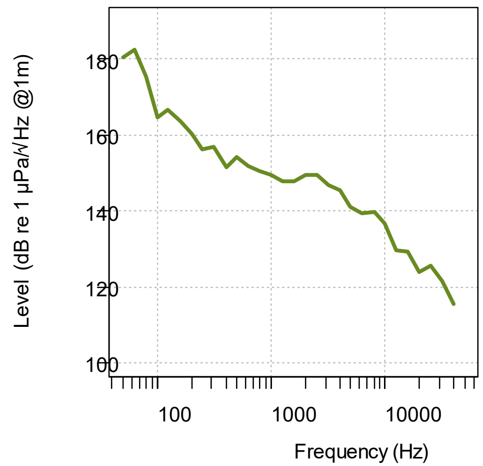
Main influential parameters:

- Type of substrate
- Diameter/size of pile/sheet pile
- Burial depth
- Bathymetry
- Type of hammer and energy transmitted
- Vibration frequency

EXAMPLE CASE STUDY

Observation conditions:

Pile diameter	1.22 m
Seabed type	Silt + rock
Bathymetry	Approximately 10 m
Type and characteristics of vibratory hammer	ICE vibratory hammer, model 416 L Hydraulic power = 209 kW Max. centrifugal force = 646 kN Dynamic weight = 2 350-2 840 kg
Vibration frequency	1,080 rpm (max = 1600 rpm)



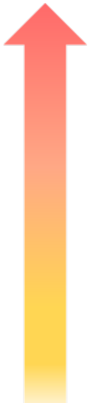
Observations:

Maximum energy frequency	63 Hz
Maximum level @ 1 m	182 dB re 1 µPa/√Hz
Duration of impulse observed	30 ms

Continuous noise

12. VIBRATORY PILE DRIVING

EXPOSED SPECIES



Low-frequency Cetaceans
Phocids
Other Carnivores
Very high-frequency Cetaceans
High-frequency Cetaceans
Sirenians
Fish
Turtles
Crustaceans and Molluscs
Diving birds

POTENTIAL IMPACTS

Variable in function of expected noise level

- PTS and TTS possible for certain categories of species (Low-frequency Cetaceans, Phocids, certain fish)
- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Modelling to evaluate the impact distance for each species-group: **at least** determination of the scope of physiological damage (PTS)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
MMO – PAM surveillance + mitigation	Establishment of a safety zone with constant surveillance by MMOs + passive acoustic system = stop in the event of presence in the exclusion zone	++	p. 124 to 129
Soft-start procedure	Progressive increase in the sound-level of works operations	+	p. 126-127

ACCOMPANY

Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p. 134

Continuous noise

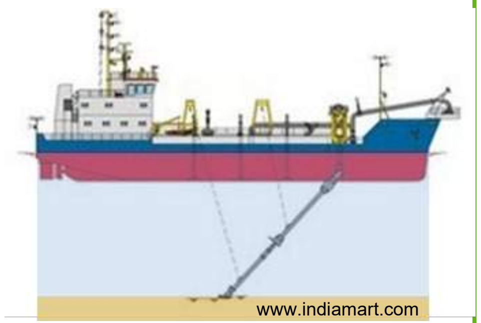
13. DREDGING BY TRAILING SUCTION HOPPER DREDGER

DESCRIPTION

Dredging by trailing suction hopper dredger (TSHD) consists in removing shallow sediments into a vessel using a drag head fitted to a pump, which sucks up the sediment.

APPLICATIONS

- Port activities
- Extraction of aggregates
- Marine Renewable Energies
- Laying of cables and pipes



GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	30 Hz - 20 kHz (100-500 Hz)
Expected level (@ 1 m): - Dredging phase - Discharge phase - In transit	 150-190 dB re 1 μPa/√Hz 154-175 dB re 1 μPa/√Hz ~ 170 dB re 1 μPa/√Hz
Directionality	Omnidirectional

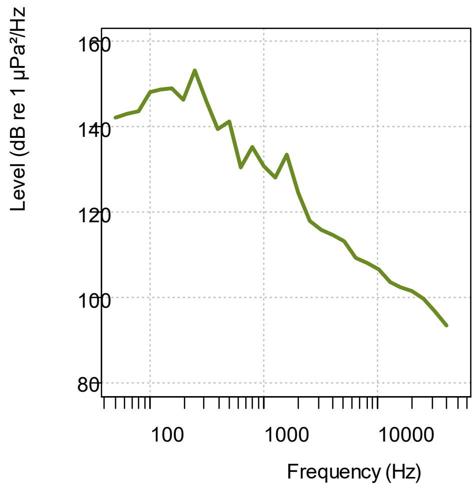
Main influential parameters:

- Type of engine
- Type of substrate
- Speed of vessel

EXAMPLE CASE STUDY

Observation conditions:

Type of dredger	Trailing suction hopper dredger with drag head
Size of vessel	117 m
Type of engine	Diesel-electric
Type of substrate	Vase
Phase recorded	Dredging
Speed of vessel	2 to 4 knots
Bathymetry	More than 15 m



Observations:

Maximum energy frequency	200 Hz
Maximum level @ 1 m	153 dB re 1 μPa²/Hz

Continuous noise

13. DREDGING BY TRAILING SUCTION HOPPER DREDGER

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids
- Other Carnivores
- Very high-frequency Cetaceans
- High-frequency Cetaceans and Sirenians
- Fish
- Turtles
- Diving birds
- Crustaceans and Molluscs

POTENTIAL IMPACTS

Variable in function of vessel, technique and operating phase

- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

- List of potentially impacted species and frequentation of the study area (seasonality)
- Importance of the area for species-and species-groups
- Existence of alternative areas?
- Combination with other pressures

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technical improvements	Design of hull, propeller, engine, etc. Reduction of cavitation phenomena and vibrations	++	p. 117-118
Adaptation	Reduce the speed of vessels in transit	++	p. 118

ACCOMPANY

Measure	Page
Acquisition of further knowledge, restoration of habitats, awareness-raising actions, etc.	p. 134

Continuous noise

14. COASTAL FISHING BOAT (< 12 m)

DESCRIPTION

Fishing boats generate underwater noise mainly through their machinery (engine, generator, accessories) and propulsion system (particularly propeller). Electrical interference and the use of echosounder(s) also contribute to the acoustic signature of fishing vessels.

Their cruising speed is generally about 10 knots.

APPLICATIONS

- Fishing
- Scientific/Research activities

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	10 Hz - 20 kHz (100 Hz - 2 kHz)
Expected level (@ 1 m)	130-160 dB re 1 µPa/√Hz
Directionality	Omnidirectional

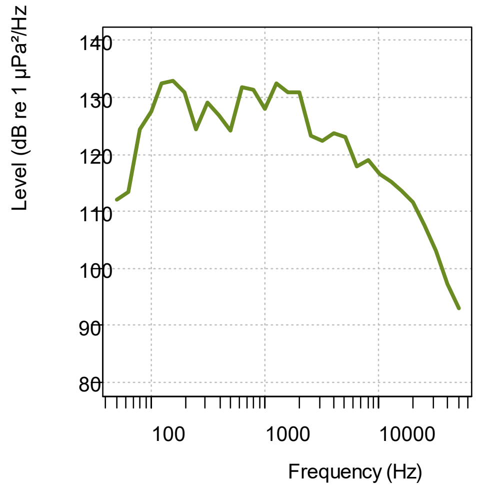
Main influential parameters:

- Size of vessel
- Characteristics of engine and propulsion system
- Speed of vessel
- Age and upkeep of vessel
- Type of hull

EXAMPLE CASE STUDY

Observation conditions:

Type of fishing boat	Trawler
Engine power	242 kW
Size du Vessel	11,98 m
Speed of vessel	Approximately 7 knots
Type of hull	Polyester
Year of construction	1989



Observations:

Maximum energy frequency	125, 160 and 250 Hz
Maximum level @ 1 m	133 dB re 1 µPa²/Hz

14 - COASTAL FISHING BOAT (< 12 M)

Continuous noise

14. COASTAL FISHING BOAT (< 12 M)

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids
- Other Carnivores
- High-frequency and Very high-frequency Cetaceans
- Sirenians
- Fish
- Turtles
- Crustaceans and Molluscs
- Diving birds

POTENTIAL IMPACTS

Variable in function of vessel and speed

- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

No recommendation

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technical improvements	Design of hull, propeller, engine, etc. Reduction of cavitation phenomena and vibrations	++	p.117-118
Adaptation	Reduce sailing speed	++	p.118

ACCOMPANY

Measure	Page
Acquisition of further knowledge and development of new practices	p. 117 to 119 p. 134

Continuous noise

15. SUPPORT VESSEL

DESCRIPTION

The category of support vessels covers all the relatively small vessels (< 50 m) involved in operating ports, marine safety and security, transporting teams to offshore worksites, checking MRE facilities, etc.

These vessels are fitted with inboard engines. Their cruising speed varies between 8 and 25 knots.

APPLICATIONS

- Port activities
- MREs
- Maritime traffic

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	1 Hz - 20 kHz (< 1 000 Hz)
Expected level (@ 1 m)	150-180 dB re 1 µPa/√Hz
Directionality	Omnidirectional

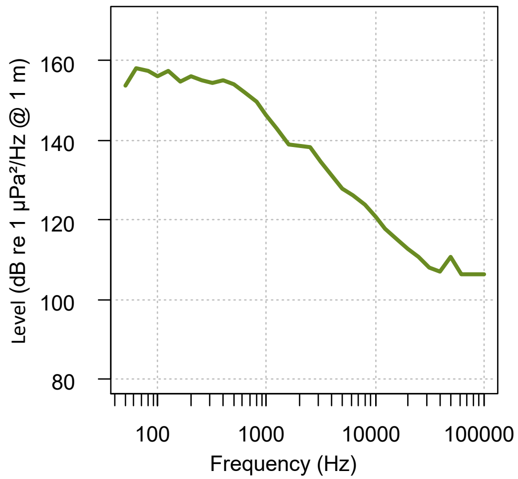
Main influential parameters:

- Size du Vessel
- Characteristics of engine and propulsion system
- Speed of vessel
- Type of hull

EXAMPLE CASE STUDY

Observation conditions:

Type of vessel	Multi-purpose works vessel
Type of propulsion	2 x 1,140 kW
Size of vessel	34 m
Speed of vessel	4 knots
Year of construction	2015



Observations:

Maximum energy frequency	63 Hz
Maximum level @ 1 m	158 dB re 1 µPa²/Hz

Continuous noise

15. SUPPORT VESSEL

EXPOSED SPECIES

Low-frequency Cetaceans
Phocids and Other Carnivores
High-frequency and Very high-frequency Cetaceans
Sirenians
Fish
Turtles
Crustaceans and Molluscs
Diving birds

POTENTIAL IMPACTS

Variable in function of vessel and speed

- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

Currently no particular recommendation. Nonetheless, an assessment of potential impacts (list of species present, frequentation of the area, modelling of impact zones) could be recommended in areas of high ecological importance (marine protected areas, spawning and feeding grounds, nurseries).

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technical improvements	Design of hull, propeller, engine, etc. Reduction of cavitation phenomena and vibrations	++	p. 117-118
Adaptation	Reduce sailing speed	++	p. 118

ACCOMPANY

Measure	Page
Acquisition of further knowledge and development of new practices	p. 117 to 119 p. 134

Continuous noise

16. COMMERCIAL VESSEL (> 100 M)

DESCRIPTION

Large commercial vessels (> 100 m) include container ships, oil tankers and supertankers, bulk freighters and cruise ships. These types of vessels contribute significantly to global ambient underwater noise.

Such vessels are characterised by low- and very low-frequency sound emissions and a cruising speed between 10 and 20 knots.

APPLICATIONS

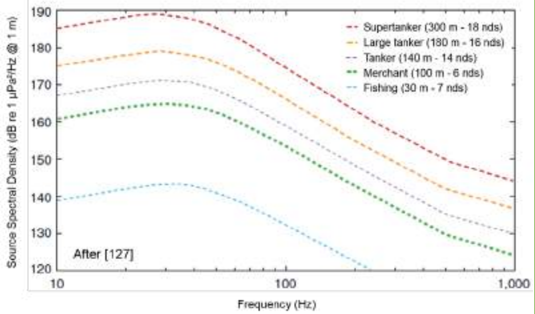
- Maritime traffic
- Port activities

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	1 Hz - 10 kHz (< 500 Hz)
Expected level (@ 1 m)	170-190 dB re 1 µPa/√Hz
Directionality	Omnidirectional

Main influential parameters:

- Size of vessel
- Characteristics of engine and propulsion system
- Speed of vessel
- Age and upkeep of vessel
- Loading weight

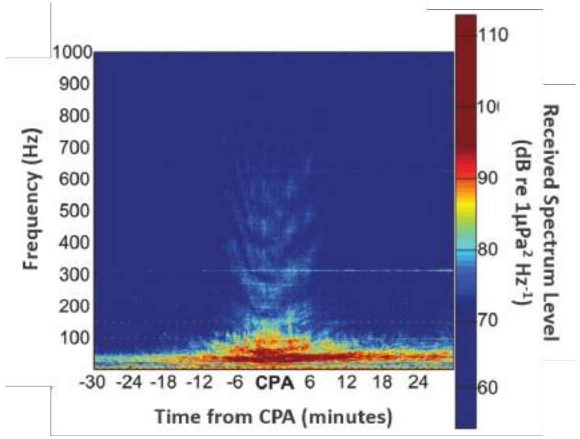


EXAMPLE CASE STUDY

Observation conditions:

Type of vessel	Oil Tanker
Size of vessel	228 m
Engine power	13,500 kW
Tonnage	42,514 t
Speed of vessel	15 knots
Year of construction	2007
Distance/recorder (CPA*)	3,100 m

*CPA: *Closest Point of Approach* (between the recorder and the vessel)



Observations:

Maximum energy frequency	< 100 Hz
Maximum level @ 1 m	183 dB re 1 µPa²/Hz

According to [117]

Continuous noise

16. COMMERCIAL VESSEL (> 100 M)

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids
- Other Carnivores
- High-frequency and Very high-frequency Cetaceans
- Sirenians
- Fish
- Turtles
- Crustaceans and Molluscs
- Diving birds

POTENTIAL IMPACTS

Variable in function of vessel and speed

- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

Currently no particular recommendation. Nonetheless, an assessment of potential impacts (list of species present, frequentation of the area, modelling of impact zones) could be recommended in areas of high ecological importance (marine protected areas, spawning and feeding grounds, nurseries).

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technical improvements	Design of hull, propeller, engine, etc. Reduction of cavitation phenomena and vibrations	++	p. 117-118
Adaptation	Reduce sailing speed	++	p. 118

ACCOMPANY

Measure	Page
Acquisition of further knowledge and development of new practices	p. 117 to 119 p. 134

Continuous noise

17. HIGH-SPEED CRAFT

DESCRIPTION

High-speed craft (HSC) are vessels generally used to transport passengers over short distances (Channel crossings, Corsica-Mainland France, etc.).

Their maximum speed is generally between 30 and 40 knots.

APPLICATIONS

- Maritime traffic (Passenger transport)

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	1 Hz - 25 kHz (< 200 Hz)
Expected level (@ 1 m)	150-200 dB re 1 µPa/√Hz
Directionality	Omnidirectional

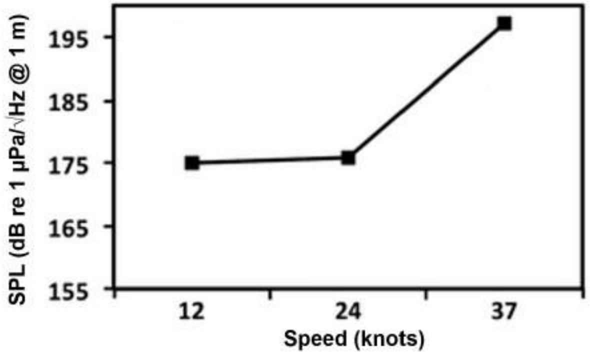
Main influential parameters:

- Size of vessel
- Characteristics of engine and propulsion system
- Speed of vessel
- Type of hull

EXAMPLE CASE STUDY

Observation conditions:

Type of vessel	Passenger and vehicle transporter
Type de propulsion	Hydrojets (4 x 8,200 kW)
Size of vessel	110 m
Observed speeds	12, 24 and 37 knots
Type of hull	Aluminium
Year of construction	2007



Observations:

Maximum energy frequency	< 100 Hz
Maximum level @ 1 m	197 dB re 1 µPa/√Hz at 37 knots

Continuous noise

17. HIGH-SPEED CRAFT

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids
- Other Carnivores
- High-frequency and Very high-frequency Cetaceans
- Sirenians
- Fish
- Turtles
- Crustaceans and Molluscs
- Diving birds

POTENTIAL IMPACTS

- TTS
- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

Currently no particular recommendation. Nonetheless, an assessment of potential impacts (list of species present, frequentation of the area, modelling of impact zones) could be recommended in areas of high ecological importance (marine protected areas, spawning and feeding grounds, nurseries).

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technical improvements	Design of hull, propeller, engine, etc. Reduction of cavitation phenomena and vibrations	++	p. 117-118
Adaptation	Reduce sailing speed	++	p. 118

ACCOMPANY

Measure	Page
Acquisition of further knowledge and development of new practices	p. 117 to 119 p. 134

Continuous noise

18. OUTBOARD-ENGINE PLEASURE BOAT (< 12 M)

DESCRIPTION

Pleasure boats equipped with outboard engines generate underwater noise, mainly connected to cavitation phenomena (bubbles) due to their propulsion system.

APPLICATIONS

- Recreational activities
- Scientific/Research activities

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	10 Hz - 20 kHz (100 Hz - 1 kHz)
Expected level (@ 1 m)	135-175 dB re 1 µPa/√Hz
Directionality	Omnidirectional

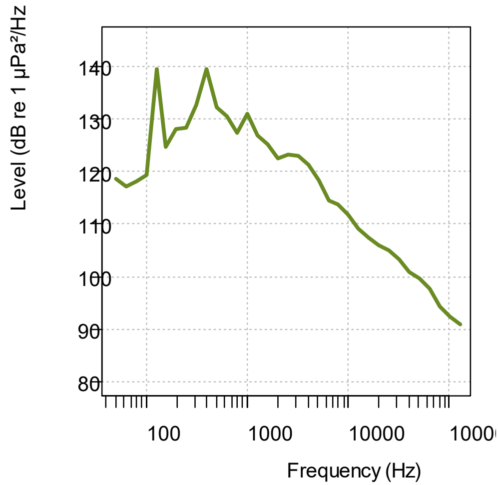
Main influential parameters:

- Size of vessel
- Speed of vessel
- Characteristics of engine and propulsion system
- Type of hull

EXAMPLE CASE STUDY

Observation conditions:

Type of vessel	Diving club boat
Engine power	Yamaha 150 hp engine
Size of vessel	8 m
Speed of vessel	Approximately 10 knots
Type of hull	Aluminium



Observations:

Maximum energy frequency	125 et 400 Hz
Maximum level @ 1 m	139 dB re 1 µPa²/Hz

Continuous noise

18. OUTBOARD-ENGINE PLEASURE BOAT (< 12 M)

EXPOSED SPECIES

- Low-frequency Cetaceans
- Phocids
- Other Carnivores
- High-frequency and Very high-frequency Cetaceans
- Sirenians
- Fish
- Turtles
- Crustaceans and Molluscs
- Diving birds

POTENTIAL IMPACTS

- **Variable in function of vessel and speed**
- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

No recommendation

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technical improvements	Design of hull, propeller, engine, etc. Reduction of cavitation phenomena and vibrations	++	p. 117-118
Adaptation	Reduce sailing speed	++	p. 118

ACCOMPANY

Measure	Page
Acquisition of further knowledge and development of new practices	p. 117 to 119 p. 134

Continuous noise

19. PERSONAL WATERCRAFT

DESCRIPTION

Personal watercraft (sea scooters) generate underwater noise mainly due to the bubbles formed by the waterjet propulsion system and rotation of the turbine blades (cavitation phenomena).

Their maximum speed is generally around 40 knots (up to 70 knots for competition vessels).

APPLICATIONS

- Recreational activities

GENERAL CASE

Type of emission	Continuous
Bandwidth (max. energy)	100 Hz - 10 kHz (< 2,000 Hz)
Expected level (@ 1 m)	120-190 dB re 1 µPa/√Hz
Directionality	Omnidirectional

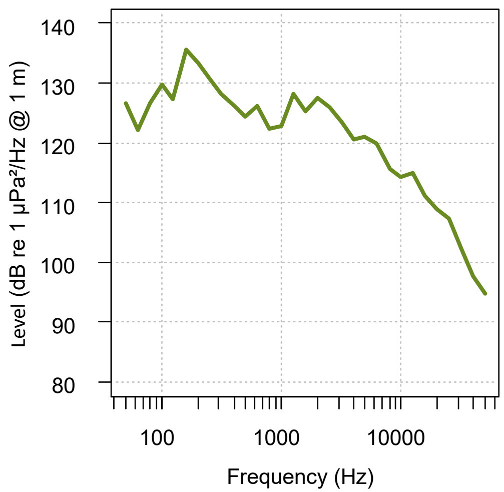
Main influential parameters:

- Type of vessel
- Engine
- Speed of vessel

EXAMPLE CASE STUDY

Observation conditions:

Type of vessel	Waterjet scooter
Type of engine	4 stroke
Engine power	110 hp
Speed of vessel	Variable, 10 knots on average



Observations:

Maximum energy frequency	160 Hz
Maximum level @ 1 m	136 dB re 1 µPa²/Hz

Continuous noise

19. PERSONAL WATERCRAFT

EXPOSED SPECIES

Low-frequency Cetaceans
Phocids
Other Carnivores
High-frequency and Very high-frequency Cetaceans
Sirenians
Fish
Turtles
Crustaceans and Molluscs
Diving birds

POTENTIAL IMPACTS

- **Variable in function of vessel and speed**
- TTS ?
- Masking
- Disturbance
- Indirect effects (fleeing of prey, loss of habitat, etc.)
- Energy-related consequences/selective value

ASSESSMENT

Currently no particular recommendation. Nonetheless, an assessment of potential impacts (list of species present, frequentation of the area, modelling of impact zones) could be recommended in areas of high ecological importance (marine protected areas, spawning and feeding grounds, nurseries).

AVOID

Measure	Description	Efficacy	Page
Avoid certain areas	Avoid areas of known ecological importance (nurseries, breeding and feeding grounds)	++	p. 111-112
Avoid certain periods	Avoid ecologically important periods (giving birth, breeding, feeding, migration)	++	p. 111 to 113

REDUCE

Measure	Description	Efficacy	Page
Technical improvements	Design of hull, propeller, engine, etc. Reduction of cavitation phenomena and vibrations	++	p. 117-118
Adaptation	Reduce sailing speed	++	p. 118

ACCOMPANY

Measure	Page
Acquisition of further knowledge and development of new practices	p. 117 to 119 p. 134

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FIGURE LIST

TABLE LIST

ANNEXES

ANNEXE 1. Complementary Information concerning the TTS and PTS acoustic thresholds and weighting functions for marine mammals

Hearing groups

Marine mammals do not all have the same hearing sensitivity, and are therefore not all affected in the same way by underwater noise. In order to take into account these differences in sensitivity, in particular their ability to perceive certain frequencies better than others, marine mammals were therefore divided into several "hearing groups" [136, 168]. For each of these hearing groups, an estimated audiogram was developed (see Figure 22, page 76).

The classification of marine mammals in function of their hearing sensitivity is presented in Table 18 below:

Table 18: Classification of marine mammals according to hearing sensitivity (according to [168]).

Hearing group	Abbreviation	Genera (or species) included
Low-frequency cetaceans	LF	Balaenidae (*Balaena, Eubalaenidae spp.*); Balaenopteridae (*Balaenoptera physalus, B. musculus*)
		Balaenopteridae (*Balaenoptera acutorostrata, B. bonaerensis, B. borealis, B. edeni, B. omurai; Megaptera novaeangliae*); Neobalenidae (*Caperea*); Eschrichtiidae (*Eschrichtius*)
High-frequency cetaceans	HF	Physeteridae (*Physeter*); Ziphiidae (*Berardius spp., Hyperoodon spp., Indopacetus, Mesoplodon spp., Tasmacetus, Ziphius*)
		Delphinidae (*Orcinus*); Delphinidae (*Delphinus, Feresa, Globicephala spp., Grampus, Lagenodelphis, Lagenorhynchus acutus, L. albirostris, L. obliquidens, L. obscurus, Lissodelphis spp., Orcaella spp., Peponocephala, Pseudorca, Sotalia spp., Sousa spp., Stenella spp., Steno, Tursiops spp.*); Montodontidae (*Delphinapterus, Monodon*); Plantanistidae (*Plantanista*)
Very high-frequency cetaceans	VHF	Delphinidae (*Cephalorhynchus spp.; Lagenorhynchus cruciger, L. austrailis*); Phocoenidae (*Neophocaena spp., Phocoena spp., Phocoenoides*); Iniidae (*Inia*); Kogiidae (*Kogia*); Lipotidae (*Lipotes*); Pontoporiidae (*Pontoporia*)
Sirenians	SI	Trichechidae (*Trichechus spp.*); Dugongidae (*Dugong*)
Phocid carnivores in water	PCW	Phocidae (*Cystophora, Erignathus, Halichoerus, Histriophoca, Hydrurga, Leptonychotes, Lobodon, Mirounga spp., Monachus, Neomonachus, Ommatophoca, Pagophilus, Phoca spp., Pusa spp.*)
Other marine carnivores in water	OCW	Odobenidae (*Odobenus*); Otariidae (*Arctocephalus spp., Callorhinus, Eumetopias, Neophoca, Otaria, Phocarctos, Zalophus spp.*); Ursidae (*Ursus maritimus*); Mustelidae (*Enhydra, Lontra feline*)

Auditory weighting functions

A weighting function was developed for each of the above-defined hearing groups. These weighting functions are justified by the fact that an animal is more likely to be affected by being exposed to sounds at frequencies to which that particular animal is more sensitive (frequencies with the lowest hearing thresholds) than at frequencies to which it is relatively insensitive. For this reason, the available information about the hearing sensitivity of marine mammals (i.e. observations having enabled the development of the audiograms of each hearing group), combined with other audiometric parameters (equal loudness, hearing loss thresholds, etc.[24]), were used to establish weighting functions, which are mathematical functions that act as band-pass filters, giving more weighting for the calculation of the TTS and PTS thresholds at frequencies to which the animals are more sensitive than for the frequencies at which their hearing is poorer (or non-existent). These weighting functions help to determine weighted hearing thresholds for each hearing group (Figure 32).

The weighting functions are calculated by means of the following equation:

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a\,[1+(f/f_2)^2]^b}\right\}$$

Where:

- $W(f)$ is the weighting function amplitude (in dB) at frequency f;
- f is the frequency (in kHz);
- C defines the vertical position of the curve; this constant is often fixed so that W is 0 dB;
- f_1 defines the lower band-pass limit, i.e. the lower frequency at which the function amplitude starts to change from the flat, central portion of the curve;
- f_2 defines the upper band-pass limit, i.e. the upper frequency at which the function amplitude starts to change from the flat, central portion of the curve;
- a defines the slope of the weighting function for low frequencies (i.e. the rate of decline of the weighting function amplitude at low frequencies);
- b defines the slope of the weighting function for high frequencies (i.e. the rate of decline of the weighting function amplitude at high frequencies).

The values of these parameters for each of the above-defined hearing groups are given in Table 19 below. The weighting functions thus established for each hearing group are presented in Figure 32.

[24] For further information, see Southall *et al.*, 2019 [168].

Table 19: Parameters used to calculate the auditory weighting functions of the various groups of marine mammals (according to [168]).

Weighting function	f1 (kHz)	f2 (kHz)	a	B	K (dB)	R^2	C (dB)
LF	0.20	19	1	2	179		0.13
HF	8.8	110	1.6	2	177	0.825	1.20
VHF	12	140	1.8	2	152	0.864	1.36
SI	4.3	25	1.8	2	183		2.62
PCW	1.9	30	1	2	180		0.75
OCW	0.94	25	2	2	198	0.557	0.64

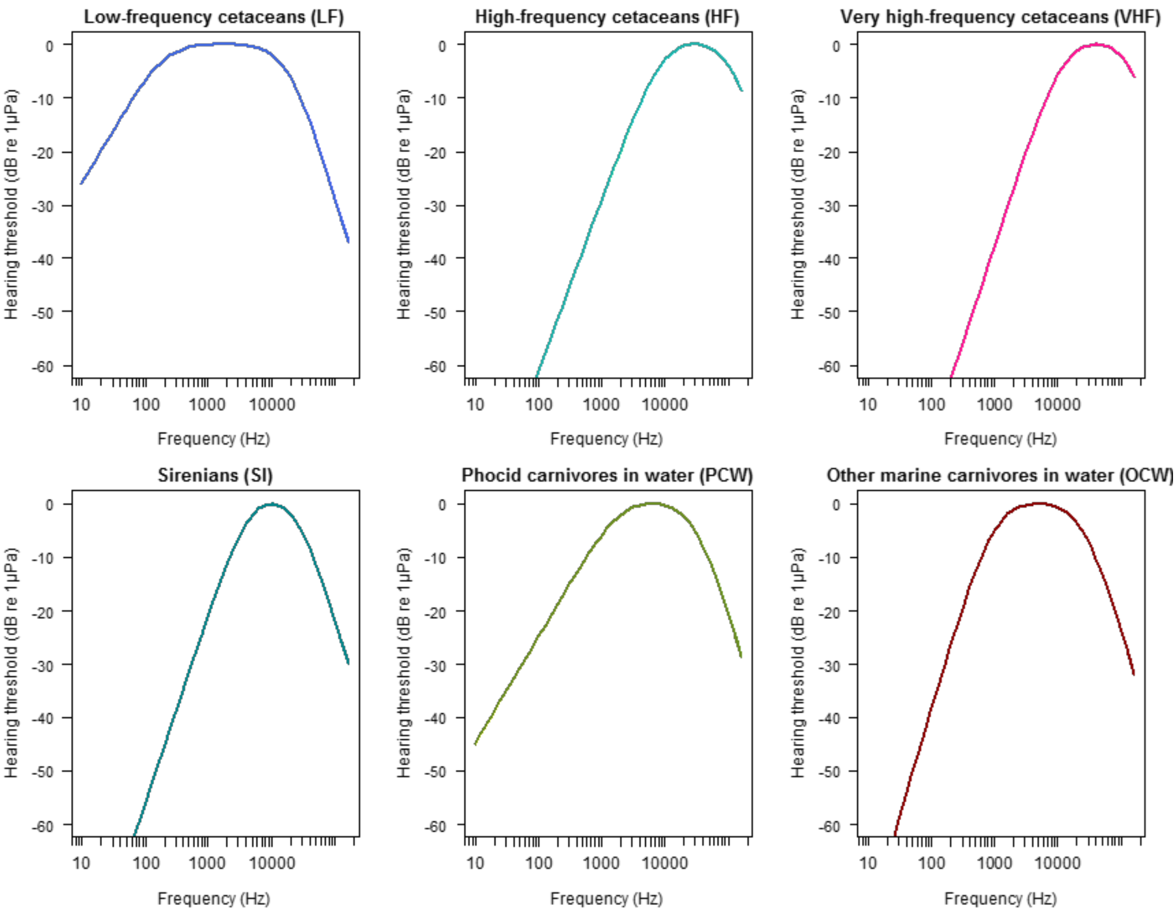

Figure 30: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), sirenians (SI), phocids in water (PCW) and other carnivores in water (OCW) (according to [168])

Noise exposure functions

The noise exposure function is derived from the weighting function and hearing threshold. It is defined as the difference between the value of the hearing threshold and the value of the weighting function for each frequency.

This function shows the noise exposure required to cause temporary or permanent hearing loss in function of frequency and thus determines the weighted TTS and PTS thresholds for each hearing group.

ANNEXE 2. Useful documentation and further information

Concerning underwater acoustics:

- Discovery of Sound in the Sea website: www.dosits.org
- The work of the NOAA on hearing thresholds and sensitivities: https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-acoustic-technical-guidance

Texts adopted in the framework of some international conventions:

- OMI (2014): “Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life” : https://www.ascobans.org/en/document/imo-mepc1circ833-guidelines-reduction-underwater-noise-commercial-shipping-address-adverse
- CDB (2016): Decision XIII/10 : Addressing impacts of marine debris and anthropogenic underwater noise on marine and coastal biodiversity: https://www.cbd.int/decisions/cop/?m=cop-13
- CMS (2017): CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities: https://www.cms.int/en/guidelines/cms-family-guidelines-EIAs-marine-noise
- OSPAR Convention (2017) Intermediate Assessment of the state of the North-East Atlantic / impulsive noise: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/distribution-reported-impulsive-sounds-sea/
- Barcelona Convention / Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast / List of IMAP Ecological Objectives (EOs) and Indicators: https://www.medqsr.org/integrated-monitoring-and-assessment-programme-mediterranean-sea-and-coast
- ACCOBAMS (2019): Resolution 7.13: Anthropogenic Noise: https://accobams.org/meetings/7th-meeting-of-the-parties-to-accobams/ /

Concerning feedback on the impact of MREs:

- Tethys website: https://tethys.pnnl.gov/

Concerning AMC measures (in France):

- MTES (2018): *Guide d’aide à la définition des mesures ERC* (Guidelines for defining AMC measures), Théma Balise. CGDD & CEREMA, available (in French) at: https://www.ecologique-solidaire.gouv.fr/sites/default/files/Th%C3%A9ma%20-%20Guide%20d%E2%80%99aide%20%C3%A0%20la%20d%C3%A9finition%20des%20mesures%20ERC.pdf

Concerning the distribution of marine mammals:

- PELAGIS Observatory (in French):

http://www.observatoire-pelagis.cnrs.fr/catalogueSI/#/search?from=1&to=20

- OBIS-SEAMAP website: http://seamap.env.duke.edu/
- ObsEnMer (in French): https://www.obsenmer.org/
- OFB (in French): https://www.afbiodiversite.fr/
- INPN: https://inpn.mnhn.fr/accueil/index?lg=en

- IUCN Red List: https://www.iucnredlist.org/

ANNEXE 3. List of contributors

In addition to the support of the Steering Committee, highlighted on page II, some people were contacted before writing these guidelines. Their advice and proposals were a great help in drawing up this document. We would therefore like to thank them for their collaboration:

Name	Institution
Abad Oliva, Núria	ScottishPower Renewables
Bougant, Julie	Port Atlantique La Rochelle
Brard Pierre	Direction Départementale des Territoires et de la Mer de la Seine-Maritime
Brown, Carrie	Vancouver Port
Caurant, Florence	Observatoire Pelagis (UMS 3462)
Chaineau, Claude-Henri	TOTAL
David, Alexandra	Direction Départementale des Territoires et de la Mer de la Manche
Delaby, Françoise	Direction Régional de l'Environnement, de l'Aménagement et du Logement des Pays de la Loire
Ducatel, Cécile	Institut Français de Recherche pour l'Exploitation de la Mer
Duthion, Pierre	EDF Renouvelables
Favilli, Costanza	Pelagos Sanctuary
Fisseau, Charline	Sanctuaire AGOA – French Biodiversity Agency (OFB)
Gicquel, Cécile	Parc Naturel Marin d'Iroise
Guellec, Jean-Pierre	GIE-Dragages Ports
Guesdon, Romain	ENGIE Green France
Guidez Bertrand	Ailes Marines
Guyon, Christelle	Direction de l'Environnement, de l'Aménagement et du Logement de la Guyane
Jewell, Rebecca	MMO/PAM Operator
Lambert, Isabelle	CGG
Laurent, Mélina	Direction de l'Environnement, de l'Aménagement et du Logement de la Guadeloupe
Lelabousse, Clément	Parcs Naturels Marins de Mayotte et des Glorieuses - French Biodiversity Agency (OFB)
Le Courtois, Florent	Service Hydrographique et Océanographique de la Marine
Le Gall, Yves	Institut Français de Recherche pour l'Exploitation de la Mer
L'her, Christophe	SERCEL
Maglio, Alessio	SINAY
Michel, Sylvain	French Biodiversity Agency (OFB)
Nolet, Véronique	Green Marine

Name	Institution
Noto, Stéphane	Association Nationale des Plaisanciers Motonautiques
Recuero Virto Laura	University of Brest
Remaud Morgane	French Biodiversity Agency (OFB)
Roitel Olivier	Préfecture Maritime de l'Atlantique
Samaran Flore	École Nationale Supérieure de Techniques Avancées de Bretagne
Southall Brandon	University of California, Southall Environmental Associates, Inc.
Troussard Corentin	RTsys
Victor François	Direction Interrégionale de la Mer Nord Atlantique-Manche Ouest

MINISTÈRE
DE LA TRANSITION
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