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Impact of Anthropogenic Sounds on Marine Mammals, Monitoring Techniques and Application to the Abysound Project

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Livable 2.4 : Impact of Anthropogenic Sounds on Marine Mammals, Monitoring Techniques and Application to the Abysound Project

P. Best, M. Ferrari, H. Glotin, M. Poupard

July 2019

FUI Abysound, Tâche 2.3.5

Research report, University of Toulon, DYNI team, LIS Laboratory, CNRS



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1

Introduction

Anthropogenic underwater sounds are known today as a great source of disturbance for marine animals. Some of the numerous consequences of those disturbance can be seriously threatening to some species, as this graphic shows I.I.

It is our responsibility to reduce this perturbation as much as possible, and it is only possible through the complete understanding of it, from the sources to the long-term effects on the fauna.

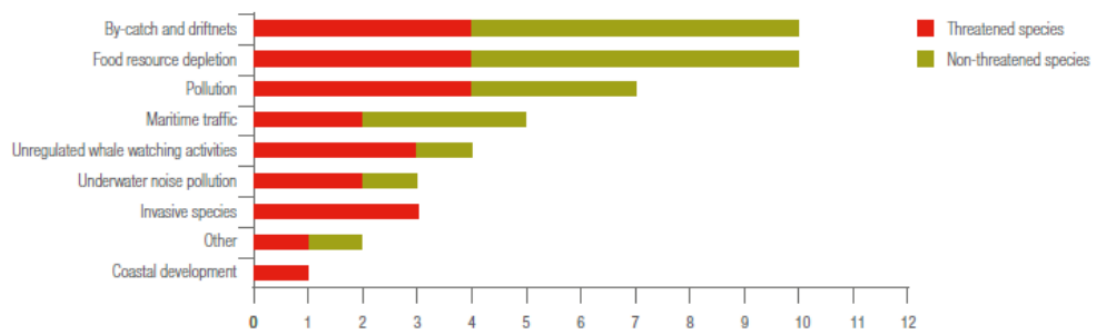


Figure 1.1: Major threats to the resident marine mammals in the Mediterranean and Black Seas¹

In this paper, we give a broad overview of maritime noise pollution. Starting with the study of the different sources of sound, we then study the many aspects of their consequences over several species. Since the monitoring of those perturbations is crucial to their understanding, we further describe classic (static) and mobile monitoring techniques. We then apply this knowledge to Alysound's Nautilus Mineral case, by comparing the planned zones of mining with the presence of marine animals, and their relative importance according to the Marine Mammals Protected Areas Task Force.

2

Sound Pollution

Sound or noise pollution describes the anthropogenic underwater vibrations in general. Similarly to air pollution, human activity modifies the natural state of oceans and seas in many different ways. We focus here on the disturbance of the acoustic state for those environments.

2.1 TYPES OF SOUND POLLUTION SOURCES

A broad range of human activities cause acoustic disturbance. We can divide those in three main categories :

- vessel traffic : freight and tourism boats use motors that emit vibrations underwater.
- sound exploration : used for underwater navigation (sonar) or seismic surveys (air-guns), sound is a powerful mean of getting information on your surroundings, especially underwater (it is also broadly used by the marine mammals).
- works : setting up structures (windmills, oil platforms...), mining, and other many work on construction or destruction are conducted underwater, and are also source of powerful vibrations.

Activity	Source	Source level (dB re 1μPa m)*	Bandwidth (Hz)	Major amplitude (Hz)	Duration (ms)	Directionality
Sonar	Military sonar low frequency	235 Peak	100 – 500		6000 – 100,000	Horizontally focused
	Military sonar mid frequency	223 – 236 rms	2800 – 8200	3500	500 – 2000	Horizontally focused
	Echosounders	235 Peak	Variable	Variable 1500 – 36000	5 – 10 ms	Vertically focused
Seismic	Airgun array	260 – 262 P-to-P	10 – 100 000	10 – 120	30- 60	Vertically focused
Coastal and offshore works	TNT (0.5 – 50 kg)	272 – 287 Peak	2 – 1000	6 – 21	1 - 10	Omnidirectional
	Pile driving	228 Peak / 243 – 257 P-to-P	20 – 20 000	100 – 500	50	Omnidirectional
	Dredging (CSD)	172 – 185 rms	30 – 20 000	100 – 500	Continuous	Omnidirectional
	Drilling	145 – 190 rms**	10 – 10 000	< 100	Continuous	Omnidirectional
	Dredging (TSHD)	186 – 188 (rms)	30 – 20 000	100Hz-500Hz	Continuous	Omnidirectional
Shipping	Small boats and ships	160 – 180 rms	20 – 10 000	> 1000	Continuous	Omnidirectional
	Large vessel	180 – 190 rms	6 – 30 000	> 200	Continuous	Omnidirectional
Other activities	Acoustic deterrent / harassment devices	132 – 200 Peak	5000 – 30 000	5000 – 30 000	Variable 15 – 500 ms	Omnidirectional
	Tidal and wave energy devices	165 – 175 rms***	10 – 50 000		Continuous	Omnidirectional

Figure 2.1: Overview of the acoustic properties of some anthropogenic sounds. * Nominal source, ** Higher source levels from drill ships use of bow thrusters, *** Projection based on literature data levels back-calculated at 1 m . CSD = Cutter Suction Dredger; TSHD = Trailing Suction Hopper Dredger. ¹⁶

2.2 MEASURING THE SOUND INTENSITY

For the following equations, with

$$p_o = I\mu Pa \quad (2.1)$$

we define the SEL as follows :

$$SEL = I_0 * \log_{10} \left(\int_{t_0}^{t_1} \frac{p(t)^2}{p_o^2} dt \right) \quad (2.2)$$

2.2.1 IMPULSIVE SOUNDS (SPL)

Impulsive sounds are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay². For these sounds, the PK (Peak Sound Pressure Level) metric is preferable.

$$PK = \max(SEL) \quad (2.3)$$

2.2.2 NON-IMPULSIVE SOUNDS (CUMULATIVE SEL)

Non-impulsive sounds can be broadband, narrow-band or tonal, brief or prolonged, continuous or intermittent, and typically do not have a high peak sound pressure with rapid rise/decay time as impulsive sounds². For these sounds, the SEL_{cum} (Cumulative Sound Exposure Level) metric is preferable in most cases.

$$SEL_{cum} = 10 \log_{10} \left(\sum_{24h} 10^{\frac{SEL}{10}} \right) \quad (2.4)$$

The SEL_{cum} metric takes into account both received level and duration of exposure³, both factors that contribute to noise induced hearing loss (NIHL). Often this metric is normalized to a single sound exposure of one second.

2.3 MODELLING AREAS OF EXPOSURES

2.3.1 PROPAGATION MODELS

Sound intensity can be monitored at a certain point in space using hydrophones, but the measures are only relevant throughout a whole area, to measure the noise's impact on a population of animals. For this purpose, instead of placing dozens of hydrophones at different locations, sound propagation models can estimate the evolution of the sound intensity through space and time.

Nevertheless, the propagation of sound is highly dependant on numerous environmental parameters. The most important ones are the characteristics of the medium, and of the boundaries for the propagation space.

For the medium, the water density (depending on the depth) and saltiness are to take into account.

For the boundaries, the shapes (topography of the bottom, surface activity) and the physical characteristics (substrate of the bottom) are to take into account to accurately predict the behaviour of the sound against them.

Accounting some of those parameters, more or less sophisticated techniques exists to model the sound's propagation, and thus the SEL by area.

One technique considered as a simple propagation model assumes a combination of spherical and cylindrical transmission losses to compute the SEL for an emission⁴.

A slightly more sophisticated model is the 2D ray-tracing model^{5,6}. The ray method is highly intuitive because the sound paths can be traced and show the path of each ray. Ray tracing is very efficient (fast). Once the rays are computed, the acoustic field levels are computed by summing the rays near the receiver⁷.

Many other types of models exist, taking into account more parameters, thus being more accurate but also heavier in computation.

Precise estimations of the SEL by area are needed when the location of the animals is well known and delineated. For rough estimations of the range of disturbance implied by a sound source, simpler models might be sufficient, but complex behaviours are to be acknowledged (e.x. sound propagating underground and resurfacing further because of topographic variations).

2.3.2 FAUNA OBSERVATION

A good approach for estimating the area of exposure from a sound source, instead of or in completion of propagation models, is actually monitoring the impact on the animals⁹. It is relatively easy to notice abnormal behaviours of animals next to noisy activities (visual or passive acoustic monitoring), and it helps to get an idea of the area of exposure from one sound source.

3

Fauna perturbation

In this chapter we describe some of the numerous aspects of marine mammals' life that are influenced by noise pollution, and the potential noxious consequences.

3.1 ACTIVITY CHANGE

Several behavioural changes were studied on mammals exposed to sound pollution. One of the main sources of pollution studied is the vessel traffic. For bottlenose dolphins for example, the presence of vessels implied longer inter-breath intervals, and quicker changes of heading, speed, and smaller inter-animal distances¹³. Those behaviours, demonstrate that the animals are actually trying to avoid the vessels. It is crucial to acknowledge that in this area of Sarasota bay Florida, vessels are encountered in an average of 6 minutes intervals during day time. The dolphins' 'natural' activities are thus heavily disturbed. For killer whales, similar behaviours of fleeing boats have been monitored¹⁴. This fleeing activity implies changes in the overall time spent for each activity by the killer whales (see figure 3.1).

Again, with harbour porpoise, present in areas next to the construction of wind turbines : changes from normal activity (stationary, feeding) to traveling was monitored when exposed to the pile-driving sound⁸.

For any animal, having to flee boats or unfamiliar sounds for a significant amount of time implies less time for necessary activities like foraging or socializing. Spending less

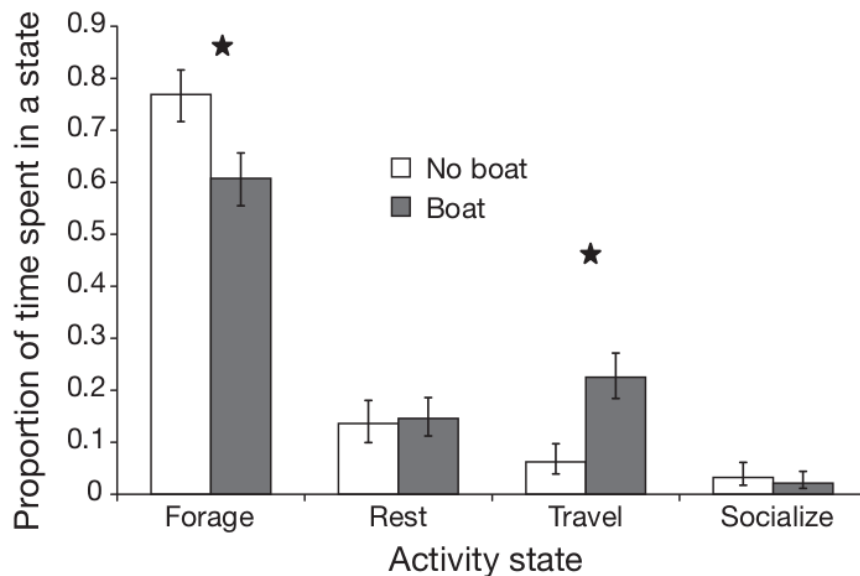


Figure 3.1: Proportion of time focal killer whales spent in each activity state (their activity budget) depending on the presence of boats within 400 m of them, pooling across years and sites. Error bars are 95% confidence intervals. Black stars indicate differences that are significant at the 0.05 level¹⁴

foraging time could imply a smaller access to food which could be critically dangerous for the animals.

3.2 DISPLACEMENT

As seen in the previous section, marine animals often flee unfamiliar noises. This phenomenon impacts their activity distribution, but also the habitat they evolve in. For pile-driving activities, the impact range goes up to 20km for harbor porpoise⁹. Vessel traffic showed a long-term decrease of bottlenose dolphins population in the affected regions¹⁰. Short term displacement of the animals might seem not dangerous for them, and preventing potential hear losses or collisions. Although, the European commission stipulates :”A 24 hour time-period is too long if we want to make sure that we stay in the ‘no-effect’ range.”⁴⁰. Indeed, as some species’ digestive system demands feeding many times per day, those animals rely on constant access to foraging areas. Thus, several hours of displacement can have sever impacts on their health.

Moreover, some construction works and other noisy activities might last a significant period of time, impeaching animals to evolve in potentially crucial areas like feeding or breeding zones. In this case, the displacement of the animals can have a heavily noxious

Hearing Group	Generalized Hearing Range*
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, <i>Kogia</i> , river dolphins, cephalorhynchid, <i>Lagenorhynchus cruciger</i> & <i>L. australis</i>)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)	60 Hz to 39 kHz
* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).	

Figure 3.2: Marine Mammals Hearing Groups²

impacts on the animals' life. It is thus important to take into account if animals are dependant on a specific area or not to measure their displacement's impact.

3.3 HEAR LOSS

Hear loss in marine mammals has been observed as an effect of noise pollution underwater. They are sub-categorized as permanent threshold shift (PTS) or temporary threshold shift (TTS). Like for humans, the threshold shift describes an augmentation of the minimum sound level needed for the sound detection.

Studies² have measured the sound level onset for PTS and TTS depending on the hearing groups of the marine mammals. Several regulations exists depending on the country of application, with different methods for computing the SEL (cumulative or not, weighted or not). This studie³⁸ has benchmarked several regulations and their computation method. We selected the National Marine Fisheries Service³⁹ method since it is more accurate (using species weighting function, animal's movement and distance, and time of exposure).

The values of Figure 3.4 were computed using the Navy Phase 3 TTS exposure functions, defined with this equation¹⁷.

$$W(f) = C + 10 \log_{10} \left(\frac{\left(\frac{f}{f_1}\right)^{2a}}{\left(1 + \left(\frac{f}{f_1}\right)^2\right)^a \left(1 + \left(\frac{f}{f_2}\right)^2\right)^b} \right) \quad (3.1)$$

Code	Name	Members
LF	Low-frequency cetaceans	Family Balaenidae (right and bowhead whales) Family Balaenopteridae (rorquals) Family Eschrichtiidae (gray whale) Family Neobalaenidae (pygmy right whale)
MF	Mid-frequency cetaceans	Family Ziphiidae (beaked whales) Family Physeteridae (Sperm whale) Family Monodontidae (Irrawaddy dolphin, beluga, narwhal) Subfamily Delphininae (white-beaked/white-sided/Risso's/bottlenose/spotted/spinner/striped/common dolphins) Subfamily Orcininae (melon-headed whales, false/pygmy killer whale, killer whale, pilot whales) Subfamily Stenoninae (rough-toothed/humpback dolphins) Genus <i>Lissodelphis</i> (right whale dolphins) <i>Lagenorhynchus albirostris</i> (white-beaked dolphin) <i>Lagenorhynchus acutus</i> (Atlantic white-sided dolphin) <i>Lagenorhynchus obliquidens</i> (Pacific white-sided dolphin) <i>Lagenorhynchus obscurus</i> (dusky dolphin)
HF	High-frequency cetaceans	Family Phocoenidae (porpoises) Family Platanistidae (Indus/Ganges river dolphins) Family Iniidae (Amazon river dolphins) Family Pontoporiidae (Baiji/ La Plata river dolphins) Family Kogiidae (Pygmy/dwarf sperm whales) Genus <i>Cephalorhynchus</i> (Commersen's, Chilean, Heaviside's, Hector's dolphins) <i>Lagenorhynchus australis</i> (Peale's or black-chinned dolphin) <i>Lagenorhynchus cruciger</i> (hourglass dolphin)
SI	Sirenians	Family Trichechidae (manatees) Family Dugongidae (dugongs)
OW	Otariids and other non-phocid marine carnivores (water)	Family Otariidae (eared seals and sea lions) Family Odobenidae (walrus) <i>Enhydra lutris</i> (sea otter) <i>Ursus maritimus</i> (polar bear)
PW	Phocids (water)	Family Phocidae (true seals)

Figure 3.3: Detailed species hearing groups including sirenias¹⁷

$W(f) = C + 10 \log_{10} \left\{ \frac{(f/f_1)^a}{[1 + (f/f_1)^2]^b [1 + (f/f_2)^2]^c} \right\}$						Non-impulsive		Impulse			
						TTS Threshold	PTS Threshold	TTS Threshold		PTS Threshold	
Group	<i>a</i>	<i>b</i>	<i>f</i> ₁ (kHz)	<i>f</i> ₂ (kHz)	<i>C</i> (dB)	SEL (Weighted)	SEL (Weighted)	SEL (Unweighted)	Peak SPL (Unweighted)	SEL (Weighted)	Peak SPL (Unweighted)
LF	1	2	0.20	19	0.13	179	199	168	213	183	219
MF	1.6	2	8.8	110	1.20	178	198	170	224	185	230
HF	1.8	2	12	140	1.36	153	173	140	196	155	202
SI	1.8	2	4.3	25	2.62	186	206	175	220	190	226
OW	2	2	0.94	25	0.64	199	219	188	226	203	232
PW	1	2	1.9	30	0.75	181	201	170	212	185	218

Figure 3.4: Summary of weighting function parameters and TTS/PTS thresholds. SEL thresholds are in dB re 1 μ Pa2s and peak SPL thresholds are in dB re 1 μ Pa¹⁷.

Potential protective mechanisms against loud sounds have been observed among marine mammals². They consist of reducing hearing sensitivity (observed on false killer whales, belugas, bottlenose dolphins), turning heads (dolphins), or surfacing (long-finned pilot whales) when exposed to loud sounds. These natural protection instinct comforts the idea that high level sounds can be harmful to the animals.

Temporal and permanent threshold shifts have big impacts on marine mammals, as they rely on their auditory system for numerous aspects of their lives. First of all, communication between mammals (for socializing, organizing hunts and travels, and mating calls) can be impaired. Echo-localization, used among numerous marine mammals, also relies on hearing, and is necessary for navigation, finding prey, and avoiding collisions. Hear loss can impeach all of those crucial aspects of the marine mammals' lives, and thus should be considered as a threat.

Moreover, studies¹⁸ found that with large, but recoverable noise-induced thresholds shifts (maximum 40 dB TS measured by auditory brainstem response (ABR)), sound could cause delayed cochlear nerve degeneration in mice. Further studies¹⁹ reported a similar pattern of neural degeneration in mice after large but recoverable noise-induced TSs (maximum 50 dB TS measured by ABR), which suggests a common phenomenon in all mammals. The long-term consequences of this degeneration remain unclear.

3.4 OCCUPATION OF THE ACOUSTIC SPACE

Besides hear losses, the marine mammals' activities that rely on sound can be impeached by the occupation of the acoustic space. Changes of the acoustic behaviour of bottlenose dolphins¹¹, sperm whales, and belugas¹² have been observed. Those changes were noticed as decreases of the rates of calls, and/or shift of frequencies used. Those behaviours are interpreted as adaptation techniques, against a noisy environment. Some animals have a free acoustic space (frequencies that the animal can use that aren't in the "polluting" noise) left at some frequencies and use it. Some other simply stop communicating and foraging. Those effects can increase the energy expenditure and decrease food access and group cohesion¹⁵, which can be harmful for the populations in the long-term.

3.5 MITIGATION TECHNIQUES

Several methods are used to reduce the impact of noise pollution on the marine fauna, among two main categories : deterring the animals' presence, and reducing the sound propagation.

3.5.1 DETERRENT TECHNIQUES

Acoustic deterrence and harassment devices such as porpoise pingers or seal-scarers prior to loud sounds (e.x. pile-driving) serve to encourage the animals in moving away from the sound exposure area. Their efficiency can be compromised by two factors. In the first hand, some animals can get used to deterrent sounds, and thus not move away as expected. Secondly, some sound sources expose very large areas⁹, and the displacement due to deterrents might not be sufficient to get away from the sound exposure.

3.5.2 SOUND REDUCTION

Sound reducing technologies for shipping, and coastal or offshore works are available. For shipping, improving the wake flow, and decreasing the cavitation shows reduced sound emission. For coastal and offshore works, bubble curtains, shells, cofferdams, or other sound dampers can be used¹⁶.

Sound reduction is usually a more reliable technique since it directly reduces the SPL, whereas deterrent methods might not move away the animals far enough or long enough.

4

Classic Monitoring

One of Alysound's goal is to monitor the environmental impact of the noise emitted by offshore works. We list here necessary components to measure the actual noise disturbance on the local fauna.

4.1 PURPOSE

4.1.1 DANGEROUS SOUND PRESSURE LEVELS

Alysound's system must detect sound exposure levels exceeding threshold shift onsets of marine mammals that could be around the offshore works. For that computation, not only SPL, but also duration and distance to potential receivers are necessary. Having those parameters, an alarm system could be built to warn the work operators of potential danger, so they could take action accordingly (temporary stopping the procedure, reducing the emitted noise if possible).

The DYNi team at the LIS lab of the University of Toulon has developed a program that detects and alerts if the SEL and SPL exceed a defined threshold.

```

#!/usr/bin/python3.5

import numpy as np
import argparse
import soundfile as sf
import datetime
import os

def main(path, out, gain, SPL_threshold, SEL_threshold):
    try:
        song, sample_rate = sf.read(path)
        assert song.ndim == 1
    except AssertionError :
        print('Only mono sound supported, got a sound with {} channels'.format(song.shape[1]))
    except (KeyboardInterrupt, SystemExit):
        raise
    except:
        print('Unable to read {}'.format(path))
    else:
        np.square(song*gain, out=song)
        SEL = 10*np.log10(song.sum())/sample_rate
        sliding_SPL = song[:sample_rate//10].mean()
        SPL = sliding_SPL
        for t in range(sample_rate//10, len(song)):
            sliding_SPL += (song[t] - song[t-sample_rate//10])/(sample_rate//10)
            if sliding_SPL > SPL :
                SPL = sliding_SPL
        SPL = 10*np.log10(SPL)
        time = datetime.datetime.now()
        if (SPL >= SPL_threshold) or (SEL > SEL_threshold):
            print('Threshold reached\n')
            os.system("sox -n -r 8000 -p synth 30 sine 500-6000| play -p")
        print('Date : {}\nSPL : {:.3}\nSEL : {:.3}'.format(time,SPL,SEL))
        if out is None :
            out = path + '.csv'
        with open(out, 'w') as file:
            file.write('{},{},{}'.format(SEL,SPL,time))
    return 0

if __name__ == '__main__':
    parser = argparse.ArgumentParser(formatter_class=argparse.ArgumentDefaultsHelpFormatter,
        description="""T0D0""")
    parser.add_argument("file", type=str, help="input file")
    parser.add_argument("--out", type=str, default=None, help="Out file. Default is input file + .csv")
    parser.add_argument("--gain", type=float, default=5.597e10 , help="sound pressure (µPa)/wav amplitude")
    parser.add_argument("--SPL_threshold", type=float, default=190, help="SPL alert threshold in dB")
    parser.add_argument("--SEL_threshold", type=float, default=177.7, help="SEL alert threshold in dB for one minute")

    args = parser.parse_args()

    path = args.file
    out = args.out
    gain = args.gain
    SPL_threshold = args.SPL_threshold
    SEL_threshold = args.SEL_threshold

    main(path, out, gain, SPL_threshold, SEL_threshold)

```

Figure 4.1: Exceeding SPL/SEL detection algorithm (this algorithm is the property of the DYNI team from University of Toulon)

4.1.2 PRESENCE, LOCALIZATION

Besides monitoring the potential hear loss of nearby animals, it is important to measure the displacement of the animals, in terms of distance and duration. Indeed, especially in IMMAs, displacement of the animals could threaten whole populations of marine mammals. For this purpose, monitoring the animals localization and presence in the

designated zones has to occur. Moreover, animal presence monitoring is important to measure their potential exposure to high level sounds, and could help making decisions on activating mitigation techniques (dissuasive) Passive acoustic techniques for simple presence detection⁹ exist and should be used. A more precise localization can be performed using multiple hydrophones, and computing TDOAs^{35 34} (time difference of arrival).

4.1.3 CLASSIFICATION

Classification of the detected animals in term of species is needed to compute their threshold shift onsets, and thus the risk of auditory impairment^{32 30 31}.

4.2 IMPLEMENTATION

4.2.1 STATIC MONITORING

Static hydrophone arrays using underwater buoys provide stable recordings and observations on foraging behavior,^{33 34 35} but can only monitor a fixed location, making it difficult to track animals over longer distances. In³⁶, a permanent quadri-phonic sonobuoy array obtained a track of the animal in only 2 dimensions. A bottom-mounted array with small aperture (2 m) and high sampling rate was used for 3D localization of multiple whales³⁷.

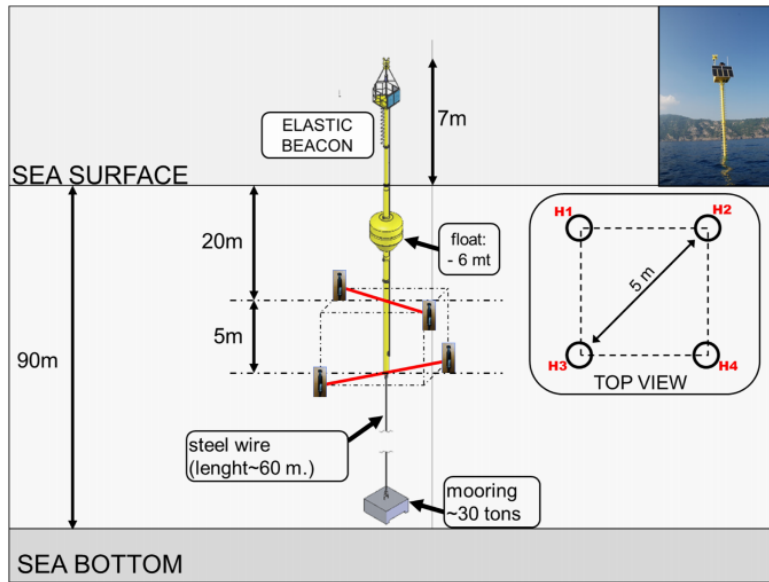


Figure 4.2: Example of a static monitoring antenna³⁶

4.2.2 MOBILE MONITORING

Recent studies²⁹ demonstrate that we can obtain a high definition 3D track of deep diving cetaceans from a five-channel, small-aperture hydrophone array on a moving autonomous surface vehicle (ASV), enabled by the vessel's hydrodynamic quality and a high recording sample rate. Real-time processing is achieved by splitting a non-uniform array into two parts for time delay of arrival estimation. Resulting 3D tracks depict the behavior of the cetacean in the abyss (-1.2 km), with one position per second. This high resolution allows to observe a correlation between the repetition rate of the predator's biosonar and the tortuosity of its track.

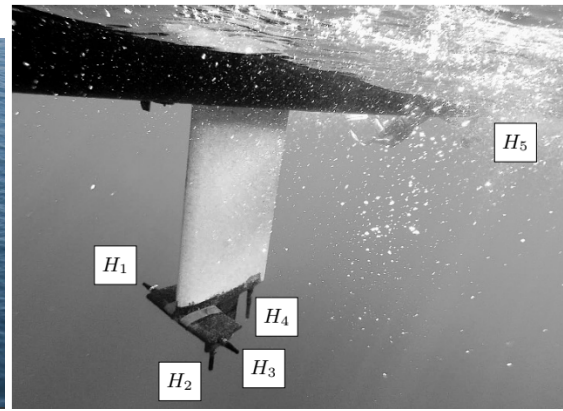


Figure 4.3: Mobile autonomous antenna²⁹

5

Abysound

The main official source of knowledge for fauna presence and relative importance of areas is the Marine Mammals Protected Areas Task Force (MMPATF). The MMPAs Task Force was developed through the IUCN (International Union for Conservation of Nature) World Commission on Protected Areas (WCPA) and Species Survival Commission (SSC), and through the International Committee on Marine Mammal Protected Areas (ICMMPA) to give a stronger voice to marine mammal needs within IUCN and to serve the larger marine mammal protected area community of practice. One of the works of the MMPATF is determining Important Marine Mammals Areas (IMMA) in the world's oceans. IMMAs are defined as “discrete portions of habitat, important to marine mammal species, that have the potential to be delineated and managed for conservation.” IMMAs consist of areas that deserve space-based protection and can be seen as a potential marine mammal layer for consideration by governments, intergovernmental organisations, conservation groups, and the general public.

5.1 MMPATF CRITERION SELECTION

The IMMA selection criteria²⁷ are designed to capture many aspects of the biology, ecology and population structure of marine mammals. These criteria are not hierarchical in design but it is advised that prospective IMMAs are assessed sequentially in the given order. Therefore, any candidate need only satisfy one of the listed criteria and/or

sub-criteria to successfully qualify for IMMA status. Though they cover a range of important attributes, and redundancies between them have been removed, there are some overlaps in the differing criteria that remain to assist assembled experts to identify IMMAs efficiently from that evidence best available.

A	<u>Species or Population Vulnerability</u> : Areas containing habitat important for the survival and recovery of threatened and declining species
Bi	<u>Distribution and Abundance</u> : Areas supporting at least one resident population, containing an important proportion of that species or population, that are occupied consistently
Bii	<u>Distribution and Abundance</u> : Areas with underlying qualities that support important concentrations of a species or population
Ci	<u>Key Life Cycle Activities</u> : Areas that are important for a species or population to mate, give birth, and/or care for young until weaning
Cii	<u>Key Life Cycle Activities</u> : Areas and conditions that provide an important nutritional base on which a species or population depends
Ciii	<u>Key Life Cycle Activities</u> : Areas used for important migration or other movements, often connecting distinct life-cycle areas or the different parts of the year-round range of a non-migratory population
Di	<u>Special Attributes</u> : Areas which sustain populations with important genetic, behavioural or ecologically distinctive characteristics
Dii	<u>Special Attributes</u> : Areas containing habitat that supports an important diversity of marine mammal species

5.2 TEST AREAS

5.2.1 ST TROPEZ : NORTH WEST MEDITERRANEAN SEA IMMA

Species with criterion A, Bii, Ci, Cii, and Ciii are present in this area.

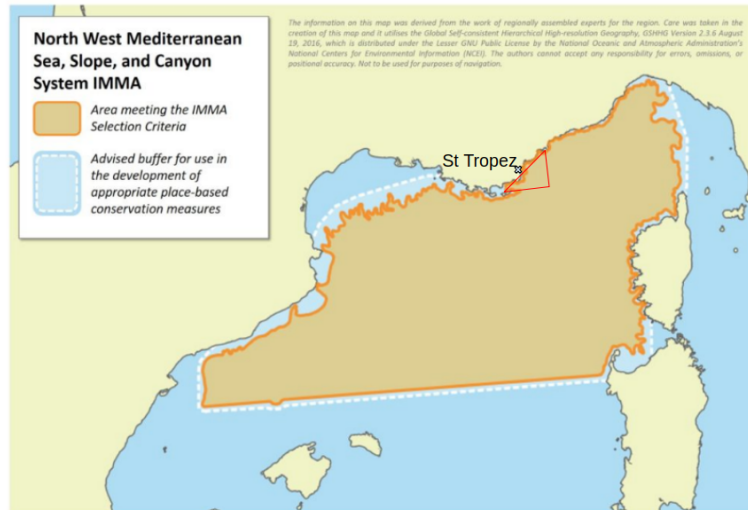


Figure 5.1: Abysound's test zone (red triangle) inside the Important Marine Mammals Area of the north-west Mediterranean sea²³

The MMPATF's summarized report²³ on why and how this area is important to numerous marine mammals : The North West Mediterranean has a set of geomorphological and oceanographic characteristics, including canyon systems and upwellings, which promote levels of productivity of extraordinary biological and ecological significance for the region. The Pelagos Sanctuary area, within the Provençal-Corsican-Ligurian Basin – complemented by an extension to the West encompassing the offshore portion of the Gulf of Lion to the Balearic sub-basin – contains habitat supporting a diversity of cetacean species regularly found in the Mediterranean Sea. In particular, this area contains important habitat for Vulnerable Mediterranean fin whales (*Balaenoptera physalus*), Endangered sperm whales (*Physeter macrocephalus*), and Risso's dolphins (*Grampus griseus*).

5.2.2 PAPUEA NEW GUINEA : BISMARCK SEA IMMA

Species with criterion A, Ci, Cii, and Dii are present in this area.

The Solwara 1 project area has been chosen for one of the two mining noise simulations. The area of the tests is part of the Bismark sea IMMA.

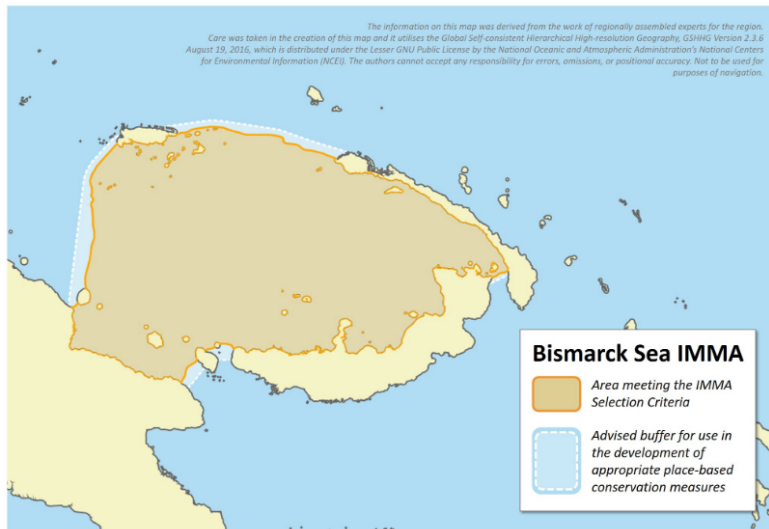


Figure 5.2: Important Marine Mammal Area of Bismarck Sea²²

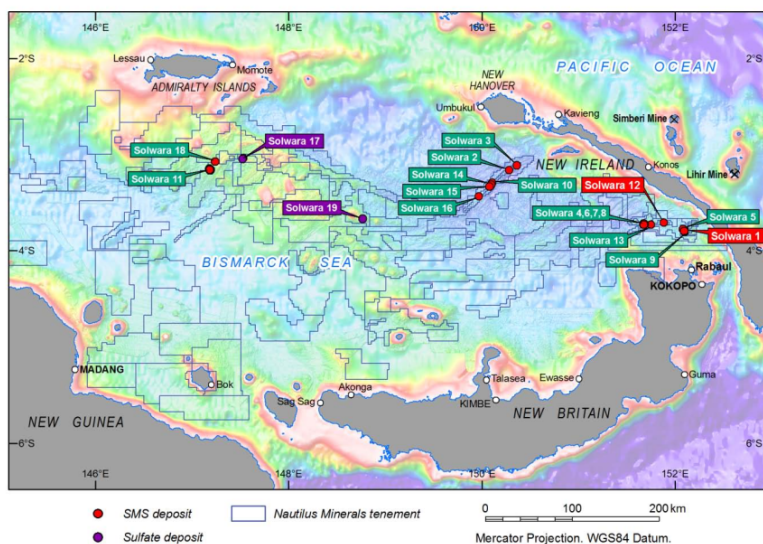


Figure 5.3: Location of Nautilus Minerals Bismarck Sea Property

The MMPATF's summarized report²² on why and how this area is important to numerous marine mammals : The Bismarck Sea of Papua New Guinea lies within the Indo-Pacific coral triangle, which is a global marine biodiversity hotspot. Consistent sightings of killer whales suggest that they are resident in Papua New Guinea, and the presence of calves and of feeding activity, have been recorded in the south of

the Bismarck Sea IMMA, especially in Kimbe Bay. Large aggregations of spinner dolphins containing relatively high numbers of calves, and considerable numbers of sperm whales also occur in the Bismarck Sea. The significant species diversity of the area is underscored by the presence of six other cetacean species that have also been recorded.

5.3 AREAS OF MINING AS OFFICIALY PLANNED BY NAUTILUS MINERALS

5.3.1 FIDJI ISLANDS : VATU-I-RA IMMA

Species with criterion A, Bi, Ci, Cii, and Dii are present in this area.

The MMPATF's summarized report²⁶ on why and how this area is important to numerous marine mammals : The Vatu-i-Ra (ViR) IMMA is a tropical marine system stretching between the two main islands (Viti Levu and Vanua Levu) of Fiji. The ViR IMMA is comprised of a variety of habitats including healthy coral reefs in the coastal areas, a deep canyon, and dynamic and productive oceanographic processes. The ViR has been documented to provide critical resting habitat for spinner dolphins, as well as calving habitat and a migration route for Endangered Oceania humpback whales. The culturally important sperm whale is also present within the ViR although in numbers much reduced as compared to pre-whaling times. Other cetacean species confirmed across this area include the short-finned pilot whale, pantropical spotted dolphin, and false killer whale.

No planned zone of action of Nautilus Mineral has been found for the Fidji Islands. So it is not yet possible to see if the mining will actually occur within the Fidji IMMA. Although, it is worth noticing that the relatively small IMMA reported here lies among other potential IMMAs that surround the area.

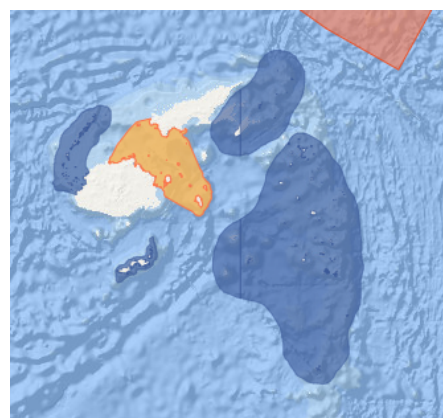
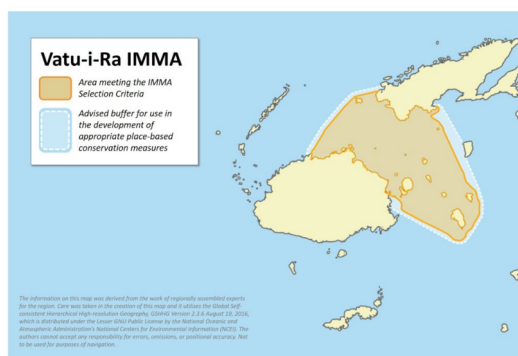


Figure 5.4: Left : IMMA of Fidji²⁶. Right : Other areas of interest surrounding Fidji.

5.3.2 TONGA : TONGA ARCHIPELAGO IMMA

Species with criterion A, Bii, Ci, and Di are present in this area.

The MMPATF's summarized report²⁵ on why and how this area is important to numerous marine mammals : The Tongan Archipelago spans approximately 800 km from Niuafou'u in the north to Eua in the south. Research has focused on the main island groups with concentrated efforts on humpback whales in the coastal waters that form their winter breeding grounds from August – November. There is natal site fidelity of humpback whales to the Tongan breeding grounds with distinctive mtDNA haplotypes for this area. Humpback whales and seven additional species of whale have been seen or acoustically detected within the Tongan Archipelago IMMA. Spinner dolphins are sighted year-round in Vava'u but no other delphinids are known to be resident despite sightings of nine additional species.

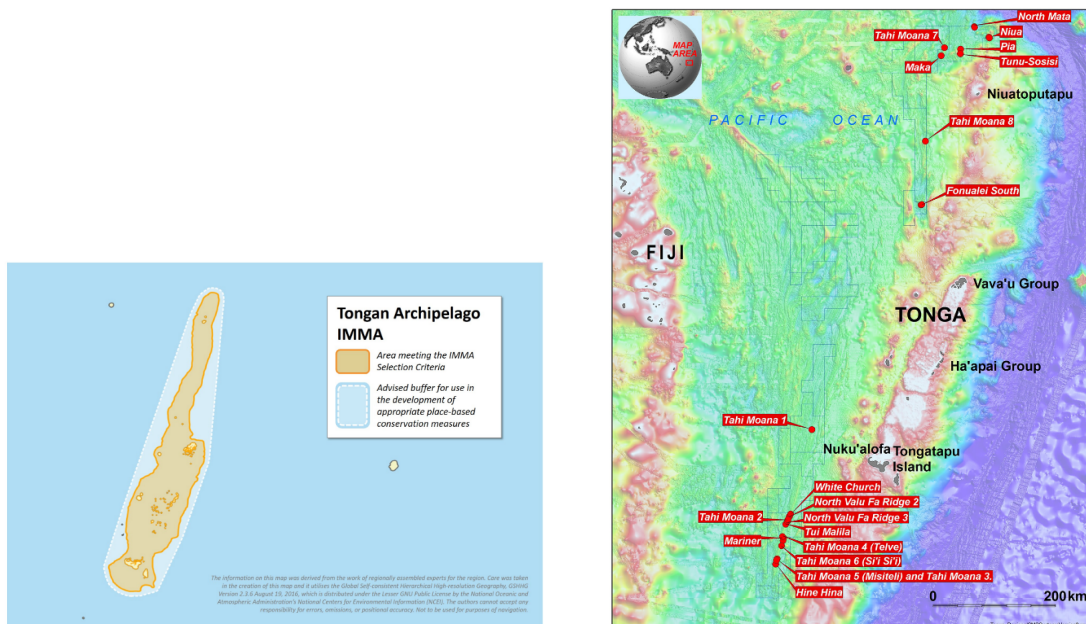


Figure 5.5: Left : IMMA of the Tonga archipelago²⁵. Right : Zones of planned mining by Nautilus Minerals.

The planned mining zones are located up to approximately 40km outside the Tonga IMMA.

5.3.3 SOLOMON : MAIN SOLOMON ISLANDS IMMA

Species with criterion A, Bii and Dii are present in this area.

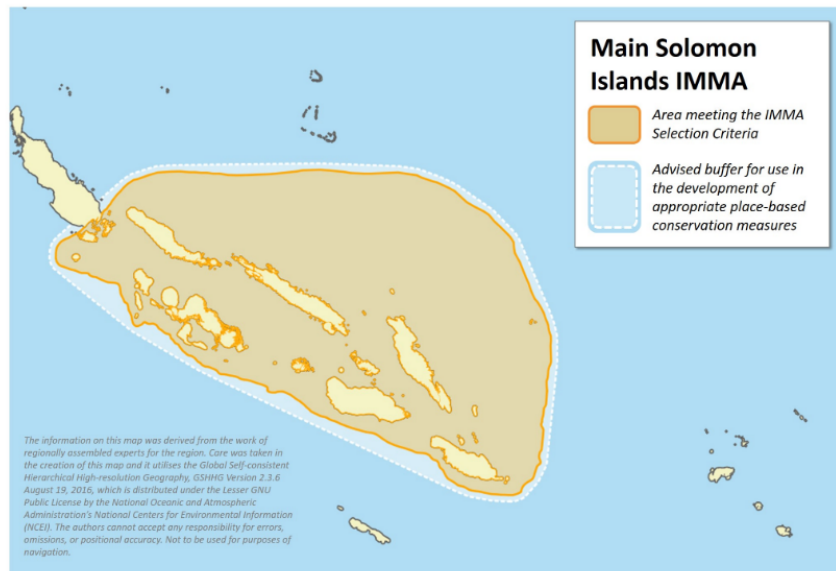


Figure 5.6: Important marine mammal area of the main Solomon islands²⁴

The MMPATF's summarized report²⁴ on why and how this area is important to numerous marine mammals : The Main Solomon Islands IMMA includes coastal and off-shore waters located in the north-west part of the Solomon Islands, around the islands of Guadalcanal, Malaita, Santa Isabel and New Georgia. Overall, knowledge on marine mammal populations in the area remains scarce but a few dedicated surveys have highlighted a high diversity of species (21) and this is an area of aggregation for Omura's whales. Photo-identification and genetic data support the presence of small, resident, populations of coastal dolphins, that are genetically distinct from neighbouring populations (spinner dolphins and Indo-pacific bottlenose dolphins). Finally, dugongs (Vulnerable on the IUCN Red List) are widely distributed in the IMMA.

5.3.4 OTHER PLANNED AREAS

New Zealand, Vanuatu islands, and the Clarion Clipperton Fracture Zone (CCZ) are located outside any IMMA as reported by the MMPATF. Nevertheless, the Vanuatu archipelago is now candidate for becoming an IMMA, moreover, not being classified as IMMA doesn't mean marine mammals don't inhabit the area, it just means it has not yet been observed as important to their survival. It is still our responsibility to impeach any harm to the animals inhabiting the mining areas.

5.4 PRESENCE OF THE MARINE MAMMALS IN THE TEST AND PLANNED AREAS

The presence of marine mammals in the listed areas is summarized in table 3.3.

Hearing group	Species	Bismark Sea (IMMA)	NW Med. Sea (IMMA)	Fidji (IMMA)	Solomon (IMMA)	Vanuatu (cIMMA)	N. Zealand	Tonga (IMMA)	CCZ	IUCN red-list
LF	Omura's whale				Bii					Data deficient
LF	Humpback whale			A, Cii	X	X	X	A, Bii, Ci, Di	X	Least concern
LF	Fin whale	Dii	A, Bii, Ci, Cii						X	Vulnerable
LF	Blue whale	Dii					X		X	Endangered
LF	Bryde's whale				X			X	X	Data deficient
LF	Sei whale				X				X	Data deficient
LF	Southern right whale						X			Least concern
LF	Minke whale			Dii	Dii				X	Least concern
MF	Sperm whale	A	A, Ci, Cii	Dii	Dii		X		X	Endangered
MF	Killer whale	Ci, Cii		Dii	Dii		X		X	Data deficient
MF	False killer whale	Dii		Dii	Dii				X	Data deficient
MF	Spinner dolphin			Bi, Ci	Dii	X		Bii, Ci, Di	X	Data deficient
MF	Hector's dolphin						X			Endangered
MF	Irrawaddy dolphin				Dii					Endangered
MF	Short-beaked common dolphin				Dii		X			Least concern
MF	Risso's dolphin	Dii	Ci, Cii		Dii				X	Least concern
MF	Common bottlenose dolphin	Dii	Dii	Dii	Dii		X		X	Least concern
MF	Indo pacific dolphin	Dii			Bi					Data deficient
MF	Pantropical spotted dolphin	Dii		Dii	Dii	X			X	Least concern
MF	Fraser's dolphin	Dii			Dii	X		X	X	Least concern
MF	Striped dolphin		Dii		Dii	X			X	Least concern
MF	Rough toothed dolphin				Dii				X	Least concern
MF	Short finned pilot whale	Dii		Dii	Dii	X		X	X	Least concern
MF	Long finned pilot whale		Dii				X			Least concern
MF	Cuvier's beaked whale	Dii			Dii				X	Least concern
MF	Blainville's beaked whale	Dii	Dii		Dii	X		X	X	Data deficient
MF	Melon-headed whale	Dii			Dii				X	Least concern
MF	Pygmy killer whale				X				X	Least concern
MF	Longman's beaked whale								X	Data deficient
MF	Hector's beaked whale					X		X		Data deficient
MF	Ginkgo-toothed beaked whale					X		X		Data deficient
MF	Andrew's beaked whale						X			Data deficient
HF	Pygmy sperm whale	Dii			Dii			X	X	Data deficient
HF	Spectacled porpoise						X			Data deficient
SI	Dugong	X			A	X				Vulnerable
OW	New Zealand sea lion						X			Endangered
OW	Fur seal						X			Least concern
PW	Leopard seal						X			Least concern
PW	Elephant seal						X			Least concern
PW	Monk seal		Dii						X	Endangered

Figure 5.7: Summary of simple presence (noted as X) or MMPATF criterion of marine mammals for each area (test or planned for mining). Hearing groups 3.3, and IUCN red-list status are also specified.

5.5 POTENTIAL CONSEQUENCES

5.5.1 DISPLACEMENT

A lot of the mining or tests zones lie in critical areas for several species (see 5.7) As seen in chapter 3, short-term displacement of the animals exposed to abnormal noises is more than likely to occur. Acknowledging these elements demands that displacements of the animals occur in small enough surfaces and times to allow the animals to pursue their normal activity, without which their populations could be endangered.

5.5.2 HEAR LOSS

INSTANTANEOUS SEL

For instantaneous exposures the noise emitted by the FPSO, the pumps, or the ground machines (considered as non-impulsive sounds) are below the PTS onset thresholds for marine mammals. Nevertheless, they are above the TTS thresholds for High frequency (HF) cetaceans. It is worth reminding that TTSs are not to neglect, as they can trigger dangerous long-term impacts on animals (see section 3.3).

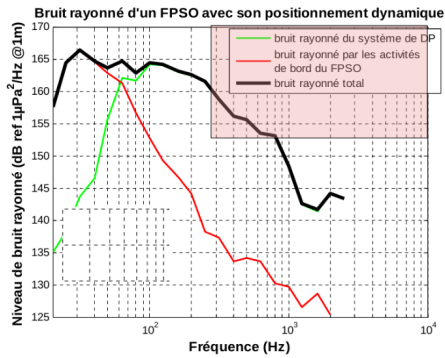


Figure 29 : Niveau spectral de bruit rayonné d'un FPSO moyenné sur bandes en tiers d'octave

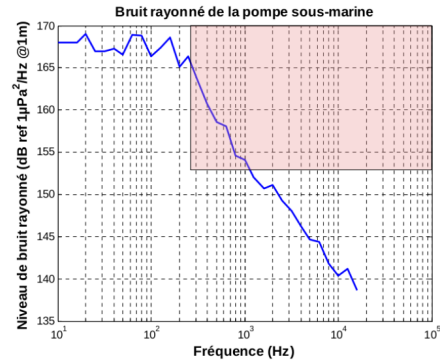


Figure 33: Niveau de bruit rayonné en tiers d'octave moyenné d'une pompe sous-marine

Figure 5.8: FPSO and pump noises overlap with TTS onsets for HF cetaceans (red rectangle) for instantaneous exposure (see Figure 3.3)

CUMULATIVE SEL

Information on the mining procedure's duration are lacking. We thus consider a constant SPL emitted by the pump, FPSO, and ground machines.

To get an idea of the potential cumulative exposures to the emitted sounds, we computed the SEL_{cum}^2 for a receiver travelling as shown by the scheme 5.9, at a speed of

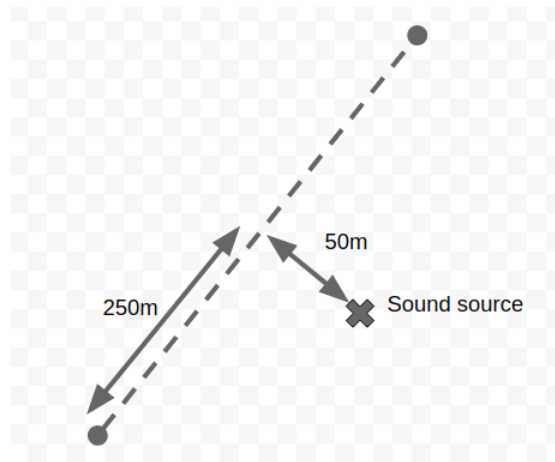


Figure 5.9: Potential travel of an animal near the noise source

m/s. Computing the transmission loss according to the distance²¹, and fitting a function to the estimated pump sound 5.10, allowed us to estimate the received sound level for each position.

By accumulating the SELs through the whole travel, we get a SELcum as shown in 5.11.

This curve intersects the onset of HF cetaceans for TTS (153dB starting at 275Hz). Which means that with any closer distance passage, or a louder noise (also taking into account the FPSO and ground machines' noises) would overlap with the TTS onsets of the HF cetaceans.

Those measures could be precised after running the tests, having the actual global sound exposure level maps. A good way of representing fauna perturbation around a powerful sound source is to draw borders around it, representing the range from which animals are subject to TTS or PTS 5.12

5.6 TEST'S PRECAUTIONS

Similar noise simulations for monitoring the impact on the local fauna have occurred²⁰. From their experience, The sound's simulation procedure (?which has not been detailed so far?) has to be set with care, since we don't want any unrealistic frequencies to be introduced by amplification processes. Marine mammal's impact will be relevant only if the sounds are strictly reproducing what will be emitted by the actual mining machines, pumps, and FPSO.

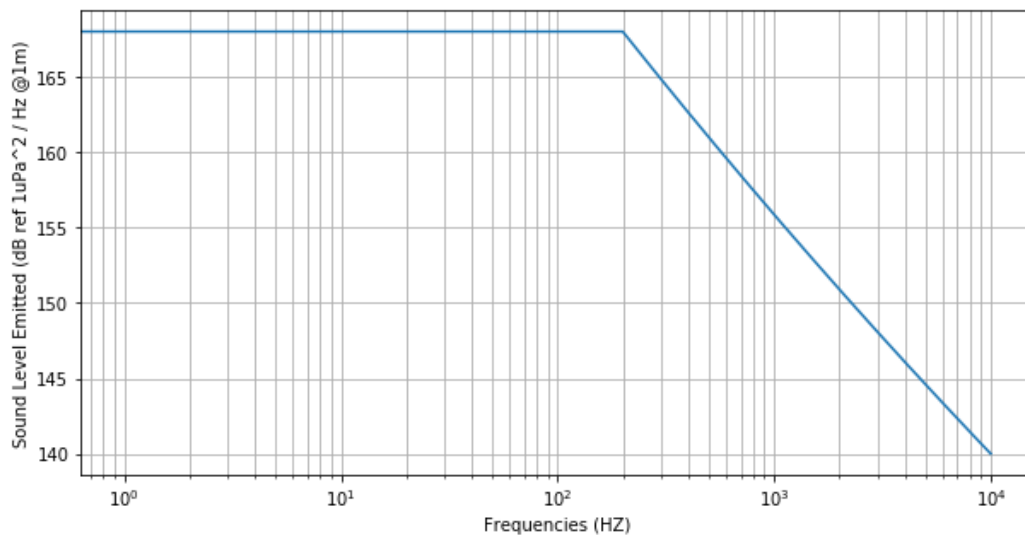


Figure 5.10: Fitted function for the pump's emitted sound

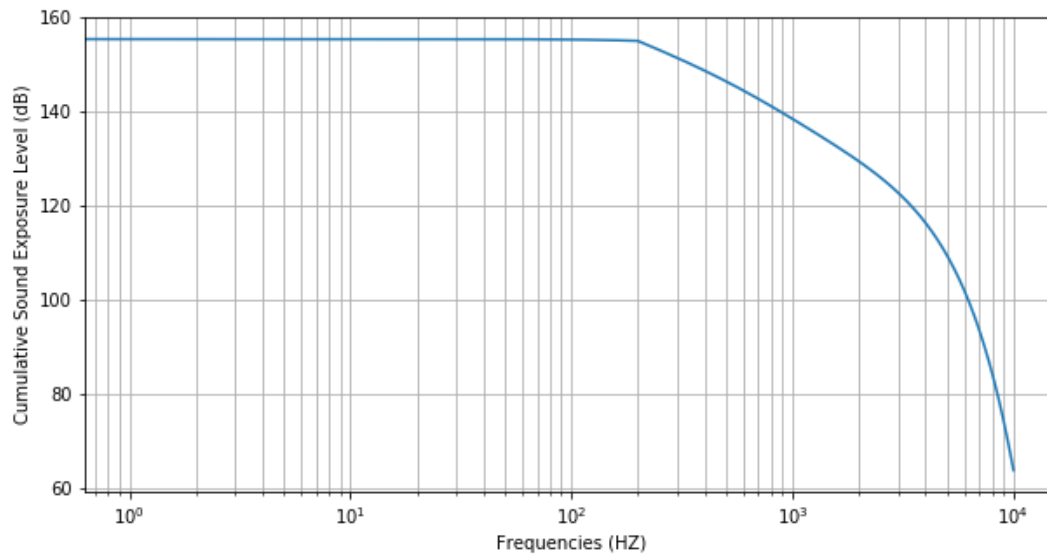


Figure 5.11: Cumulative Sound Exposure Level for the travelling receiver

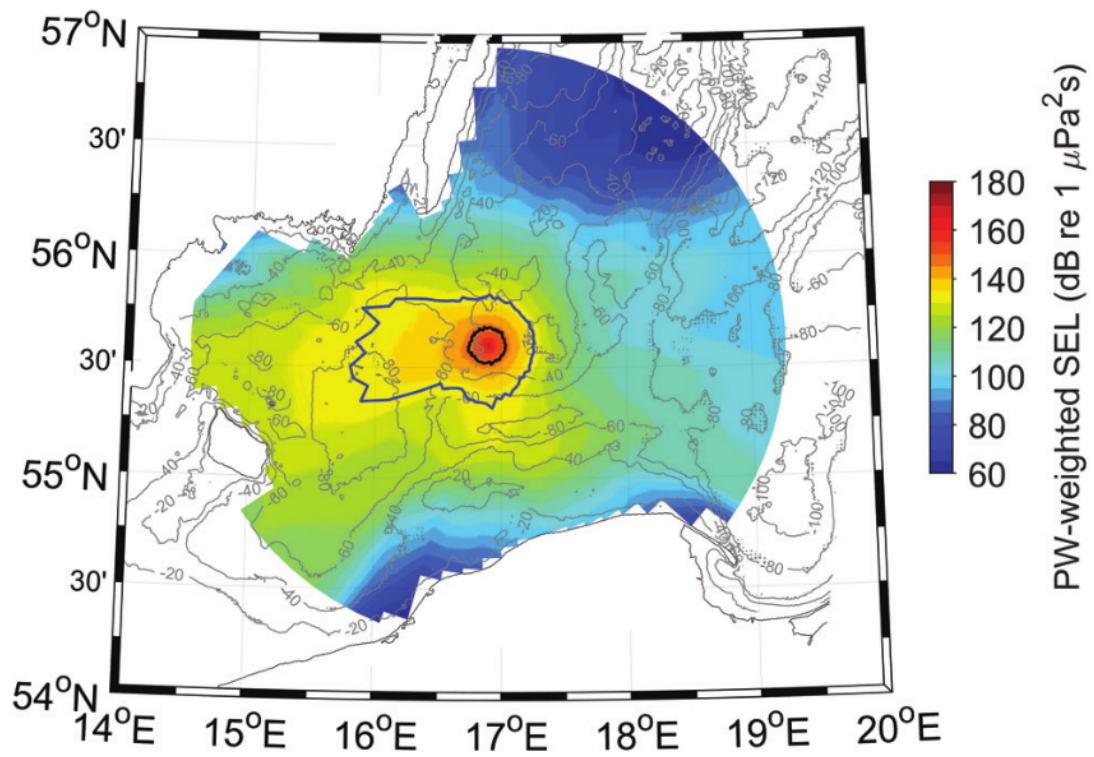


Figure 5.12: Visualization method for hear loss risks. Here in blue, the range from which animals are subject to TTS, and in black, the range of potential PTS.³⁸

6

Conclusion

The Abysound project can help the industries to monitor their acoustic impact on local marine mammals. For this purpose, measuring the emitted sound levels and the potential auditory damages of surrounding animals is important, but not sufficient. Indeed, the displacement of animals away from areas that are important to their well being (a.x. feeding / reproduction zones) can harm them critically. Technologies exist to automatically monitor the animals presence, localization, and activities, at relatively cheap costs. Abysound must gather and apply those techniques, and monitor the impact of sound on the surrounding animal's activities, to fully complete its initial goal.

For the Nautilus Mineral case, more data are needed for the scenarios, especially in terms of duration and periodicity. The tests are gonna provide more data on the emitted sounds and animal presence/reaction, which are gonna be useful for later studies.

For the ST Tropez tests end of april 2019, we proposed 6.1, a monitoring of the displacement of the animals using two static close to shore stations, combined with one mobile station (drone²⁹), or a similar antenna mounted on a Zodiak). Those static and mobile stations would be sufficient to monitor the presence and activity of marine mammals (most probable in this area and time are several species of dolphins) before, during, and after the sound emissions. We would then be able to correlate the displacements and activity changes with the sound emissions.



Figure 6.1: Example of placement of the static and mobile stations

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