Listening to cetaceans

Auteur :
PATRIS Julie, Docteur, professeur agrégée à l'Université d'Aix-Marseille, Laboratoire d'Informatique et Systèmes du CNRS, équipe DYNI

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From the famous modulated song of humpback whales to the ultrasound sonar of pink dolphins in the Amazon, the mammals inhabiting the oceans and rivers have developed ways of using sound that amaze us more and more every day. Why sound? What kind of sounds? How can researchers study these modes of communication or location, and what do they tell us about our giant cousins in the seas? These are some of the questions that marine bioacoustics [1], a discipline that combines biology and physics, but also computer science, ecology, data processing and oceanology, is trying to answer.

1. Sound in the ocean

1.1. The Importance of sound waves in water

Water (especially salty water) **conducts electricity**. As a result, electromagnetic **waves** (light, radio waves, etc.) propagate quite badly, which explains why the sea is an extremely dark environment as soon as the depth reaches a few tens of metres. Although most marine animals, especially mammals, have very powerful eyes, these cannot be used as effectively as in terrestrial environments, at least not for long-distance exchanges. On the other hand, **sound propagates** well there, **more rapidly than in the air**, and is little attenuated. As a result, many marine animals use sound to collect or transmit information, just as humans do for their installations and vessels (submarines, surveillance or geological prospecting devices).

1.2. Physics of sound in the ocean

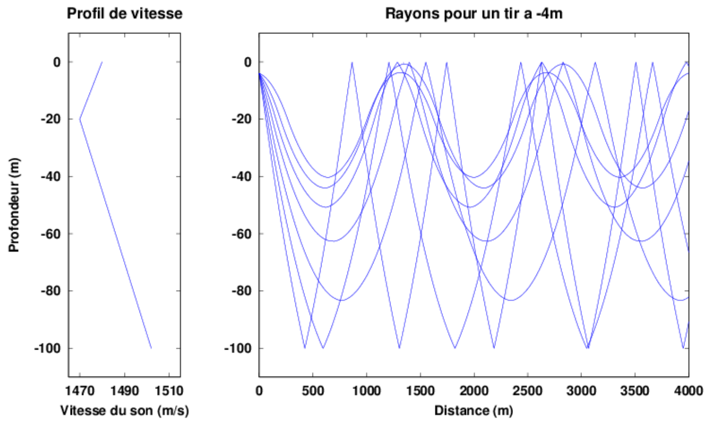

Figure 1. Modelling sound propagation in water. Rays from the same point are channelled into the water layer corresponding to the minimum sound velocity. [Source: Author's modelling]

The physics of sound is described in this encyclopedia (See: The Emission, Propagation and Perception of Sound). **Sound** is defined as the **propagation of an overpressure**, often measured in decibels (i.e., a logarithmic unit that can be used to accurately measure both very strong and much weaker values). The definition of the pressure in **decibel** is P(dB) = *20 log10 (p/pref)*. It requires a reference pressure *pref*; for practical reasons, this is **not the same in air and water**. Conventionally, if the *pref* reference pressure is 20 µPa in air, it is 1 µPa in water: it is therefore not possible to compare a decibel level in water with measurements taken in air.

The **speed of sound** in water **varies** with **depth** along the water column. This creates acoustic "waveguides" that allow sound to propagate very efficiently over long distances. The diagram shown in Figure 1, obtained by modelling the propagation of sound in the water by "acoustic rays" shows that the rays coming from the same point, instead of diverging regularly (and possibly being absorbed by the bottom) are channelled into the layer of water corresponding to the minimum of the speed of sound.

1.3. Recording underwater

Figure 2. Preparation of an acoustic antenna by the LIS team on the Amazon for recording river dolphins (Inia goeffrensis). [Source: Photo M. Trone]

Since the middle of the 20th century, rather simple devices have allowed us to study sound in water. At present, the measuring chain is generally made up of:

a sensor, the **hydrophone** (aquatic microphone), normally based on the properties of piezoelectricity and provided with a soft envelope allowing its acoustic adaptation to the environment;

a **recorder**, a device that digitizes the signal (after possibly filtering it) and stores it in a digital form. The digitization step involves the sampling rate and resolution, parameters that will depend on the type of sound being sought.

The signal thus acquired can then be processed or analysed, either manually or by automated procedures (Figure 2).

1.4. View sound

To **analyse a sound**, acousticians have a tool provided by 19th and 20th century mathematics: the **Fourier transform**. Thanks to this processing, it is possible to shift the signal from the time domain (pressure varies with time) to the frequency domain. The frequency domain allows a sound to be analysed according to its high frequency or low frequency components, in the same way that a colour spectrum allows the components of a light beam to be assessed. By making certain hypotheses, we can then visualize the sound in a **representation** called **"time-frequency"**, which allows us to see its frequency content as a function of time. This representation, based on advanced mathematical theories, allows a visualization close to a musical score!

Video 1. Illustration of the time-frequency representation of a sound. Time is on the x-axis and frequency on the y-axis, with colour representing intensity. We can see that a sinusoidal sound of the whistling type corresponds to an intensity concentrated on a single frequency (here of the order of a kilo Hertz), possibly variable when the sound is modulated. On the contrary, a snap is a short sound (localized in time, here at seconds 6 and 7) but whose energy is distributed over a wide frequency band.

2. Sounds produced by aquatic mammals

2.1. Which aquatic mammals?

Figure 3. The Amazonian pink dolphin (Inia geofrensis), a freshwater cetacean from Latin America. [Source: Photo J. Patris]

An **aquatic mammal** is defined by the time it spends in the water: thus, polar bears are currently considered marine mammals. However, we will focus here mainly on the most 'specialized' aquatic mammals, grouped mainly in the sub-order of cetaceans, as well as the order of carnivores (which includes phocids and otarids) and sirenians. They generally live in the ocean, and sometimes in rivers or lakes (Figure 3), and have little (carnivores) or no (cetaceans, sirenians) contact with land. Some are mainly coastal and remain at shallow depths, but many species can hunt at very great depths, sometimes down to more than a thousand metres. Despite this way of life, and their appearance close to that of a fish or shark, they are mammals that suckle their young and breathe in the air [2].

2.2. Examples of sounds produced

Noise emissions from **aquatic mammals** are extremely varied and cover a part of the acoustic spectrum far beyond human hearing [3]. For example, the largest rorqual whales (blue whales, fin whales, etc.) can produce very intense infrasound for up to a few tens of seconds. These emissions, whose frequency is around ten Hertz, are among the strongest in the animal world: they reach 190 dB (reference 1µPa) at one metre (the level of a large commercial ship at average speed). The intensity of these sounds enables large marine mammals to communicate over distances of **several tens of kilometres**. In contrast, porpoises and river dolphins emit brief and repeated ultrasounds, called "**clicks**", which can reach extremely high frequencies of several hundred kHz.

Between these two extremes, we will also find dolphin **whistles** (such as those of the bottlenose dolphin, but also those of killer whales or pilot whales) presenting a great variety, often in frequencies perceptible by humans (a few kHz). Similarly, the vocal repertoire of humpback whales has made them the "stars" of underwater bioacoustics, ranging from deep roars to multiple squeaky or modulated sounds that are quite remarkable and accessible to the human ear.

Video 2. **Example of sounds produced by the bottlenose dolphin** *(Tursiops truncatus*). We will recognize the whistles, high-pitched, frequency modulated sounds (between 5kHz and 20 kHz), the clicks, short and wide band (of which only a part is recorded here, the rest going too high in frequency for the recording device), as well as short barks at low frequency (around 1 kHz).

2.3. Biological function of some particular sounds

Figure 4. Bottlenose dolphin (Tursiops truncatus). [Source: © Willy Volk, Flickr (CC BY-NC-SA 2.0)]

These different sounds are involved in **various biological functions**. For example, short '**clicks**' are a characteristic shared by all odontocetes (or toothed cetaceans, such as dolphins, porpoises, sperm whales or the little-known group of toothed whales or *Ziphius*). They play a major role in the **orientation** of these animals, which are hunters pursuing and catching their prey in a targeted and dynamic manner in the dark depths. These clicks have the same function as those of bats: they allow the animal to locate a prey or obstacle thanks to the echo sent back. This function is called **echolocation** (see Focus Echolocation).

Some baleen whales (or true whales, or mysticetes) emit **modulated sounds** that are repeated in highly structured series. These series are called "songs", by analogy with the songs of birds. These songs seem to be the prerogative of males, and therefore probably have a function related to reproduction, such as attracting the attention of females or competition between males. Moreover, these songs are sometimes **true dialects**, which make it possible to distinguish different populations or clans of the same species (See Focus The decline in frequency of blue whale songs).

A third example is the **whistling** of some dolphins, such as the bottlenose dolphin (*Tursiops truncatus*), which has been shown to transmit a "signature" specific to an individual [4]. During the encounter between two individuals, each one repeats his 'signature', sometimes until the other one repeats it in turn, probably as a mark of recognition of his interlocutor (Figure 4).

3. Passive acoustic monitoring

Figure 5. The fixed hydrophone: an inexpensive and minimally invasive technique for exploring the local acoustic landscape. Here, a device placed on a buoy in northern Chile. [Source: Author's photo]

Sound is widely used by aquatic mammals and can be extremely useful for studying them. In contrast to "active" acoustics, which consists of emitting sounds and studying the behaviour of reflected or transmitted waves (a use like medical ultrasound, for example), passive acoustics is defined as simply **recording sounds in the environment**. No energy is transmitted to the environment being studied: it is therefore a very minimally invasive method a priori.

A variety of techniques are used, which allow access to different data, are more or less expensive and have a greater or lesser impact on the object of study. Placing a device directly on the animal under study ("tag") is undoubtedly the most delicate: several studies have shown that it can modify the behaviour, and in some cases even injure the host [5] - on the other hand, it can lead to spectacular results at the level of an individual, such as the depth at which sounds are emitted, the energy produced, but also to verify which species is at the origin of a given sound.

Other devices are used from a boat:

these include **antennas** consisting of several hydrophones **towed behind a ship**. These techniques are useful for population censuses, allowing "acoustic transects" to be made, which are generally complementary to visual counts.

the installation of one or more **fixed sensors**, on buoys or on the bottom, is one of the simplest and least invasive techniques (Figure 5).

These devices generally operate "blind" since **no visual data** are added to the recorded sounds, but they are safe, inexpensive, durable techniques that allow local, long-term population censuses and the precise study of the characteristics of a particular vocalization.

4. Some results obtained by bioacoustics

In the fifty years of its existence, the bioacoustics of aquatic mammals has produced some interesting advances, of which we highlight a few examples here.

4.1. Physiology

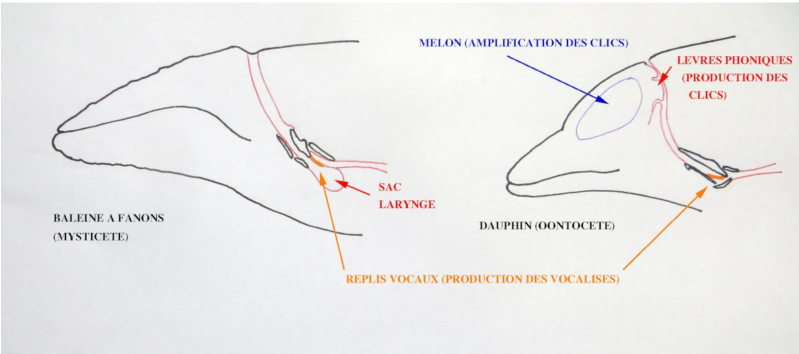

Figure 6. Location of the main elements of sound production in cetaceans. [Source: diagram by J. Patris after Reidenberg, [6]]

Cetaceans present physiological adaptations to their environment that sometimes distinguish them in a spectacular way from other mammals: the most obvious example is size, the blue whale being the largest known animal, living or fossil.

However, studying the physiology of animals of this size is a challenge, since for many species, we only have stranded animals that have been dead for quite a long time. In particular, the **mode of sound production by large cetaceans remains largely mysterious**. Nevertheless, recent studies mixing dissections of stranded animals, analysis of sound types, physical models reconstructed in the laboratory and computer simulations, have shown two main sources of sound production (Figure 6).

Vocalizations (whistling, roaring, etc.) are produced by the passage of air through "**vocal folds**" (an equivalent of the vocal cords, at the level of the larynx) but without expulsion of air, which circulates between the lungs and a closed circuit, the " **laryngeal sac**" [6].

The production of **"clicks"** by odontocetes is due to a specialized organ (the phonic lips). The sound is then amplified in the **melon** (protruding part of the head of odontocetes, from dolphin to sperm whale). The melon serves to amplify the sound and to focus it in a specific direction.

The knowledge of the role played by the melon has notably given rise to an interesting strategy for the study of sperm whales: the capture and study of the "clicks" emitted by an individual allows to obtain an **estimate of its size**! Indeed, a series of bounces in the melon can be detected, and the time between bounces makes it possible to evaluate the size of the animal's head. As this species has a strong sexual dimorphism (males are on average 50% larger than females), we can therefore know whether the individual is an adult male, or whether it is a female or a young male (both having the same size) [7].

4.2. Behaviour

Passive acoustic monitoring also makes it possible - with minimal disturbance - to gain insight into the behaviour of individuals. For example, by recording the clicks of a sperm whale during a dive, its **trajectory could be reconstructed**. The video below (Video 3) shows the movements of the animal, which reaches a depth of several hundred meters, but also the success of its search for food: it is indeed estimated that an acceleration of the rhythm of the clicks corresponds to an active hunt (the prey is spotted and pursued) and that the silent interval marks the moment of capture and absorption of the prey (a cephalopod in general).

Video 3. *Link of the video: click here !* **Three-dimensional animation showing the trajectory of a sperm whale reconstructed from acoustic recordings** [8]. You can hear the recording and read the time between two clicks. The periods of acceleration of the clicks, followed by a silence, are interpreted as an episode of successful hunting, with capture and ingestion of the prey (usually a squid).

Passive acoustics can also be used to understand the **so-called "cultural" behaviour of cetaceans**: a study published in 2013 highlighted the transmission of humpback whale songs from east to west in the western South Pacific basin. It was noted that "fashionable" themes towards Australia were taken up by males in New Caledonia the following year, and so on by different populations on an oceanic scale.

4.3. Population census

Counting the individuals of a species is always a difficult exercise; it becomes a challenge for aquatic mammals, for which many of the usual techniques are unusable: it is impossible to find traces or footprints, to place photographic traps...

With a few exceptions (stable coastal populations for example) **visual observations are difficult and not very effective**. Indeed, cetaceans are discreet, few in number compared to the immensity of the seas, and spend most of their time underwater, invisible. Finally, it is impossible to observe them as soon as weather conditions deteriorate.

It is therefore understandable that bioacoustics has an important role to play in the **detection and counting of individuals**, as it combines a few advantages:

surveillance can be conducted day and night,

the range of the instruments can extend to several tens of kilometres for some species (great baleen whales, in particular),

the instrument can operate for long periods of time (several months) at a reduced cost.

Despite this potential, the use of passive acoustic monitoring for population censuses is a **nascent technique**, which is encountering many difficulties [9]. The evaluation of the range of each instrument is a necessary parameter to make a statistical model of density, but it depends on the species, the intensity of the emitted signal, environmental conditions, the topology of the terrain, the response of the instrument... The sound signals emitted by cetaceans are for the moment not distinguishable between two individuals: it is difficult to know if the same individual has been heard many times or if the place is frequented by several individuals. Some species are very vocal at certain times, and totally silent at others, passing unnoticed.

However, it is possible to make comparisons between different acoustic surveys, and thus determine whether a species is stable in a given location, or whether its density varies with the seasons or years. The acoustic behaviour of species is also becoming better known. In addition, **sophisticated sound propagation models** are now available. Thanks to these tools, many studies have succeeded in overcoming the obstacles mentioned. For example, the very discrete *Ziphius*, or toothed whales, one of the first specimens of which, stranded on the Côte Bleue near Marseille, was described by Cuvier, are increasingly being identified by passive acoustic monitoring techniques involving a random mesh of floating buoys, capable of perceiving their probes at depth [10].

4.4. Protection

The density calculation described above is an essential means of population management and species protection. All techniques combined (strandings, visual and acoustic surveys, etc.), it has been shown that the Antarctic blue whale (Figure 7) suffered a catastrophic decline in numbers during the middle of the twentieth century, from some 300,000 individuals distributed throughout the southern seas to around 400 individuals recorded fifty years later [11]. Hardly more than **one individual in a thousand escaped hunting**, over a period of less than the average lifespan of the species! Current estimates tend to show a timid recovery (the number of individuals is currently around 1,000) that is still very fragile, more than 50 years after the first moratorium on blue whale hunting.

Bioacoustics can also be used to develop **real-time protective devices**. This is the case during underwater geological prospecting, a technique that consists of sending a very strong acoustic pulse into the marine environment to probe the subsoil (a giant ultrasound scan), which is highly invasive for the environment, especially for marine mammals. During these campaigns, scientists are responsible for permanent visual and acoustic vigilance: if cetaceans are spotted in the vicinity, the emissions are interrupted.

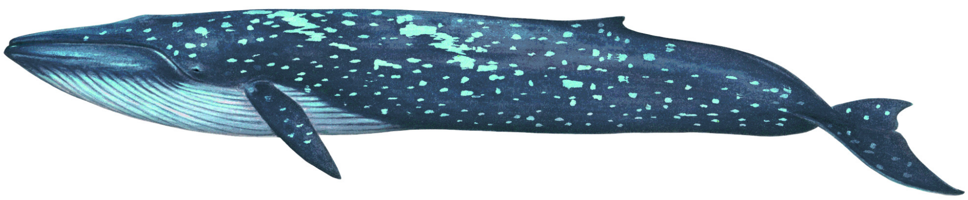

Figure 7. Blue whale (Balaenoptera musculus). [Source: Illustration by Andrés Calderón]

Another example [12] of a point protection device is installed in Boston Bay, USA. A set of underwater sensors detect the presence of the Atlantic right whale, the most threatened of the large cetaceans, classified as Critically Endangered by the IUCN. When a presence is detected, ships in the area are alerted and must reduce their speed (noise and collisions are the major risks currently weighing on this species [13]).

5. Messages to remember

All cetaceans and many pinnipeds use the **good propagation of sound in the water** to communicate, to find their way around, to feed, to identify dangers...

The goal of marine mammal bioacoustics is to understand **what sounds** aquatic mammals emit and what their **biological functions** are.

In addition to visual studies, this discipline is also used to **identify** endangered populations in order to **improve their protection**.

Notes and References

Cover image. A female humpback whale leaps out of the cold waters of the Strait of Magellan under the interested eye of a fellow whale. [Source: Cliché J. Patris]

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