JUMP

Joint Action: a stepping-stone for underwater noise monitoring in Portuguese water

Review of the state-of-the-art and selection of the acoustic propagation models to be used in the jUMP project

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1 SUMÁRIO EXECUTIVO

O principal objetivo do projeto jUMP é contribuir para a gestão sustentável do ruído subaquático e ajudar as autoridades nacionais a resolver os problemas do Descritor 11. Entre vários objetivos distintos, os modelos acústicos oceânicos são uma das ferramentas necessárias e utilizadas pela comunidade científica para estudar a propagação do som e as suas consequências no meio marinho. A modelação numérica pode simular cenários hipotéticos e avaliar a propagação sonora gerada por atividades humanas, como tráfego de navios ou mesmo a instalação de campos de geração de energia marinha (e.g. geradores eólicos ou oceanográficos), em águas oceânicas e costeiras. Além disso, essas ferramentas de modelação numérica podem aperfeiçoar o conhecimento sobre a propagação de som no ambiente marinho com uma fração muito reduzida dos custos normais de campanhas de campo e medições in situ.

Este relatório tem como objetivo apresentar uma breve revisão do estado da arte dos modelos acústicos numéricos marinhos e apoiar a escolha de dois modelos, Bellhop e Kraken, que serão implementados no portal de modelação desenvolvido durante o projeto. O portal de modelação acústica será um dos resultados do projeto e estará disponível gratuitamente para todas as comunidades científicas para fins de investigação. O presente relatório corresponde à primeira etapa do desenvolvimento de um portal de modelação adequado para apoiar os gestores costeiros, decisores políticos e a própria comunidade científica no estudo do descritor temático 11 da Diretiva-Quadro da Estratégia Marinha.

2 EXECUTIVE SUMMARY

The main goal of the jUMP project is to contribute to the sustainable management of underwater noise and help the national authorities to address Descriptor 11 problems. Among several distinct objectives, the ocean acoustic models are one of the tools needed and used by the scientific community to study sound propagation and its consequences in the marine environment. The numerical tools can simulate hypothetical scenarios and evaluate the sound propagation generated by anthropogenic causes, such as ships or even the implementation of marine energy generation farms in ocean and coastal waters. Furthermore, these numerical modeling tools can enhance the knowledge by simulating scenarios of sound propagation in the marine environment with a fraction of the costs of field campaigns and in-situ measurements.

This report aims to present a brief review of the state-of-the-art marine numerical acoustic models and support the choice of two models, Bellhop and Kraken, which will be implemented in the modeling portal developed during the project. The acoustic modeling portal will be one of the project's outcomes and will be freely available for all scientific communities for research purposes. The present report corresponds to the first step towards developing an appropriate modeling portal to support decision-makers and the research community in the thematic descriptor 11 of the Marine Strategy Framework Directive.

3 INTRODUCTION

Man's interest in sound dates to Ancient Greece, and the word acoustic itself derives from the Greek word *akouein*, which means heard. During this period, much of the research at the acoustic level was related to music (Rossing, 2007).

During the 18th and 19th centuries, several attempts were made to determine the speed of sound in the air. Still, it was not until 1816 that Pierre Simon Laplace corrected Newton and Lagrange's calculations and obtained correct values for the speed of sound propagation in the air. The speed of sound in water was measured in 1826 by Daniel Colladon in an experiment on Lake Geneva (Rossing, 2007).

Historically, the first developments in marine acoustics as the scientific area that we know today occurred during the two world wars and the cold war due to the need to improve the sonar systems essential for submarines' location (Jensen et al., 2011). The sonar systems developed by the Allies in World War II were crucial for this war's victory (Rossing, 2007). Technological and computational developments have enormously boosted marine acoustics developments in the past 60 years through increased processing capacity, better measurement instruments, increased digital storage capacity, or implementation of GPS systems (Duda et al., 2008).

The first modeling attempts were based on theoretical solutions of the ray method. The following approach was the normal method with the implementation of elastic waves that allowed the modeling of shallow water environments (Bjørnø et al., 1999). In the 1960s, this technique started to consider the adiabatic and coupled-mode approach, allowing the modeling of more complex environments (Duda et al., 2008).

Other techniques ended up being conceived, such as the parabolic equation in the '60s. The increase in computational power enables the adoption of more complex approaches, and in 1990 there was a significant development in the knowledge of the acoustic field structure. The better modeling ability allowed the study of ocean fronts, internal waves, and oceanic vortices. In the last two decades, several methods have adopted and considered the three-dimensional component. In addition, the monitoring of sound in the ocean has grown, promoting the study of tidal acoustic effects, mesoscale structures, noise, among others (Duda et al., 2008).

Thus, computational advancement allowed the improvement of aquatic acoustic models and the development of new methods. There are currently several applications, such as the description of acoustic communication channels, the propagation of sound on a global scale, the prediction and characterization of environmental noise caused by human activities, and the monitoring of long-term variations in the ocean.

It is essential to have a balance between numerical modeling and observations or laboratory experiments. Thus, numerical modeling can be seen as a stage in the scientific method between theory and experimental activities (Etter, 2018).

In the current report, a brief theoretical description of the propagation of sound in the ocean is presented in section 4. In section 5, the principal methods used for the study of the propagation of the acoustic signal in the marine environment are described. In the last section, a concise summary of the models chosen for the current project is presented.

4 THEORETICAL BACKGROUND

4.1 The sound in the aquatic environments

Sound is the propagation of a mechanical compression front. Therefore, it is a longitudinal wave that propagates in three dimensions and only in material media. In the longitudinal waves, the particles vibrate around their equilibrium position with no displacement.

The speed of sound is one of the fundamental variables for studying acoustic propagation. For aquatic environments, this speed will depend on salinity, temperature, and pressure (depth). However, as the salinity is almost constant in deeper waters, it will not be a very relevant parameter for the acoustic field.

On the other hand, the sound speed will increase with temperature and pressure, so the profile results from combining the two variables (Talley et al., 2011). An example of the possible profiles of temperature, pressure, and speed of sound with depth is shown in Figure 4.1:

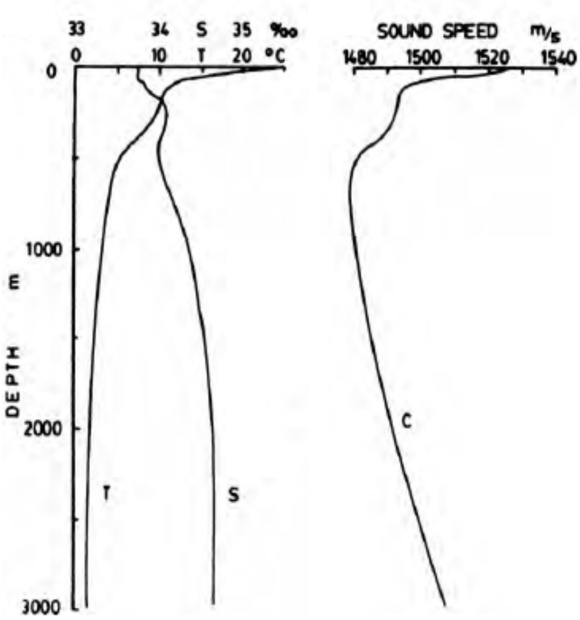

Figure 4.1: Temperature (°C) profile, salinity (PSU) profile, and resultant in situ sound-speed profile for a station in the Pacific Ocean (39ºN, 146ºW), August 1959. (Talley et al., 2011)

In general, there is a minimum speed of sound of 1485 $m.s^{-1}$ at 1000 m. Although there is only a 3% variation in speed, the consequences for propagation are essential. The depth where the speed of sound is minimal is called the SOFAR channel (Sound Fixing and Ranging) and has the particularity of propagating the sound with little attenuation over great distances (Tindle, 2017).

4.1.1 Distribution of the speed of sound

Close to the surface, there is the sonic layer where the speed is influenced by the heating and cooling of the surface and the wind's action. This layer is also associated with a maximum surface speed of sound (Figure 4.2).

Under the mixing layer, there is a thermocline, which is characterized by a marked sharp decrease in temperature with depth. In this way, there is a negative gradient in the speed of sound. Below the thermocline and to the bottom of the ocean, there is an isothermal layer with an approximately constant temperature. In this region, the speed of sound increases due to the effect of pressure and has an almost linear profile with a positive gradient (Etter, 2018).

It is between the negative gradient in the thermocline and the positive gradient in the isothermal layer that the minimum speed of sound exists. Thus, schematically the distribution of temperature and speed of sound can be given by Figure 4.2:

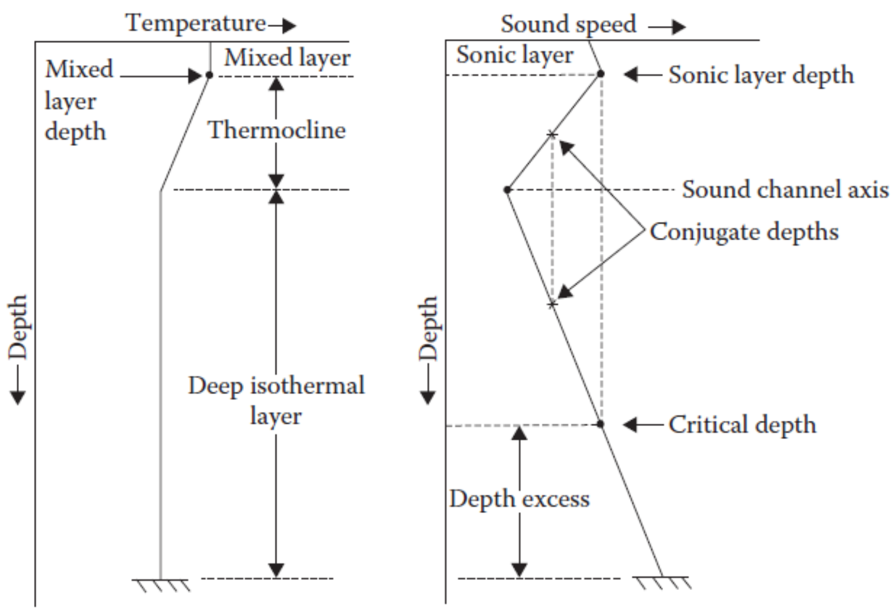

Figure 4.2: Illustrative diagram of the temperature and speed of sound profiles. (Etter, 2018)

4.1.2 Calculation of the speed of sound

The speed of sound can be determined directly using speedometers and indirectly using mathematical formulas that are a function of salinity, temperature, and pressure/depth. As a rule, the speed of sound is obtained indirectly since the algorithms are highly accurate for most applications, and the temperature, pressure, and salinity profiles are of more interest for the oceanographic study. One of the oceanographic instruments used to collect temperature data as a function of depth is the bathythermograph (BT) or a disposable version of the XBT (Etter, 2018).

Several empirical expressions have been developed over the years with different domains of applicability, associated error, and the number of terms present. The simplest algorithm (Eq. below4.1) was developed by Medwin (Medwin et al., 1998):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016z \quad (4.1)$$

In which T represents the temperature in degrees Celsius, S the salinity without physical units with a numerical value equal to the mass of dissolved salts, and z correspond to the depth in meters.

4.2 Sound rays

The distribution of sound rays in the ocean obeys the law of Snell's (Eq. 4.2), and thus, locally, it is found that the sound rays are turned concave up in places where the speed of sound (c) is less (minimum).

$$const = \frac{cos\theta}{c} \quad (4.2)$$

The various types of propagation are illustrated in Figure 4.3. Points A, B, and C are the minimum sound speed. The rays A and B are in the surface sound duct where the minimum is at the ocean's surface. On the other hand, ray C already reaches higher depths reaching the deep sound channel, where the sound propagates over long distances with minor loss. The ray D finds a convergence zone (CZ), a spatially periodic phenomenon that creates a high-intensity zone close to the surface caused by refraction. Reflection with the ocean floor (ray E) is also a cyclical event, but with shorter distances from each other and travels a shorter propagation distance due to losses (Jensen et al., 2011).

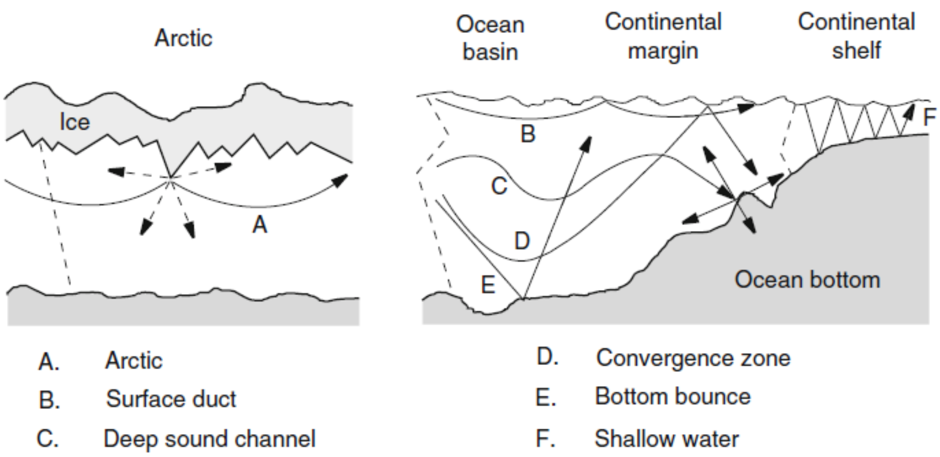

Figure 4.3: Scheme illustrating the various types of propagation present in the ocean. (adapted from Jensen et al., 2011)

The deep sound channel is also called the SOFAR channel (Sound Fixing and Ranging), and the propagation of the sound is done through refractions, which implies a propagation that reaches large distances since, there is no reflection with the borders and consequently negligible losses (Tindle, 2017). However, the efficiency of this channel varies with latitude since the depth of the minimum speed depends on latitude, and the more superficial this minimum is, the greater the interactions with the surface, which results in losses.

The convergence zone is a phenomenon that occurs in deep waters in which the sound emitted by a source close to the surface reaches the bottom and, through refraction, reappears on the surface, creating a zone of high sound intensity. The occurrence of these zones allows the transmission of acoustic signals with high intensity over long distances (Jensen et al., 20 11).

The sound field is the sum of all the rays between the source and the receiver, and these paths of the rays are called eigenvalues. These eigenvalues can be known through numerical processes where the rays are tracing at a certain angle until they have the same length as the distance to the receiver. Then, the angles are adapted until the rays pass an acceptable distance from the receiver (Tindle, 2017).

As a rule, there are four different trajectories since the rays can leave the source traveling up or down and reach the receiver from above or below, as shown in Figure 4.4.

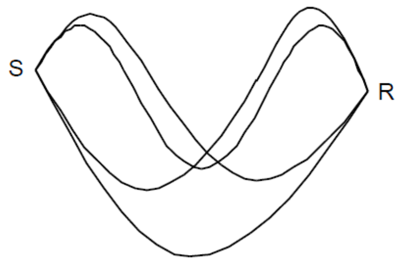

Figure 4.4: Schematic illustration of the possible trajectories between the source and the receiver. (Tindle, 2017)

A caustic zone exists when acoustic beams with different angles form a boundary (curve of a set of rays) from a shadow area where the rays do not reach and an insonify zone with two rays of each point. One must take special care with these areas because it generates infinite energy situations in the simulations (Tindle, 2017).

There is an infinite number of modes in the ocean, but only a part can travel long distances. The propagation of the modes will depend on the frequency, density, composition of the ocean floor, and speed of sound. The modes that are not propagated are the evanescent modes (Wang et al., 2014). The modes that only propagate in the water column are the discrete modes, and those that propagate through the bottom are the continuous modes.

Sonars can be defined as water radars, but instead of using radio waves, they use sound waves to analyze the environment. It is an instrument that operates using acoustic waves since the ocean is opaque to most of the electromagnetic spectrum but has little absorption of acoustic waves facilitating the propagation of sound (Ainslie, 2010). Passive sonar detects the sound referring to the object of interest, while active sonar signals and receives its echo.

Marine noise can be defined as an unwanted background sound at a given location in the ocean during a given period (Etter, 2012). Reverberation is created when a sound is reflected several times and dispersed across the domain's boundaries or an inhomogeneous object before it reaches the receiver. It is a sound that ends up being produced by the sonar itself (Ainslie, 2010).

Depending on environmental factors, there are two subcategories, models that are range-dependent and those that are range-independent. When there is range independence, horizontal stratification is assumed, in which the properties only depend on the depth. On the other hand, range dependence implies that some properties vary with distance, depth, and azimuth (Jensen et al., 2011).

Coastal areas are characterized by significant spatial and temporal variability, which makes them acoustically complex environments. In addition to the interactions with the bottom being significant, there may be hydrography with high seasonality and annual phenomena, such as upwelling or jets. The ocean-atmosphere interactions are also intense, and an atmosphere-ocean model can be incorporated into the acoustic model to determine the initial conditions (Etter, 2012).

In deep water regions, there are propagation phenomena over great distances through deep sound channels and convergence zones. It is also possible that there are variations in the acoustic field due to mesoscale processes, variation of bathymetry, environmental variability, and internal tides (internal waves with the same frequency as the tides and are generated due to the surface movement created by the tide) (Etter, 2018).

Inversion is a process of determining system information by measuring physical characteristics. For example, in marine acoustics, the system is usually a part of the ocean that includes boundaries and the receiving emitting system (Havelock et al., 2008). In this way, the inverse method combines direct measurements with theoretical models for acoustic propagation in a marine environment. However, it should be noted that it is only possible to obtain parameters based on the model for the system. Therefore, the inversion process is constrained by the model and its limitations (Etter, 2012).

4.3 Sources of noise and spectrum

In the ocean are various noise sources with different features, and one of the possible environmental noise spectra for the open ocean is illustrated in Figure 4.5. This spectrum is divided into five bands in which the first refers to frequencies lower than $1\ Hz$ associated with tides, waves, and seismic activity, the second band is between $1-20\ Hz$ and is related to turbulence, the third band is $20-500\ Hz$, and is related to noise from maritime traffic to distance, the fourth band is between $500-50000\ Hz$ and is relative to surface noise and the last band with frequencies higher than $50000\ Hz$ is due to thermal noise caused by molecular movements (Etter, 2018).

The source of the noise can be natural or caused by human activities. Natural noise can be generated by earthquakes, wind on the surface, sea waves, rain, and marine living beings. Bioacoustic noise is caused mainly by mollusks, fish, and marine mammals and is associated with the dynamics of reef populations, including detection, retention, and orientation (Etter, 2018).

The rain also has a characteristic spectrum with a peak at $13-15\ kHz$, and the primary source of noise is the creation of bubbles at the time of impact on the surface. Methods have been developed to determine the amount of precipitation across the sound spectrum since indirect ways of establishing the precipitation are essential to improve knowledge of heat and water transfers from the oceans (Etter, 2018).

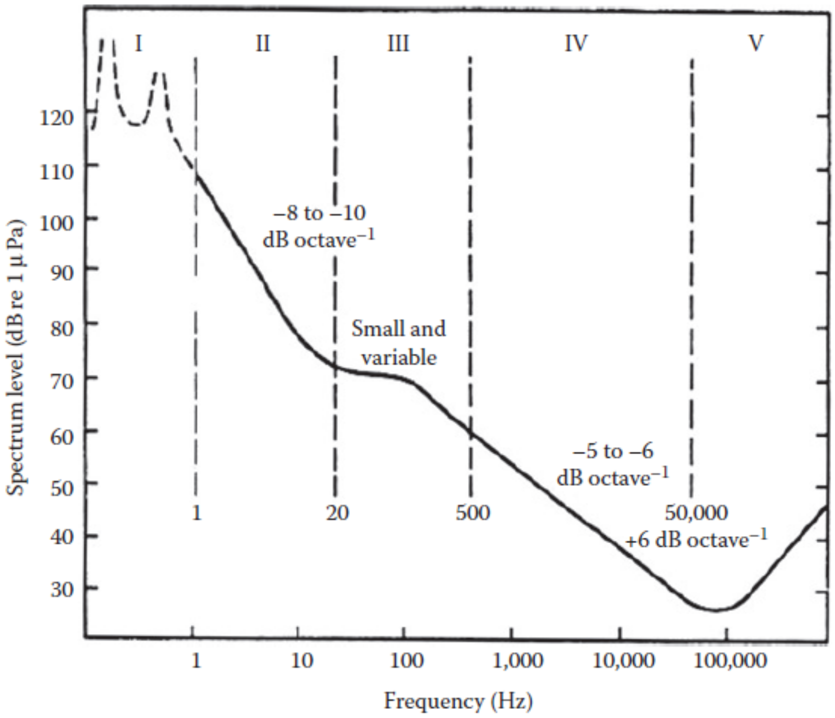

Figure 4.5: General spectrum of environmental noise in the deep ocean. It is divided into five frequency bands according to the spectral slope expressed in dB per octave of frequency (Etter, 2018).

The wind also plays a role in ambient noise that is produced mainly in the range of intermediate frequencies ($500\ Hz\ - 25\ kHz$), and it is difficult to detect this noise at lower frequencies due to its overlap with the noise of the ships that dominate these frequencies (Hildebrand, 2009).

4.3.1 Anthropogenic noise

Anthropogenic noises are produced by maritime traffic, oil or gas exploration, military activity, recreational water activities, and fishing. These activities are concentrated in coastal areas and continental shelf places that are important habitats for marine species.

One of the noises created by human activity is that associated with boats. Recent studies have shown an increased marine noise in various parts of the world, as the maritime traffic has increased, whether caused by large vessels or by smaller vessels. Through altimetry data, it appears that between 1992 and 2012, the global density of boats increased by a factor of 4, with the most significant increase being in the Indian Ocean (Erbe et al., 2019). The noise created by the vessels is generated by the hydrodynamic flow, mechanical equipment, and mainly by cavitation (formation of cavities filled with gas because of the movement of the propellers of the engines). In general, maritime traffic produces noise up to a frequency of $1\ kHz$. However, although the dominant frequencies are low, they can also reach tens of kHz (Southall et al., 2017).

Larger vessels generate more noise, but the peak is at lower frequencies when compared to smaller boats. The sound field produced is not isotropic with a predominantly downward direction. The noise spectrum of the boats shows spatial variability since it depends on the maritime traffic in the region and temporal variability associated with seasonality. In addition to these factors, the sound field created by the boats depends on their size, speed, and local environment (Erbe et al., 2019).

A vessel contributes to the region's noise in which it is located and to other regions since ship noise at high latitudes can propagate through deep sound channels to the subtropical/tropical regions. So low frequencies ($> 100\ Hz$) can spread over great distances by ocean sound channels (Etter, 2018).

Explosions used in seismic surveys, military functions, removal of structures are sources of noise that propagate equally in all directions and covers a regional scale. These explosions can be generated with chemicals but also with compressed air (Hildebrand, 2009). There is a wide variety of sonar for different functionalities that can generate signals in a sequence that can last for weeks or be sporadic and cover a wide range of frequencies, both lower and higher. The higher the frequency, the greater the attenuation; thus, frequency signals above $1\ kHz$ have a regional influence, while lower frequencies have a higher range (Ainslie, 2010).

Offshore wind farms create noise in the low-frequency range where the source level is highest during the construction period and lower levels during operational times. Oil exploration also contributes to an increase in noise at low frequencies. Traditionally, these activities were usually located in shallow water areas on the continental shelf, but with the increasing exploitation of these resources, exploration is already moving to deep water areas, facilitating the propagation of noise (Hildebrand, 2009).

Therefore, the noise spectrum at low frequencies is dominated by the sounds generated by the activity of the vessels and seismic surveying. At intermediate frequencies ($500\ Hz\ - 25\ kHz$), wind and sea waves are the primary sources of noise, and their propagation is more intense in the vertical since, in the horizontal, the attenuation processes are more intense.

Finally, at high frequencies, thermal noise dominates when the pressure fluctuations are associated with the thermal agitation of the ocean medium itself. Thus, thermal noise dictates the shape and level of ambient noise spectra above 50-100 kHz (NAP, 2003).

4.3.2 Consequences of noise for marine animals

Sound is an efficient way to propagate energy across the ocean, and thus, aquatic beings have developed capabilities to exploit this property. For several species, sound detection and production are fundamental for communication, reproduction, orientation, and predatory and protection mechanisms (Southall et al., 2017). The predominant sounds in the low frequencies characteristic of boats overlap the range of sounds used by many marine mammals, particularly whales, as shown in Figure 4.6.

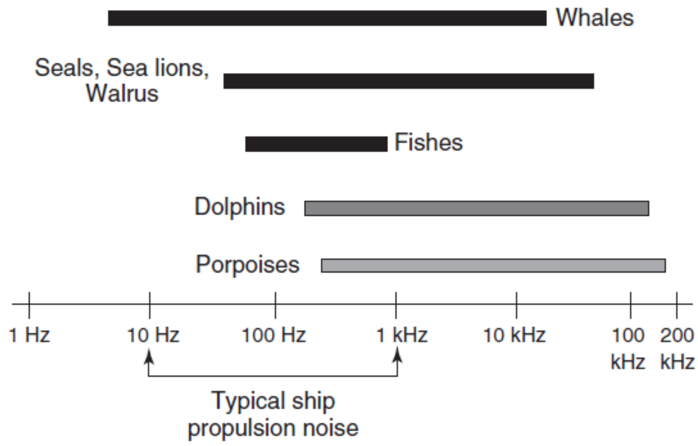

Figure 4.6: Comparison of the auditory frequencies of whales, seals, sea lions, walruses (walruses), fish (fish), dolphins (dolphins), and porpoises (porpoises) with the frequencies emitted by the vessels. (Southall et al., 2017)

In the presence of boats, the rate of vocalization increases, as does the range of frequencies used. For example, Humpback whales increase $0.8\,dB$ their vocalization for each increase $1\,dB$ in the environment. In general, there is a change in the peak frequency, and frequency range used when there is an increase in noise. Their breathing behavior is also altered, and they tend to move away from vessels (Erbe et al., 2019).

One of the metrics to study the impact of noise on mammals is the cumulative sound exposure levels, and another is the peak sound pressure levels. While the cumulative Sound Exposure Level (SEL) considers the level and duration of exposure, the peak sound pressure level is related to the transient components that can cause injury to the inner ear. Therefore, the peak sound pressure level was defined as twenty times the base-ten logarithm of the ratio between the peak sound pressure and the reference sound pressure (for water, the value is usually used is $1 \times 10^{-6}\,Pa$), in a given time interval and frequency (Küsel et al., 2019).

Studies show that aquatic mammals are more sensitive to pressure, and fish and invertebrates are more vulnerable to particle movement. Fish create sounds in the low-frequency range, predominantly between $100 - 500\,Hz$ (Hildebrand., 2009).

In general, it is difficult to accurately understand the scale of the impacts that the increased noise generated by human activities has on aquatic beings. Given that the behavior varies from species to species and even within individuals of the same species, for practical and economic reasons, it is not always possible to study the optimal number of individuals, and how the audible noise is a problem on a global scale is difficult to see what the default behavior is, as the current populations end up by having a chronic exposure.

5 ACOUSTIC PROPAGATION METHODS

5.1 Numerical modeling techniques

Regarding numerical models, different techniques are depending on the problem under analysis. Thus, there are propagation, noise, sonar, and reverberation models.

The propagation models determine the propagation loss due to absorption, diffraction, diffusion, and sound energy leakage in sound channels. The higher the frequency, the greater the propagation losses as a result of the absorption effects. The propagation of sound is influenced by background and surface conditions and variations in the speed of sound (Etter, 2012).

In the case of propagation models, six different methods solve the wave equation, each of which has a specific domain of applicability. Since a propagation model will be used for the work of this project, each of these methods will be described in the next section. All these models are derived from the wave equation, and they can be used for sonar applications. Sometimes it is also possible to combine two methods to develop a hybrid formulation that allows a broader domain of applicability.

The noise models are divided into two categories the environmental noise and the statistical beam models. Environmental noise models can be applied to a wide range of frequencies and are considered noises of biological origin, ships, commercial activities, and noise due to meteorological weather. On the other hand, beam models predict the noise of vessels at low frequencies using simulations or analytically (Etter, 2012).

Regarding the reverberation models, two types can be highlighted, cell-scattering and point-scattering. The first one divides the area into cells, where each cell is composed of one high number of scatterers evenly distributed, while in the second type, the scatterers are randomly distributed in the field.

The sonar models will encompass all the models described above together with signal processing to solve the sonar equations. In the case of passive sonar, it is possible to apply propagation and noise models, and with active sonar, it is more appropriate to use reverberation models (Ainslie, 2010).

There are also inversion techniques that aim to characterize the environment. It is a methodology used to compare with data obtained by remote sensing, estimate average ocean conditions, and monitor long-term variations.

The propagation models can infer properties of the water column, such as temperature, density, currents, and speed of sound. Regarding noise models, they can be used to obtain wind speed and precipitation measurements. Finally, the reverb models have the same uses as the noise models, but they also manage to obtain ocean floor images (Etter, 2012).

5.2 Wave Equation

All acoustic propagation models in a marine environment provide a solution to the wave equation (5.1), which corresponds to the fundamental equation's derivation for the moment and continuity. Of course, the exact expression will vary, but most applications use a second-order partial differential equation with linear simplification (Etter, 2018):

$$\nabla^2\Phi = \frac{1}{c^2}\frac{\partial^2\Phi}{\partial t^2} \tag{5.1}$$

Where, ∇^2 is the Laplacian operator, Φ is a potential function, c corresponds to the speed of sound, and t is time. If a harmonic solution is considered for the equation, the potential function will be:

$$\Phi = \phi\, e^{-i\omega t} \tag{5.2}$$

Where ϕ is the time-dependent potential function, and ω is the frequency of the source ($\omega = 2\pi f$). Through the harmonic solution, the wave equation (Equation 5.1) is simplified to the Helmholtz equation (Equation 5.3). One form of this equation is (Wang et al. 2014):

$$[\nabla^2 + k(r)^2]\emptyset(r,f) = 0 \tag{5.3}$$

Where $\emptyset$ is the solution that depends on the position vector (r) and frequency (f), and it is necessary to know the characteristics of the source, as well as the boundary conditions. The same equation (Equation 5.3) can also be represented using cylindrical coordinates (Jensen et al., 2011):

$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{\partial^2\phi}{\partial z^2}\, k^2(z)\phi = 0 \tag{5.4}$$

One of the quantities that is used in this scientific area and that is determined in some models is the propagation loss (or usually referred to as Transmission Loss - TL) that measure the strength of the signal and can be defined as the difference in pressure level between the field point and the point at 1m from the source and is expressed in decibels (dB) (Talley et al., 2011). In the case of the potential function (ϕ) representing the pressure field, the Transmission Loss (TL) presents the following expression (Jensen et al., 2011):

$$\mathrm{TL} = 10\log_{10}[\phi^2]^{-1} = -20\log_{10}|\phi| \tag{5.5}$$

Environmental factors influence this magnitude, since the characteristics of the bottom, the profile of the speed of sound in the water column, surface roughness, the presence of air bubbles in the water, bathymetry, among other factors, alter the propagation of sound (Wang et al., 2014).

5.3 Types of methods

To solve the Helmholtz equation, the models implement different methods: rays, normal mode, parabolic equation, energy flow, integration of the wavenumber, and finite differences. In the following sections, the principal methods are presented.

5.3.1 Ray method

It is an intuitive method representing the sound field by adding the sound rays using an approximation of the wave equation for higher frequencies through Snell´s equation associated with the eikonal equation (Wang et al., 2014).

$$p = Ae^{j\varphi} \tag{5.6}$$

Where A is the amplitude and φ is the phase, both of which are functions of the distance between the source and the receiver. When this solution is applied to the wave equation, two equations are obtained. In the first, a partial non-linear differential equation (eikonal equation) is obtained that ignores the second derivative of the amplitude. The second equation is to determine the amplitude and is called the transport equation (Wang et al., 2014). Because of the approximations used, variations in amplitude and speed of sound must be small in relation to the wavelength (Equation 5.7) (Etter, 2018).

$$f > 10\frac{c}{H} \tag{5.7}$$

Where f is the frequency, H is the duct depth, and c is the speed of sound. The performance of the models that implement this method is better in deep waters and high frequencies since it does not accurately model the most complex diffusion and interactions with the ocean floor. In addition, these models are sensitive to numerical discretization and the description of the environment.

There may be two anomalies in this method: the occurrence of shadow zones where the pressure field is zero and the occurrence of caustics where the predicted intensity is infinite. These situations are an artifact of the ray method since the solution to the wave equation is finite (Jensen et al., 2011). In optics, a caustic is the envelope of light rays reflected or refracted by a curved surface or object or the projection of that envelope of rays onto another surface. Caustic can also refer to the curve to which light rays are tangent, defining a boundary of an envelope of rays as a curve of concentrated light. It can also refer to the curve to which light rays are tangent, defining a boundary of an envelope of rays (Etter, 2018).

In the shadow areas, TL descends abruptly, while for the exact solution, there is a gradual decrease. This phenomenon occurs because not all rays are considered just a set of them depending on the range of angles considered. Therefore, considering complex rays is a possible solution in the shadow zones. However, this type of rays is rarely used since they significantly increase the complexity in identifying eigenrays (Jensen et al., 2011).

One of the ray model variations is the beam tracing method that solves problems in shallow waters since it associates the beamwidth with the rays to determine the pressure amplitude. It also minimizes the problems with shadow zone and at caustics (Wang et al., 2014). In our days, this method is more used in an operational environment in which computational speed is more important than precision.

Regarding the numerical models that implement this method, there is a wide variety (Etter, 2018), both range-independent and range-dependent, but not all are freely available to the public. All numeric models accessible to the public that implement the ray method and the other methods are available in the Ocean acoustics library (OALIB). One of the most used models is the BELLHOP (Porter, 1991, 2011). However, Ray, Traceo, TV -APM, USML, WOSS, HWT_3D, and Eigenray models are also available.

5.3.2 Normal Mode

The normal mode method offers a complete solution (full-field solution) for the wave equation (Equation 5.1), dividing variables into their vertical and horizontal component. Considering a cylindrical symmetry and a stratified medium, the Helmholtz equation (Equation 5.3) has the following representation (Etter, 2018):

$$\phi = \mathrm{F(z).\,S(r)} \qquad 5.8$$

Where $F(z)$ is the component in depth and $S(r)$ is the component in range. Thus, each mode can be interpreted as a progressive wave in the horizontal and a stationary wave in depth. The vertical solution is also called normal or eigenvalues and represents a set of discrete values that are a solution of the mode function (Wang et al., 2014). If the source only has one frequency, the complete solution is given through an infinite integral (Etter, 2018):

$$\phi = \int_{-\infty}^{\infty} \mathrm{G(z, z_0, \xi).\, H_0^{(1)}(\xi r).\, \xi\, d\xi} \qquad 5.9$$

As there is a problem of eigenvalues, Green's function ($G(z, z_0, \xi)$) is used, and since the horizontal equation is a Bessel equation of order zero is written in terms of Hankel function of zero-order ($H_0^{(1)}$).

The purpose of these models is to obtain the contribution of all modes depending on the depth and, for that, there are two different approaches, one that only looks for the propagating modes and the other that also looks for the evanescent modes. The advantage of the latter approach is that it improves accuracy at the source but is computationally slower (Wang et al., 2014).

This method applies to situations in which environmental factors do not vary with the distance (range independent). However, two techniques were developed to solve this problem, the adiabatic method and the coupled method. The adiabatic method assumes that all the energy in a particular mode is correspondingly transferred to the new environment, whereas the coupled method considers the energy that is scattered from one mode to the other (Etter, 2018).

Both these methods can deal with the variation of the environmental parameters; however, this variation must be slow when using the adiabatic mode. This type of model is suitable for both shallow waters and deep waters at low frequencies. For high frequencies, it is complicated to calculate all modes (Wang et al., 2014).

Regarding the ray method, the normal mode method has the advantage that calculations can be easily performed for any combination of frequencies, depth of the sound source, distance, and depths of the receivers. However, it is necessary to have more information about the ocean floor. Unlike the ray method, which is to be applied at high frequencies as a result of the approximations used (physical limitation), the normal mode method is more suitable for lower frequencies due to the computational requirement because the higher the frequency, the more modes are needed (Etter, 2018).

As in the method presented in the previous section, the freely available models are at OALIB. Only KRAKEN is available for this method.

5.3.3 Parabolic Equation Method

The Parabolic Equation method is applied in other scientific areas in addition to ocean acoustics, such as optics, seismic, and wave propagation in the atmosphere. It is well known and applied in marine acoustics since it can solve range-dependent problems. It was developed to address the need to predict sound propagation at low frequencies and over great distances to simulate sound channels (Jensen et al., 2011).

The reduced elliptic equation (Equation 5.4) is replaced by the parabolic equation assuming that the energy propagates close to the reference speed. Thus, the equation for acoustic propagation has the following formulation (Etter, 2018):

$$\nabla^2\phi + k_0^2 n^2 \phi = 0 \qquad 5.10$$

Where, k_0 is the reference wave number, n it is the index of refraction (ratio with the reference speed), and ϕ corresponds to the potential speed. From the previous equation (Equation 5.10) separating two differential equations using k_0^2 as a separation constant and using the equation Bessel of order zero is possible to obtain the following parabolic wave equation (Etter, 2018):

$$\frac{\partial^2\Psi}{\partial z^2} + 2ik_0\frac{\partial\Psi}{\partial r} + k_0^2(n^2-1)\Psi = 0 \qquad 5.11$$

$$with, \qquad \phi = \Psi(r,z).S(r) \qquad 5.12$$

An approximation is made where only are considered outgoing waves. Thus, it turns out to be a problem of initial boundary conditions in which the sound field is calculated at the source, and then it is calculated successively over range. It is possible to obtain a variation of the environmental values (range-dependent) by dividing the domain into static elements (range-independent) in which the energy will be conserved (Wang et al., 2014).

There are four numerical techniques within the parabolic equation method, Fourier split-step algorithm, implicit finite differences (IFD), ordinary differential equation (ODE), and finite elements (FE). The split-step algorithm is efficient in solving the initial conditions problem, but if there is a strong interaction with the seafloor, the IFD and ODE techniques are more suitable.

Therefore, for short-range situations in which propagation has greater angles and where interactions with the bottom are relevant, the FE and IFD methods are the most suitable. On the other hand, when interactions with the seafloor are not important, the propagation angles are smaller, and the distances are larger, the best algorithm is split-step. So, the split-step technique is widely used in sonar simulations, while the scientific community usually uses FD and FE due to their precision and ability to model interactions with the bottom (Jensen et al., 2011).

One of the errors that can exist with this method is the phase errors that can decrease the precision over great distances. To minimize this error are range-refraction corrections that can undergo phase using an average speed that depends on the distance (Etter, 2018). This phase-related error will depend on the type of parabolic equation method used and the angle of propagation. The greater this angle, the greater the phase error. In general, what has been verified is that the models that use the Padé extension have fewer errors (Jensen et al., 20 11).

Another problem with this method is the conservation of energy when there are inclined surfaces where there is a loss of energy on the way up, and there is a gain on the way down. This problem is transversal to all the parabolic equation algorithms, given that the calculations are made successively along with the domain (stair-step approximation). The boundary conditions in the horizontal are implemented with precision, but in the vertical, the same does not happen. As it is assumed that the solution only encompasses the outgoing waves, only the condition of continuity of the vertical pressure field is satisfied. Thus, the boundary conditions are not met when the solution is not complete (one-way solution). The solution to this problem of energy conservation is to correct the pressure of the reduced density $(p/\sqrt{\rho c})$. In this way, energy is conserved horizontally (Jensen et al., 2011).

Regarding the frequency range, this method becomes impractical at high frequencies due to its computational intensity that is proportional to the number of range-interval steps. Moreover, this number also increases with frequency, with computational requirements increasing squared with frequency (Wang et al., 2014).

The computational advantage of the parabolic equation is that it is numerically solved in distance, while the reduced elliptical wave equation must be solved in terms of distance and depth simultaneously. Solutions have already been developed that allow the incorporation of backscattered energy, allowing simulations of reverberation and in three dimensions and models in the temporal domain that use the progressive wave equation (Jensen et al., 2011).

At OLIB, the available models are FOR3D, MMPE, RAM, RAMD, RAMGeo, RAMSurf, MPIRAM, UMPE, and PECan. In addition, for the RAM model, there are adaptations for Matlab and Python.

5.3.4 Wave Number Integration Method

The method of wavenumber integration can also be called Fast-Field, and as the name implies, a numerical approximation of spectral integration of the wavenumber is used. In the same way, as in the normal mode method, the variables are also separated, but the first term of asymptotic development replaces the Hankel function. Thus, Equations 5.11 and 5.12 stays (Etter, 2018):

$$\phi = \int_{-\infty}^{\infty} \sqrt{\frac{2\xi}{\pi r}} G(z, z_0, \xi)\, e^{i(\xi r)}\, d\xi \tag{5.13}$$

This infinite integral is determined using the Fast Fourier transform (FFT). Green's function is used as a function of depth, so properties only vary in depth. The exact solution is obtained since it includes the propagating modes and the evanescent modes (Wang et al., 2014). Thus, it can be used in situations where evanescent modes are important.

Some models implement strategies so that environmental factors can vary across the domain (range dependence). One of the first techniques was to increase Green's function to allow variation in the horizontal, but it was computationally intensive (Gilbert and Evans, 1986). Another technique is to use a hybrid model that combines the integration of the wavenumber with the Galerkin boundary element method referred to as the SAFRAN model (Seong, 1990) (Etter 2018).

It is also possible to apply the approach of super-element where the environment consists of a series of elements that are range-independent but forms a field with range-dependence (Goh and Schmidt, 1996). Likewise, there are also variations of this method that can model acoustic pulses, consisting of a formulation in the temporal domain (Etter, 2018).

The following OASES, RPRESS, SCOOTER, and SPARC models are available from OALIB for this method.

5.3.5 Energy Flux Method

The first approach to this method was developed by Weston (1980), who foresaw the propagation in a channel with constant speed and arbitrary bottom in which the sound field can be seen as several rays that are propagated through the reflections with the boundaries.

The solution of this method turns out to be between the ray method and the normal mode and is more suitable for situations where the precision does not have to be high, just average values of TL. The models that implement this method present a fast computation since it is not necessary to find their own modes or values (Etter, 2018).

This method is best suited for shallow waters, regardless of the frequency range, and has some limitations in deep water (Wang et al., 2014). Unlike the other methods already mentioned in this chapter, no model is available that applies this method at OALIB.

5.3.6 WKB Method

This method is also called multipath expansion and transforms the wave equation (Equation **5.9**) into a sum of integrals finite, each of which is associated with a family of rays (Etter, 2018). The Wentzel – Kramers – Brillouin (WKB) approximation is used to solve the vertical equation derived from the normal mode method. This approach facilitates the asymptotic development of the normal mode method since it is assumed that the speed of sound varies gradually with depth.

Each mode will be associated with the corresponding rays; therefore, this method can be interpreted as applying the theory of rays to one dimension (Jensen et al., 2011). Furthermore, the WKB solution turns out to be a spatial case of Gaussian beam tracing. Therefore, this method has some similarities with the ray method. However, unlike the ray method, the WKB method considers the effects of first-order diffraction and caustic zones.

The RAYMODE model uses this method and already models the environmental factors (range dependence) through the stationary approach of the phase. This method is indicated for situations of deep waters and high frequencies (Etter, 2018). At OALIB, no model is available that implements this method.

5.3.7 Finite Differences Method

It is a method that is not as used in this scientific area as the methods already mentioned in this chapter. However, it meets the needs that the other approaches, due to their numerical efficiency, end up sacrificing, namely the diffraction and reverberation with the boundaries. These two effects are excluded when horizontal stratification is assumed, as in the normal mode and wavenumber integration method, or if propagation is assumed in only one direction, which does not include problems with backscattering (Wang et al., 2014).

There are different numerical techniques for this method. For example,

i. the Finite Difference Method (FDM) is based on the discretization of differential equations using finite differences.
ii. the Finite Element Method (FEM), in which the environment is divided into discrete elements.
iii. Moreover, the Boundary Element Method (BEM), which is like FEM, however, is not a discretization of the wave equation, but the field surface integral using Green's theorem (Jensen et al., 2011).

All these methods are computationally demanding since a complete spatial, and temporal representation of the variation of the acoustic field is made. For this reason, and in general, they are only used for reference solutions. However, they can also be used in conjunction with one of the other already mentioned methods, in which the finite difference method models the part of the diffusive processes and the other method models the part of the propagation (Jensen et al., 2011).

5.4 Three-dimensional models

For most applications, two-dimensional models are sufficient to determine the propagation loss, but horizontal refraction, diffraction, and reflection are not modeled. In cases where these processes are relevant or when the horizontal gradient of the domain is high, three-dimensional models must be used. One of the situations in which the models in three dimensions are necessary is, for example, in landmasses between the sender and the receiver (Wang et al., 2014).

The three-dimensional development methods are implemented in the following methods: ray, integration of the wavenumber, normal mode, and parabolic equation. As a rule, it is necessary to use three-dimensional models in seismic acoustics, reverberations, and situations with dispersion (Jensen et al., 20 11).

One technique for obtaining three-dimensional maps is to combine several two-dimensional sections in depth and distance (N x 2D) through interpolation. However, this technique is not effective when the phase variation of the sound waves is significant, as in cases of accentuated topography or the presence of vortices and fronts. In general, three-dimensional models are computationally intense, and the input data is more detailed, which can be a problem (Etter, 2018).

At OALIB, the following three-dimensional models BELLHOP3D, KRAKEN3D, TRACEO3D, USML, and HWT_3D, are available.

5.5 Domain of applicability

The propagation of sound is influenced by environmental factors, such as bathymetry, boundary roughness, water column thermohaline properties, and how the models can recreate these factors determines the model chosen to be applied in each study.

The selection of parameters of a method can be grouped into three categories, considering the frequency of the source, dependence on environmental factors, and depth. These are the categories that will indicate the domain of applicability of the respective acoustic model.

Regarding the frequency range, the larger the band, the more demanding the computation will be. There is no reference value when considering high frequencies, as a rule starting from $500\ Hz$ (Etter, 2018), or it can also be starting from $1000\ Hz$ (Jensen et al., 2003).

Concerning depth, the models can be for shallow water, deep water, or even for both situations. Typically, shallow waters go to $200\ m$, depths in which the interaction between the sound and the bottom must be considered (Etter, 2012). When the models are for deep water cases, the interaction with the seabed may be small or even neglected. The opposite occurs in shallow water situations in which these interactions are dominant and associated with boundary conditions, with the representation of the ocean floor having importance in the results achieved by the model (Etter, 2018).

In general, the method of integrating the wavenumber and energy flow can be applied to any range of frequencies. On the other hand, the parabolic equation method and normal mode are indicated for low frequencies, up to $1\ kHz$. Finally, the ray method is the most suitable for high frequencies.

Other crucial elements for choosing a model are whether domain features keep spatially constant, in other words, if the environment is range-independent or range-dependent. For example, the methods of normal modes, integration of the wavenumber, and energy flow are for range-independent environments, while the method of rays, and parabolic equation are more suitable for range-dependent environments (Wang et al., 2014).

Summing up, the domain of applicability of the different methods is illustrated schematically in Table 1 (Etter, 2018).

Table 1: Schematic table with the applicability domain of the different methods. A black circle means that this method is applicable both computationally and physically; a black and white circle states that there are computational limitations, and a white circle when is not applicable in this domain. (Etter., 2018)

Model type	Applications							
	Shallow water				Deep water			
	Low frequency		High frequency		Low frequency		High frequency	
	RI	RD	RI	RD	RI	RD	RI	RD
Ray theory	○	○	◐	●	◐	◐	●	●
Normal mode	●	◐	●	◐	●	◐	◐	○
Multipath expansion	○	○	◐	◐	◐	◐	●	◐
Fast field	●	◐	●	◐	●	◐	◐	◐
Parabolic equation	◐	●	○	○	◐	●	◐	◐

Low frequency (<500 Hz)
High frequency (>500 Hz)

RI: Range-independent environment
RD: Range-dependent environment

● Modeling approach is both applicable (physically) and practical (computationally)
◐ Limitations in accuracy or in speed of execution
○ Neither applicable nor practical

5.6 Factors that influence the results of the models

Numerical models require input data to start the simulation. These data are for the representation of the water column, surface, and ocean floor. The representation of the bathymetry is essential for the model's accuracy, especially in shallow water situations since the bottom topography affects the propagation of sound. On the other hand, the resolution and quality of these data also influence the vertical reference, since, in certain places, the tides can be significant and the data are generally referenced in relation to the average sea level (Wang et al., 2014).

It is important to have as much information as possible about the seabed, as its characteristics influence how the sound is reflected, absorbed, and transmitted. The speed of sound is another parameter that influences how the sound propagates, especially in deep water situations. Therefore, it is relevant to know the characteristics of the water column, namely, temperature, pressure, and salinity.

Therefore, it is important that the model input data present accurately as possible because the accuracy of the results is dependent on this data (Wang et al., 2014). In the case of TL calculation, the geometric parameters, that is, distance from the domain, depth of the source and receiver, are those that have greater influence when compared with the parameters related to the environments (Meyer et al, 2018).

6 SELECTION OF THE ACOUSTICS MODELS

6.1 Factors of choice for the models

The purpose of the acoustic models is to model the noise created by human activity with focus on the noise generated by shipping and by fields of wind generators. Thus, it must be a model for low frequencies ($< 1kHz$), that is, all methods can be used except for the ray method which is more suitable for high frequencies. However, to increase the applicability domain, two models will be used, one for low frequencies and the other for higher frequencies.

Regarding the implementation of the domain factors, the model must be range-dependent in order to simulate the environment in the most complete and realistic way possible. With regard to depth, it must be able to be applied in shallow and deep water situations. If there is a parallelized version of the model, preference is given to that version, to take advantage of the computational power available improving computing time.

The last criterion is that the software must be freely accessible. If this criterion were not imposed, there was a wide variety of models that are synthesized in Etter, 2018. However, taking into account this criterion, the models that can be considered are those that are available at OALIB.

6.2 Selected acoustic models

At OALIB there are available several models that are grouped according to the method they use. In addition to the various models available, there is also a Toolbox in which the most recent version is AcTUP v2.2L (Acoustic Toolbox User interface and Post processor). In this toolbox are available BELLHOP, KRAKEN, KRAKENC, RAMGEO, RAMSGEO, SCOOTER (Maggi et al,. 2006).

The interface was developed for Matlab and in addition to providing the output files with the results it also includes several graphical representation tools (Duncan et al,. 2006). Also available at OALIB is an interface for the Python toolbox developed by Hunter Akins, UCSD and Python scripts for reading the output files created by Orlando Rodriguez, University of Algarve.

Then, considering all the criteria and models available for low frequency situations, the implemented model will be BELLHOP. In the case of the lower frequencies, the RAM and KRAKEN models were pre-selected and after being tested KRAKEN was the chosen model, since the results of the two models are similar (Sertlek et al,. 2013 & Küsel et al., 2019), however KRAKEN has input files similar to those of BELLHOP which facilitates the implementation of the two models. Therefore, the toolbox that incorporates both models will be used with its implementation in Python.

7 CONCLUDING REMARKS

This project is a stepping-stone for the proper implementation of the MSFD's descriptor 11 and will contribute to:

- The national marine waters knowledge at the level of any of the descriptors of the Marine Strategy Framework Directive – through the development of tools to implement descriptor 11, which will contribute to the maintenance of biodiversity (descriptor 1).
- The accomplishment of International Conventions (IMO and EU) aims to prevent marine pollution – through involving the maritime transport companies and ports as active stakeholders to follow the project's development and engage in workshops on underwater noise.
- The development of innovative Information and Communication Technologies to support decision-making in the context of the monitoring, assessment, and management of underwater noise – through the Web portal and its mapping of soundscapes and underwater noise along the Portuguese coast and distribution of acoustically sensitive species.

The present report aims to contribute to this project's third objective by developing a numerical modeling portal that can support the research community in the study of sound in Portuguese waters.

A revision of the state-of-the-art acoustic numerical models and formulations was made. However, considering several formulations and types of access to each of the existing models, two models were chosen to implement in the portal, acknowledging a paradigm of open access, sustainability, and usefulness to the research community. However, this does not mean that in the future, it will not be possible to add more advanced and precise models, even with restricted access, as long as there is funding and willing power of the decision-makers and national authorities.

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9 ANEXO I. ACRONYMS

BELLHOP - Gaussian-Beam, Finite-Element, Range-Dependent Propagation Model

BELLHOP3D - BELLHOP Extended to 3D

Eigenray - Eigenray Acoustic Ray Tracing Code

HWT_3D - Huygens Wavefront Tracing in 3D

OALIB – Ocean Acoustic Library

RAY - Range-Dependent Raytracing Program

SEL - Cumulative Sound Exposure Level

TL – Transmission loss

TRACEO - Beam Tracing code

TV-APM - Time-Variable Acoustic Propagation Model

USML - Under Sea Modeling Library

WOSS - World Ocean Simulation System

underwater noise JUMP

Cofinanciado por:

REPÚBLICA PORTUGUESA MAR

fundoazul

underwater noise JUMP

Partners: WavEC Offshore Renewables, ISPA + MARE, Ciências ULisboa, LNEC Laboratório Nacional de Engenharia Civil, Porto de Aveiro, museu da baleia, InnoSea, Fórum Oceano, Oceans ON!, Quercus