Underwater Noise Modelling of Wave Energy Devices

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Abstract

Future large-scale implementation of wave energy converts (WECs) will introduce an anthropogenic activity in the ocean which may contribute to underwater noise. The Ocean houses several marine species with acoustic sensibility; consequently the potential impact of the underwater noise needs to be addressed. At present, there are no acoustic impact studies based on acquired data. The WEAM project (Wave Energy Acoustic Monitoring) aims at developing an underwater noise monitoring plan for WECs.

The development of an acoustic monitoring plan must consider the sound propagation in the ocean, identify noise sources, understand the operational characteristics and select adequate instrumentation.

Any monitoring strategy must involve *in-situ* measurements. However, the vast distances which sound travels within the ocean, can make *in-situ* measurements covering the entire area of interest, impracticable. This difficulty can be partially overcome through acoustic numerical modelling.

This paper presents a synthetic study, on the application of acoustic forward modelling and the evaluation of the impact of noise produced by wave energy devices on marine mammals using criteria based on audiograms of dolphins, or other species. The idea is to illustrate the application of that methodology, and to show to what extent it allows for estimating distances of impacts due to acoustic noise.

Keywords: Acoustic Modelling, Environmental Impact Assessment, Underwater Noise, Wave Energy Converters

Nomenclature

ht = hearing threshold
NM = Normal Modes
SPL = Sound Pressure Level
PTS = Permanent Threshold Shift
TTS = Temporary Threshold Shift
WEC = Wave Energy Converter
WEAM = Wave Energy Acoustic Monitoring

1 Introduction

The growing concern for a sustainable energy development on a global scale, in association with the goals of the Kyoto Protocol emphasizes the need to push for renewable energy development.

Wave energy represents a vast renewable energy source worldwide. In the long term, it is estimated that electric power coming from waves could produce about 10% of electrical energy consumption in the world [1,2].

Scientific research in wave energy utilization began in the mid 1970s, prompted by the oil crisis, and since then a large number of conversion devices have been developed. At present, there are several technologies that are specific to the deployment site (onshore, nearshore, offshore) and power take-off equipment. As opposed to other established renewable energy technologies, wave energy has yet to converge to one dominating design, as the 3-blade turbine in wind energy. However, as the devices are designed and tuned to operate at different conditions, such as sea states and bathymetry, it is possible that more than one technology will prevail.

The deployment of wave energy farms is likely to have positive and negative environmental impacts. Reduction of CO_2 emissions in energy production, contribution to marine sanctuaries, employment

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opportunities are examples of positive impacts of wave energy.

On the other hand, regarding the potential negative impacts, the introduction of this new anthropogenic activity in the ocean has raised some concern in the last years, in particular in areas of important biological diversity. The concern also results from the reduced number of environmental impact studies based on field data. Among the negative impacts of concern are included the effects of underwater noise on marine life in general and on marine mammals in particular [3]. Future large-scale implementation of WECs may contribute as a noisy source in the ocean. Whilst it is not expected that each individual device will produce a high level of acoustic noise, the deployment of a large number of devices in the same farm operating day and night may have an effect on the fauna.

There is scarce information on the characteristics of the noise produced during the different project phases of wave energy farms (especially during operation). The first deployments of wave energy devices and first wave energy pilot zones should provide the opportunity to initiate studies based on the monitoring of the underwater noise produced by WECs. In Portugal, there are at least two types of WECs in demonstration stages: one is the Oscillating Water Column (OWC) power plant of the Pico Island, Azores, and the other is the Pelamis wave farm at Aguçadoura, off the Portuguese West Coast.

The Wave Energy Acoustic Monitoring (WEAM) project aims at the development of validated noise monitoring strategies for WECs, as a collaboration effort of the Wave Energy Centre (WavEC) and the CINTAL (Technological Research Centre of Algarve). The results are expected to guide the development of an environmental friendly technology and to clarify limits for the number and density of wave energy devices in a farm [4].

So far, no experimental work at sea has been carried out. Meanwhile, the implementation of acoustic modeling software has been carried out, and state-of-the-art bibliography review on the evaluation of noise impact on marine mammals is being undertaken. The present paper discusses the acoustic noise impact on the marine fauna and presents simulation results on acoustic propagation and impact evaluation using the Pelamis deployment site at Aguçadoura as environmental scenario.

2 Acoustic Approach

Assessing the acoustic impact involves several steps. The task may start by performing *in-situ* recording of the noise generated by the WEC under observation, whose analysis should aim at obtaining relevant impact characteristics, such as, for example, maximum and average broadband sound pressure level (SPL), the amplitude spectrum in the frequency domain over different phases of operation, and duty cycle of noise production. Noise recordings are typically performed over the area of interest, at a certain range of distances away from the noise source.

These characteristics may have no meaning by itself. As the final aim is to find out to what extend an animal may be affected by a given noise source it is necessary to proceed with a criterion. There are several studies that attempt to characterize the hearing sensitivity of marine species, which results in an audiogram. An audiogram of an animal represents the lowest sound level as a function of frequency that it can perceive. There are other studies that attempted to measure the effects of certain noise doses on the animal. The most common effects that these studies can assess are on behavioural changes or temporary damages in the hearing system, which are usually described as a temporary loss of hearing sensitivity, known as temporary threshold shift (TTS) [5]. Such studies can be used to evaluate the impact in a real scenario, by using the *in-situ* measurements and application of available criteria. The result of this interpretation may be an evaluation in terms of influence zones where the experimenter roughly produces a set of plots as a function of space indicating whether a certain level of impact is taking place or not. These influence zones usually range from *audibility* to *temporary injury,* or *permanent injury* or even *death* in very severe cases.

Performing *in-situ* measurements over space in the area of the WEC may be sufficient for a minimal impact assessment. However, in some cases this may not be sufficient to completely characterize the noise impact on the marine life. The observed noise may vary with time and space due to several factors: operating device conditions may vary according to the sea state; the sound pressure level (SPL) depends on range, depth and bearing, etc. A complete spatial and time coverage via *in-situ* measurements may become time consuming and expensive. Fortunately, there are very accurate acoustic propagation models that can be used as a complement to *in-situ* measurements. Acoustic propagation models require a description of the environment as input (water column temperature and salinity, bathymetry, bottom properties), an interval of ranges, depths, and bearings, and the frequency interval to be analysed. To estimate the SPL over a certain ocean volume or area, one needs the amplitude spectrum of the acoustic noise source and validation of the transmission loss (TL) calculated by the acoustic model. Thanks to the computational resources available nowadays accurate estimates on SPL over a wide area can be obtained in reasonable processing time.

Computer acoustic modelling allows to consider other issues such as taking into account the fact that in some systems consist of multiple noise sources that do not produce noise in synchronized mode; or it allows for modelling underwater noise produced under sea states that do not allow the collection of *in-situ* acoustic data with the presence of human resources. Finally, acoustic modelling could aid in setting up the layout of wave energy farms (geometry, number of devices, distance apart, etc.) and development of individual devices such that the environmental performance related to underwater acoustic noise is maximized.

The noise emitted by each WEC is expected to be produced from a variety of different components (mechanical or other moving parts) related with the device itself and/or by its interaction with the environment. There may be some similarity to vessel machinery noise which has been well studied by the underwater sound community. Machinery noise has been identified as being originated by (a) rotating parts (shafts and motor armatures); (b) repetitive discontinuities (gear teeth, armature slots, turbine blades) like, for example, in Wells and Pelton turbines; (c) explosion in cylinders in internal combustion motors; (d) cavitation and fluid flow (pumps, pipes, cylinders, valves, etc.); and (e) mechanical friction. Factors (a) to (c) cause noise dominated by a fundamental frequency and harmonics of the vibration-producing process. The others components give rise to noise with continuous spectrum. Usually the superposition of these two types of spectrum is observed with a strong outstanding of the tonal components from the continuous spectrum.

3 Acoustic Modelling

Sound propagation in the ocean is mathematically described by the wave equation, whose parameters and boundary conditions are descriptive of the ocean environment. Propagation models use as input bathymetric databases, geoacoustic information, oceanographic parameters and boundary roughness models to produce estimates of the acoustic field at any point far from the source. The quality of the estimate is directly related to the quality of the environmental information used in the model [6]. There are essentially five types of models: Fast Field Program (FFP); normal mode (NM); ray and parabolic equation (PE), and direct finite-difference (FD) or finite-element (FE) solutions of the full wave equation. The FFP and NM permit to treat both range independent and range dependent environments [7]. NM models can be significantly more efficient for modeling in some environments at frequencies below 1 kHz. These models assume that the acoustic field can be decomposed into normal modes and eigenfunctions, which are obtained from an Helmholtz wave equation that accounts for the boundary conditions of the medium being described. NM theory is particularly interesting to describe sound propagation in shallow-waters [8] and it is easily adaptable to multiple layers. Typical shallow-water environments are found on the continental shelf for water depths less than 200m [7].

Each model has its particularities and applicability limitations regarding sound frequency range and environmental characteristics. The choice of a specific acoustic model to apply to WECs must take into account the characteristics of the deployment site and operational principles.

WECs can be classified regarding the operational principle and location. Concerning the location there are three different groups of devices: onshore; nearshore (until 30 meters depth); and offshore (usually until 100 meters depth). The operational principle to extract energy is developed basically also in three groups: oscillating water columns; overtopping systems and floating/oscillating devices. Several alternatives with impact in the acoustic noise generation can also be considered with respect to the power take-off equipment: air turbines, water turbines, hydraulic rams and motors, linear generators and mechanical drives. The energy extracted from waves will be converted in several types of energy such as pneumatic, hydraulic, potential, mechanical and finally in electric. From the acoustic point of view, this represents a case of low frequencies in shallow water. The KRAKEN normal modes code was chosen for being computationally efficient and relatively easy to use. Normal modes are very efficient when the experimenter has fixed environmental conditions and only needs to perform changes in the emitter and receiver geometry, as the acoustic propagation is independent on source or emitter position. The acoustic modes can be stored on the computer disk and restored for acoustic response computation each time changes in the emitter and receiver positions occur. The KRAKEN code has an additional feature, which is a built-in algorithm for 3-dimensional field calculations. In fact, it calculates Nx2D fields since the field is calculated for 2D range-depth planes over an interval of bearings, and finally combining the 2D field calculations in something that resembles a 3D field. This algorithm is based on the triangulation of the environment, where the vertice of each triangle is a node, and for each node the acoustic modes are readily calculated. By means of that triangulation the acoustic modes are interpolated in order to obtain estimates of the mode amplitudes at an intermediate position of interest.

In the scope of the WEAM project, a MATLAB interface to KRAKEN is being developed. This software reads an input file that sets up the model with the emitter and receiver geometries, environmental properties of the acoustic propagation channel, frequency range, and other KRAKEN input parameters. Simultaneously, routines that yield plots on the influence zones are being implemented.

Acoustic modelling includes also defining assumptions for the received signal. In the present study, it is assumed that the noise is radiated from multiple emitters, corresponding to multiple wave energy devices, and that the signal received at a point of the space is the superposition of several uncorrelated waveforms. This assumption is acceptable in most real world scenarios, as in general signals travelling across the ocean tend to acquire features of random nature, and in particular, in this case it can be considered that the multiple waveforms are generated independently. This assumption significantly simplifies the acoustic modelling.

4 Marine Mammals and Influence Zones

Usually, the species adapt to the specific environment where they live, creating several specific mechanisms, such as defense, communication, navigation, prey detection and feeding.

Some marine species, particularly marine mammals depend intimately of acoustic mechanisms, making it effectively their primary sense. The fundamental reason is that as opposed to light and other forms of electromagnetic radiation, the ocean is transparent to sound (especially at low-frequency), which allows sound to travel at great distances. Consequently, the acoustic disturbance introduced by noisy activities may have impacts at different levels in some species, causing adverse effects. The effects of underwater noise on marine life can be [9]:

- Physical – Auditory or non-auditory
- Behavioural
- Perceptual
- Chronic/Stress
- Indirect Effects

Each marine mammal species has its specific auditive sensitivity related with the communication and echolocation functions. Through the specific audiogram of each species it is possible to attempt to calculate and define the influence areas for each one.

Richardson et al. (1995) define four zones of noise influences, depending on the distance between source and receiver. The zone of audibility is defined as the area within which the animal is able to detect the sound. The zone of responsiveness is the region in which the animal reacts behaviourally or physiologically. The zone of masking is highly variable in size, usually somewhere between audibility and responsiveness and defines the region within which noise is strong enough to interfere with detection of other sounds, such as communication signals or echolocation clicks. The zone of hearing loss is the area near the noise source where the received sound level is high enough to cause tissue damage resulting in either temporary threshold shift (TTS) or permanent threshold shift (PTS) or even more severe damage.

5 Acoustic Simulation - Example

This section provides an example aiming at the illustration of a based approach to model the propagation of noise produced by wave energy devices. The scenario is a wave farm deployed off the Portuguese West coast.

A MATLAB code that interacts with the KRAKEN propagation model has been implemented in order to accomplish several steps required to noise impact assessment. These steps consist of assimilating the environmental data that define the parameters for the transmission loss computation. These data are used to create model input files for TL computation. The TL is then combined with the noise input to obtain the broadband SPL over the area of interest. The final step is to compute the influence zones as follows [11, 12]:

- Audibility zone requires the noise amplitude as a function of frequency for each position of interest and the audiogram of the animal subject to be exposed to the noise. Ideally one should consider the noise spectrum typical of the study area, since it may mask the noise which the experimenter is interested in. In the present case, it was considered that, as an *ad-hoc* solution, instead of using a noise spectrum, to exclude all points where the broadband SPL is less that 20 dB above the animal's audiogram from the audibility zone, due to that for these small noise level the animal, since the animal may not be able to detect a weak noise embedded in environmental background noise.
- Disturbance zone: includes an area where it is very likely that behavioural disturbance will occur for most species. Animal reaction may include cessation of feeding, resting, socializing, and an onset of alertness and avoidance. For many marine mammals, disturbance can occur for a broadband SPL above 120 dB. This criterion does not take into account the animal's audiogram.
- Temporary auditory injury: one of the criterion found in the literature is to consider the noise dosis resulting from an exposition to noise with and broadband SPL 60 dB above the animal's audiogram, which causes a TTS of 4-6 dB. This represents a loss in hearing sensitivity, which usually can be recovered within 24 hours. However, the repetition of TTS can lead to a permanent loss of sensitivity.

There are other criteria for higher severity in terms of auditory injury, which are not considered herein since these cases are not expected to occur in the scope of wave energy devices.

The simulations considered the audiogram of the Harbour Porpoise (*Phocoena phocoena*) [13,14], and the acoustic modelling was carried out taking an environmental model similar to that expected off the Portuguese West Coast where the Pelamis wave farm is deployed. Note that this is only an indicative example, where the noise used as input does not come from real measurements or data. The synthetic noise spectrum consists of a superposition of four discrete tones at frequencies of 200, 400, 600, and 800 Hz, and a continuous noise spectrum in the band 200 to 1000 Hz, and the broadband SPL is 175 dB, which is less that that generated by most vessels in cruise speed or under heavy duty. In a real scenario also the natural background noise should be taken into account, in order to determine the outstanding of the new noise sources relative to that noise, and therefore be able to rigorously determine the impact zones. The noise radiated by the point sources is embedded in the natural background noise, and will become undetectable after a certain range for that reason.

Figure 1 shows a schematic drawing of a semi-submersible WEC, where up to 65% of the diameter is submersed. In this case, each semi-submersible WEC could have three generators associated.

For model input, the bathymetric data shown in figure 2 was used. The bathymetry is range-dependent over the West direction and of mild range-dependence over the North direction. The temperature profile was taken from archival data and was taken during July 2007 in the Portuguese West Coast (Fig.3).

Concerning the geometric parameters, a point source at depth 2.275m was considered, and the SPL was measured at 30m depth. The deployment coordinates are close longitude 8.85W and latitude 41.15N.

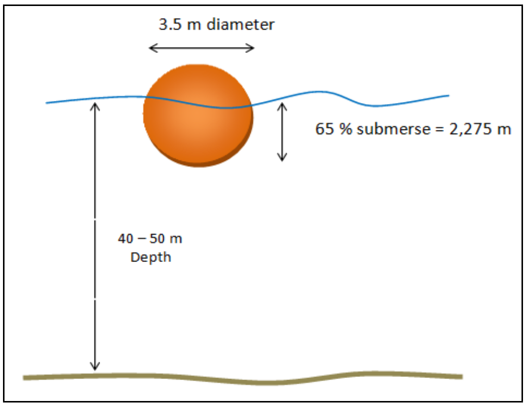

Figure 1: WEC deployment in depth

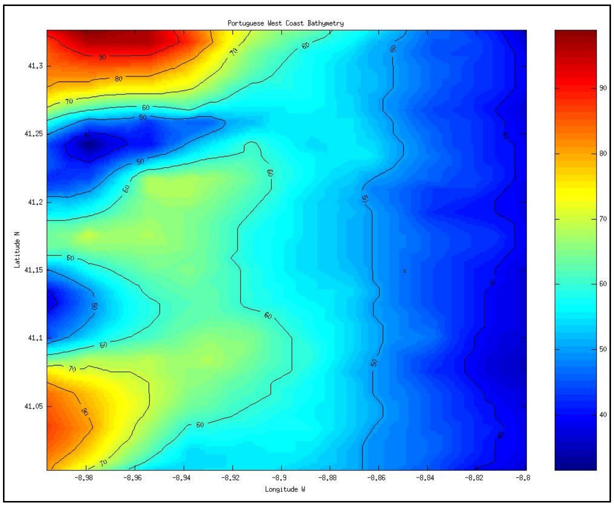

Figure 2: Bathymetry of Portuguese West Coast

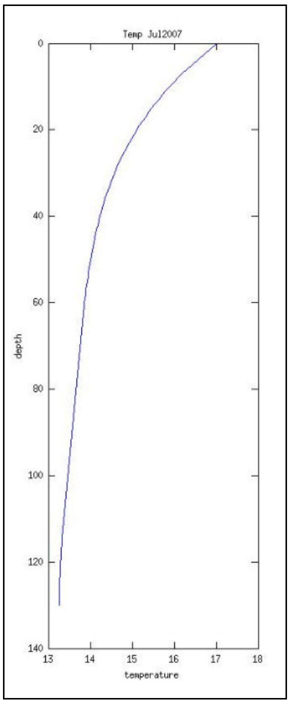

Figure 3: Temperature profile July 2007

Since there are uncertainties related to the operation of the WEC system related to the fluid decompressing time, and whether more than one of the three generator will be working simultaneously for a certain maritime regime, two cases were simulated: one considers each WEC (semi-submersible device) device as a single noise source (Case A), representing the assumption that only one of the three generators will be working at each time; and the other considers the worst case where the generators may be working simultaneously (Case B – Fig.4). Figure 4 depicts a scheme showing how the semi-submersible WECs are positioned in the ocean. These systems are usually moored in a bathymetry between 40 and 50 m, in this case that represent about 5 to 10 km from the coast, and about 200 m between each other. Case A considers one noise source coincident with each semi-submersible device, for example each device can be a Pelamis device.

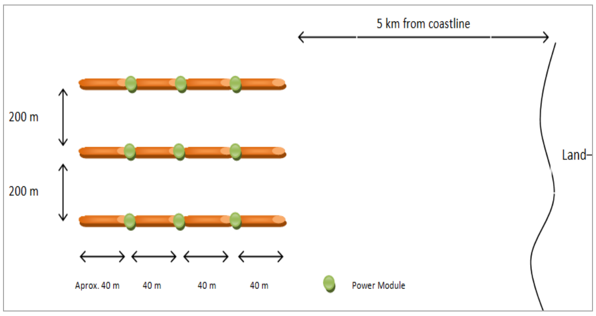

Figure 4: Scheme of 3 semi-submersible WECs deployment (each green point correspond to a power module)

Figure 5 shows the simulated SPL obtained for 3 simultaneous noise sources (Case A). The TL was calculated for a radius of 10 km for each. Note that the colorbar maximum value is approximately 160 dB, which is caused by the fact that the minimum distance used for TL calculation is 100 m, and by then already about 15 dB of loss has taken place mainly due to the spherical spreading loss mechanism. It can be observed that the TL attains about 80 dB at maximum range, and that TL is higher for noise propagating towards the coast than in the opposite direction, which can only be attributed to the bathymetry since this is the only property that depends on range and bearing.

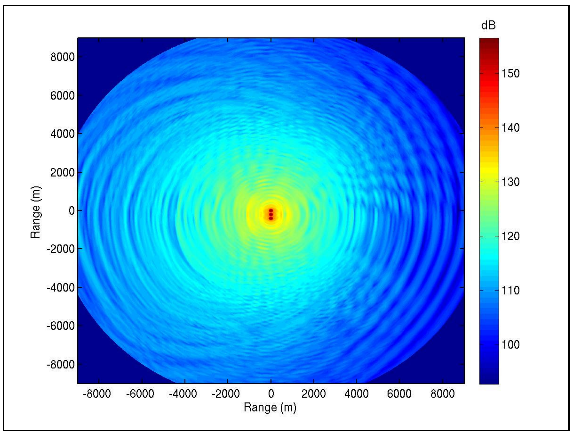

Figure 5: Case A -SPL over the distance from the wave farm with 3 simultaneous noise sources

Figure 6 shows the SPL based on the animals audiogram. This is a broadband SPL where at each frequency only the excess sound level is considered for the broadband SPL computation. Table 1 shows the hearing threshold of the Harbour Porpoise for some values in the band of interest, 115 dB at 200 Hz and 80 dB at 1000 Hz [13, 14]. The values in between were obtained by linear interpolation.

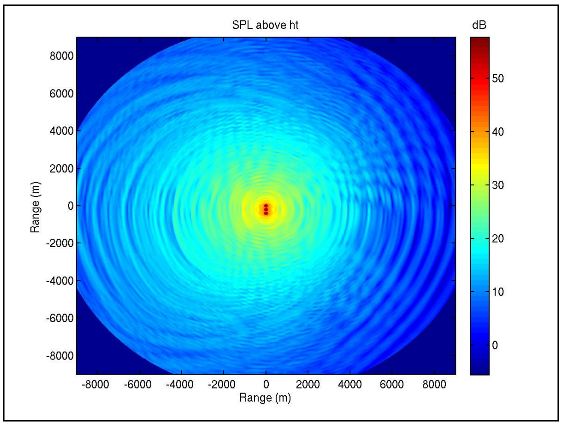

Figure 6: Case A - SPL above hearing threshold for Harbour Porpoise

Frequency (Hz)	Hearing threshold (dB)
200	115
500	93
1000	80

Table 1: Hearing threshold of the Harbour Porpoise in the band 200 to 1000 Hz.

The result in Figure 6 may lead to the evaluation of the impact of noise, resulting in the influence zones described above. Figure 7 shows the audibility zone, based on the result shown in Figure 6. If there were other noise sources, such as natural background noise, one could roughly take all points with a SPL more than 0 dB above the animal's audiogram. However natural noise also masks anthropogenic noise, and therefore noise power density curve should be used. Here, for the sake of simplicity only points with more than 20 dB above the audiogram were considered. The result indicates that these species of dolphin would hear the noise produced by the system at a distance of 5 km. This example illustrates the importance of taking into account the animal's audiogram: while for a human 100 dB would still be audible, according to this criterion, for a dolphin it may not. This depends on the frequency at which the noise is generated. Note the audiogram of a dolphin attain values as low as 40 dB or less, usually at frequencies of about 50 to 70 kHz. Also, natural noise decreases significantly with frequency, which could decay several dB per octave, depending on the frequency band.

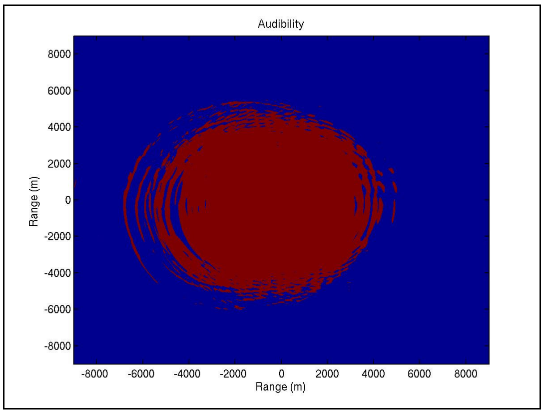

Figure 7: Case A - Audibility zone based on the SPL and the animal's audiogram. All points SPL more than 20 dB the hearing threshold are included in the audibility zone.

Figure 8 shows where behavioural disturbance is expected to occur according to the criterion described above. This does not take any audiogram into account and considers broadband SPL above 120 dB. In this case, one can consider that the influence in terms of behavioural disturbance may take place within at a distance of 3 km. It is expected that the animals would remain for short time in that region or even avoid that region.

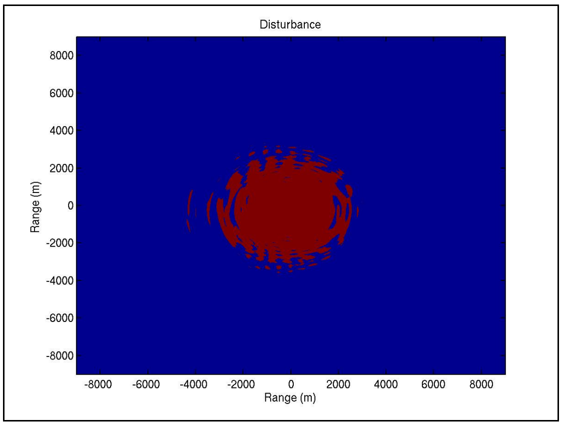

Figure 8: Case A - Zone of behavioural disturbance, considering every point with an SPL of more than 120 dB.

The next influence zone considered would be a temporary auditory injury, a TTS of up to 6 dB. The present case would not cause physical harm to that dolphin since according to figure 6, the SPL barely attains 60 dB above the animal's audiogram. For the sake of illustration we assumed an increase of 30 dB in noise produced by each device and calculated that influence zone (see figure 9). The result indicates that an influence zone with a radius of 1 km would be obtained according to the criterion presented above. However, this is not very likely to occur, due to the fact it is unlikely that an animal would remain close to such a severe noise level for a long time.

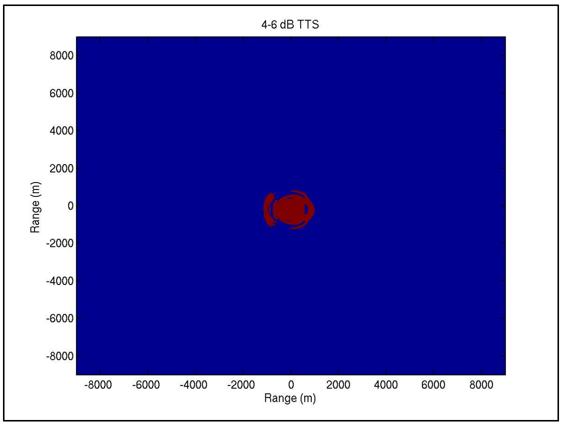

Figure 9: Case A - Zone of TTS of 6 dB considering a source level with 30 dB excess in the broadband SPL.

Next, Case B is treated (fig.4). The idea is to illustrate what happens in terms of influence zones when the density of noise sources is increased. In this case, it is simply assumed that all generators will be working simultaneously, as a result 9 noise sources are considered. Now the noise sources are placed on a 2-dimensional grid, with rows 200 m and columns 40 m apart. This layout could correspond to a wave farm of Pelamis where each noise source will correspond to a power module. All the other settings remain essentially the same.

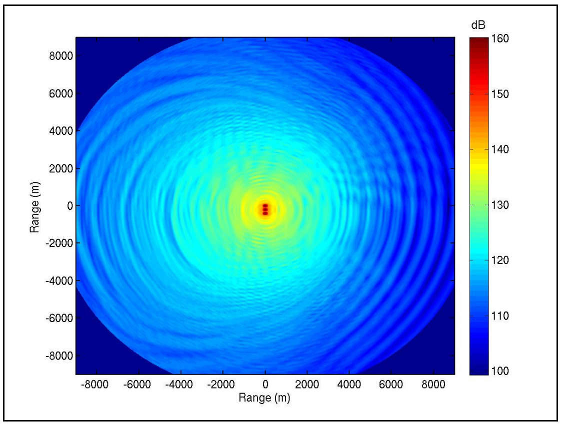

Figure 10: SPL over distance from the Wave Farm of Case B.

Figure 10 shows the SPL obtained for Case B. The main difference to Case A is an almost uniform rise of 10 dB over the area. This is close to 20log10(3)= 9.54, which means that this is simply due to a factor of 3 in the number of source in the area.

The radius of the audibility zone increased to 6 km (Figure 11) while the disturbance zone has a radius of about 4 km (Figure 12). Roughly having 3 times the number of devices has increased the radius of the impact zones by 1 km.

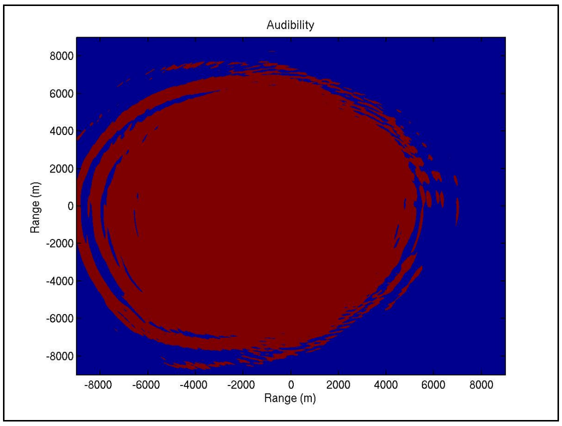

Figure 11: Case B - Audibility zone based on the SPL and the animal's audiogram. All points SPL more than 20 dB the hearing threshold are included in the audibility zone.

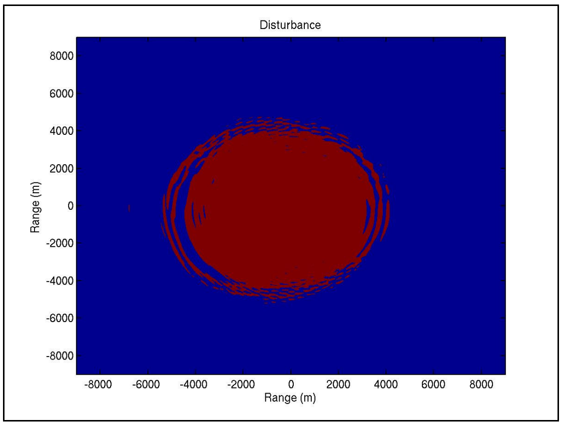

Figure 12: Case B **-** Zone of behavioral disturbance, considering every point with an SPL of more than 120 dB.

Finally, Figure 13 shows the TTS influence zone for an excess of 30 dB in the original signal. This resulted in an increase of this influence zone to 2 km in comparison of 1 km in Case A.

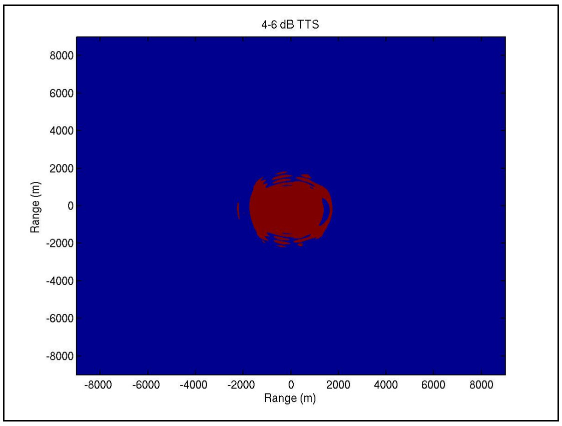

Figure 13: Case B - Zone of TTS of 6 dB considering a source level with 30 dB excess in the broadband SPL.

6 Conclusion

This paper considers the problem of the potential impact of noise generated by wave energy devices deployed in the ocean. That impact can be evaluated by means of audiograms and past experiences that attempted to evaluate the consequences of the exposition of marine mammals to underwater noise.

The approach presented herein is a classical forward acoustic modelling problem where the experimenter assumes certain environmental conditions, emitter-receiver geometry, and a noise spectrum. Then, a normal modes propagation model is used to calculate transmission loss in an area away from the noise sources, considering a representative input signal.

Although no idea of the real noise is available, using a realistic noise level within a limited frequency band allowed to produce a first insight of the application of current evaluation criteria to the present problem. The example treated herein allowed to establish the range of the influence zones to be expected, and to model to what extent this type of device can produce harm to the marine fauna due to noise. According to these results it is likely that audibility and disturbance zones will be generated by the deployment wave energy farms, that may potentially cause avoidance by these animals.

In future, in the scope, of the WEAM project, simulations will be repeated using real data measurements of noise recorded close to the device, in order to obtain a real frequency spectrum and amplitudes.

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