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Shipping noise in the Azores: a threat to the Faial-Pico cetacean community?

Cristiano Soares
MarSensing Lda., Faro, 8005-294, PORTUGAL; contact@marsensing.com

Ricardo J. Duarte
Universidade do Algarve, Faro, 8005-294, PORTUGAL; rjduarte@ualg.pt

Monica A. Silva and Miriam Romagosa
University of the Azores: Universidade dos Acores, Horta, PORTUGAL; masilva@mare-centre.pt, m.romagosa4@gmail.com

Sergio M. Jesus
Universidade do Algarve, Faro, 8005-294, PORTUGAL; sjesus@ualg.pt

The Azores archipelago is an important cetacean habitat spot, registering a very relevant resident and migratory population. Due to its geographical position, it also represents an important commercial crossroad between America and Europe. Vessels represent the major source of underwater noise which may affect cetaceans. Since 2017 acoustic measurements have been performed in the southern side of the channel between Pico-Faial. Although foreground biological signatures are numerous and relatively easy to spot in the data, it is not clear how to separate background abiotic, biotic and man made noise and, therefore, to single out the noise due to shipping. In order to address these questions, a shipping noise prediction tool using a 10-min resolution AIS coverage of the area, together with bathymetric, water column space-time descriptors and surface wind generated noise model, showed a significant noise variability between Pico-Faial islands. This variability was mainly observed in the strait and to the south of it, both along the coast associated with ferries and around offshore banks due to fishing activity. Time series of predicted sound pressure level at three receiver locations favorably compare with it *in-situ* noise measurements in the 44-177Hz a frequency band.

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1. INTRODUCTION

The Azores archipelago is known in the marine biology community as a rich site in terms of cetaceans and represents an important habitat for sperm, fin and blue whales.[1,2] Cetaceans are known to rely on underwater sound to forage, to interact in community, to orientate and to perceive their surrounding environment.[3,4]

The Azores archipelago, due to its' geographical location in the center North Atlantic, is in the middle of intense marine traffic routes that connect Central and North America to Europe. Recent studies indicate that the cetaceans' behavior and physiology may be affected by anthropogenic ambient noise.[5] Considering that vessels are the major contributors to underwater noise, one question arises: is the Faial-Pico cetacean community at risk?

The first step to answer this question is to evaluate ship traffic in the area and the inherent generated noise. Experimentally assessing the entire area is costly, time-consuming and foremost practically impossible. One way to predict the underwater noise resulting from anthropogenic sources is by generating numerical shipping noise maps.[6]

In parallel to other similar initiatives, Soares *et al.*[7] developed a noise mapping tool for shipping noise prediction in a wide area and for long periods of time, using as base information ship location and type, provided by the Automatic Identification System (AIS). The accuracy of noise maps greatly depends on the quality of the input.

Since 2017, acoustic measurements have been performed in the southern side of the channel between the islands of Pico and Faial, that will provide a basis for comparison with model predicted shipping noise in the area and, therefore to approximate numerical models to a more realistic scenario. This comparison will be carried out for the entire month of June of 2018 of three self-recording hydrophones positioned in both sides and in the center of the channel connecting the two islands.

This paper is organized as follows: section II describes materials and methods used during the experimental deployments at Azores archipelago for acoustic recording, as well as methods employed to obtain useful sound pressure level and the shipping noise mapping tool for the area at hand; section III describes and discusses the results obtained and section IV gives some conclusions and perspectives for future work.

2. MATERIALS AND METHODS

A. EXPERIMENTAL DEPLOYMENTS

The experiment took place in the southern area of the islands of Faial and Pico during the whole month of June 2018. During this period, three recording locations were setup for continuous recording between 14:00 and 20:00 UTC every single day.

i. Deployment locations

Taking into account the intense marine life and ship traffic between Faial and Pico, the three receivers were located as shown Fig.4 : CA on the Pico side, IN at the channel border and MG on the Faial slope. The exact locations and depths of CA, IN and MG receivers are:

- CA receiver at 38.456N, 28.563W at 484 m depth
- IN receiver at 38.490N, 28.579W at 200 m depth
- MG receiver at 38.504N, 28.628W at 200 m depth

ii. Experimental setup

The deployment setup is shown in Fig. 1 and is composed by a 70 kg bottom anchor, an acoustic release, and an acoustic recorder at 10 m from the bottom. The mooring line buoyancy is distributed along the water column by various floating elements. A surface marker with a flag is used to signal the position and for mooring recovery. In this experiment, two types of release were considered, depending on the depth of the deployment. For deployments under 300 m depth a Sub Sea Sonics AR60 (*www.subseasonics.com*) was used, and for deployments between 300 m and 3500 m an Edgetech PORT MFE Push Off Release Transponder (*www.edgetech.com*) was chosen.

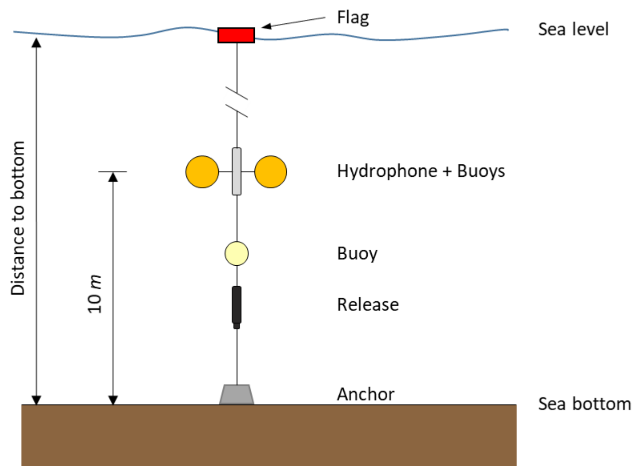


Figure 1: Deployment setup.

iii. Acoustic data acquisition

An Ecological Acoustic Recorder (EAR) was used to record the acoustic data.[8] An EAR is a digital recorder based on a $Persistor^{TM}$ CF2 microprocessor that follows a programmable recording duty cycle with a flat sensitivity of -194 dB // 1VμPa ($\pm$ 1.5dB) over the band 20-1000Hz, operated at a sample rate of 2000Hz. EARS has a 16-bit resolution system with a 47.5 dB gain.[8] The acoustic data was recorder-calibrated taking into account the hydrophone sensitivity, the acquisition gain and the ADC peak input value.

iv. Experimental acoustic data processing

Since presently there is no widely available software for the production of standard sound pressure level (SPL) from experimental data, in this study, the PAM Guide package[9] and home made routines were used. Herein, the SPL was estimated from the experimental data for the one-third octave bands with centre frequencies of 63 Hz and 126 Hz. First, periodograms were computed by means of Welch's method, with a 50% overlap and Hann tapering window of 1 s duration. Then, from each resulting periodogram, the SPL for each one-third octave band was estimated by integrating the power spectrum in the respective frequency interval. The SPL in the 63 Hz and 126 Hz one-third octave bands become the observable for characterizing the soundscape by means of a subsequent statistical processing procedure.

B. NOISE MAPPING TOOL

Numerical noise maps are widely used as tools for predicting sound pressure level due to ship traffic in wide areas and along given periods of time. To produce reliable predictions it is necessary to approximate the model inputs as much as possible to the real variables. Developing a prediction noise map should take into account six different inputs in order to achieve a satisfactory accuracy: AIS data, noise source level, bathymetry, water column properties, bottom information and surface generated wind noise, which will be described in the following subsections for the Pico-Faial region during the period of interest.

The numerical model was computed taking into account Kraken normal modes propagation model.[10,11]

i. AIS data

The AIS is an automated tracking tool that allows to obtain information about the ships' type, position, speed and draught, which is a valuable input for noise mapping prediction models. The AIS data of the period of interest, used in this study was provided by MarSensing Lda. as a data sharing agreement with AIS Hub (*www.aishub.net*). The AIS archival data was segmented in 10 minute slots, for a total of 4320 time frames. The vessels anchored or not underway were excluded from the data set.

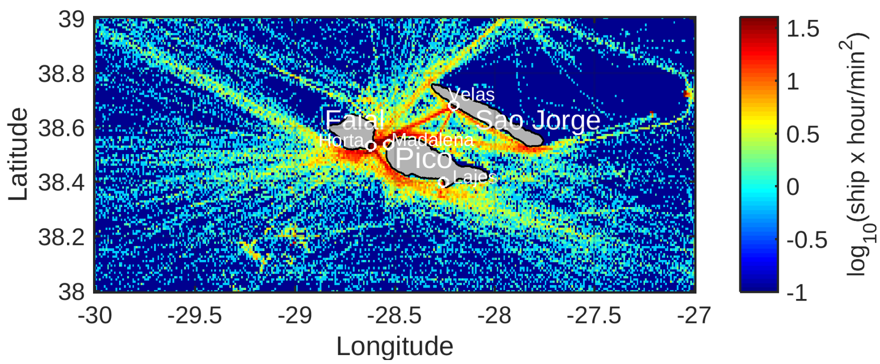


Figure 2: Cumulative shipping density based on AIS data collected from the 1st to 30th of June 2018.

The shipping density in the considered area is shown in Fig. 2 as the ship occupation hours in logarithmic scale (ship x hour/min^2). The area was normalized into spatial squares of 1 arc-minute square. Note that the logarithmic scale runs from 10^{-1} h = 6 minutes to $10^{1.6}$ h $\approx 40\tilde{h}$. So, as an example, a value of zero means one ship during one hour or, say, 60 ships during one minute each, in an arc minute square area.

It is possible to note an intense ship traffic lane connecting the ports of Horta (at Faial), Madalena (at Pico) and Velas (at São Jorge), as well as an intense vessel traffic in the southern side of both Pico and Faial, possibly due to fishing and pleasure boats.

To evaluate which activity contributes the most for the traffic connecting these three islands it is necessary to distinguish the various vessel types and the number of contacts of each type in the area (Table 1). The number of sailing vessels contacts (22373) (Fig.3) demonstrate that this type of vessels are strongly present in the area, representing almost 3 times more than fishing boats and passengers boats(7477 and 7263 respectively) and more than 4 times the number of pleasure crafts (5167). In fact, these four categories alone dominate the total number of contacts.

ii. Source level

As previously mentioned, one of the main sources of underwater noise are the vessels' engines and, more specifically, the cavitation effect of their propellers. The depth of the propeller may change according to the vessels' type and load, which may have an impact on the emitted source level. Since the exact depth of the propeller is frequently not available, in this study, the previous work of Scrimger and Heitmeyer[12] was used to set the propeller depth interval for each type of vessel.

Table 1: Ship number of contacts and classification according to AIS.

Ship type	Classification	Nb. of contacts
Fishing	30	7477
Tug	31, 32	469
Dredger	33	661
Sailing vessel	36	22373
Pleasure Craft	37	5167
High-Speed Craft	40-49	186
Special Crafts	50-59	1540
Passenger	60-69	7263
Cargo	70-79	5937
Tanker	80-89	1172

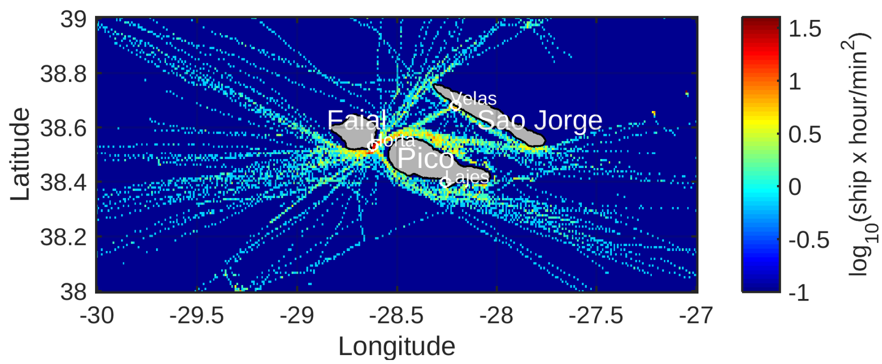


Figure 3: Cumulative sailing vessel density.

According to this, we consider source depths of 1 m for all pleasure crafts and sailing boats, of 2 m for fishing boats, 4 m for passenger vessels and of 8 m for cargos, tugs, dredgers and tankers. The emitted source level, which is the major parameter for weighting each source contribution to the total noise field, was defined based on the generic source level obtained by McKenna *et al.*,[13] except in the case of the sailing vessels. In this specific case, since no values are suggested in the general bibliography, in this study, it was decided to empirically attribute a source level of 1% of the cargo source level, which is ≈ 20 dB.

iii. Bathymetry

The bathymetric data of the surrounding area of Faial, Pico and São Jorge was taken from the General Bathymetric Chart of Oceans (GEBCO) database (*www.gebco.net*), with a 15 arc-second interval generated by the assimilation of heterogeneous data, all referred to mean sea level.[14] A detailed view of the bathymetry of the area and the hydrophone location is presented in Fig. 4. The black stars indicate the cumulative AIS ship positions in the interval 14:00 to 20:0 UTC of day June 26, 2018, as an example. Note that the colored diamond symbols denote the hydrophone locations.

The topography of the area is highly variable, presenting a very steep section around the islands, which may easily reach 1000 m or more, and a relatively flat area in the channel between Faial and Pico, which

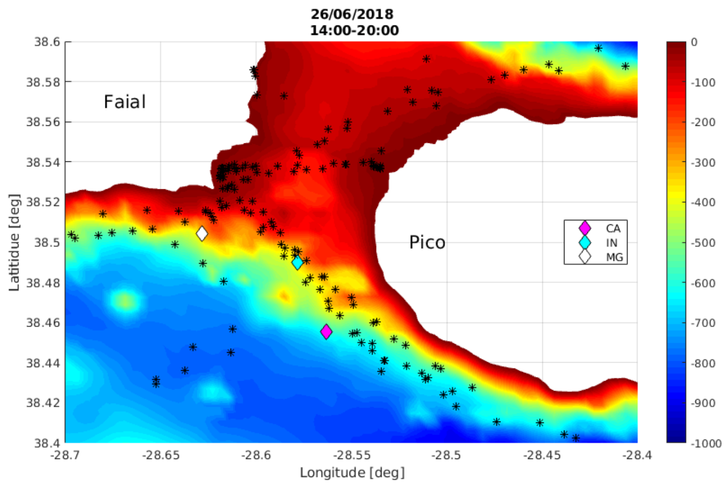


Figure 4: Faial and Pico islands surrounding area bathymetry with hydrophone locations CA, IN and MG and AIS ship positions for time interval of 14:00 to 20:00 UTC of June 26, 2018.

ranges between 50 and 200 m water depth. Note that the hydrophones were located at the southern limit of the island platform or on the slope to deeper water.

iv. Sound speed profile

The sound speed varies according to water temperature, salinity and depth profiles. The water-column was parameterized based on temperature and salinity models provided by the Copernicus database (*www.copernicus.eu*) using Mackenzie[15] nine-term equation to calculate the sound-speed profile (SSP).

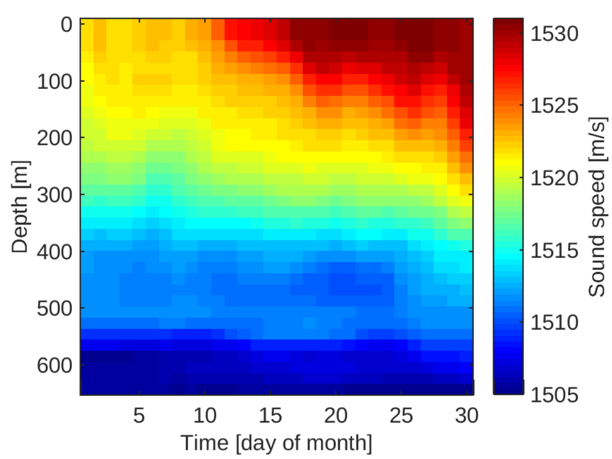


Figure 5: Sound speed variation during June 2018 at position with coordinates (38.417N, -28.583W).

Figure 5 shows the sound speed profile in a central position, taking into account the three hydrophone locations. It is observed that sound speed increases in the first half of the water column along the month of June due to the formation of a summer thermocline. However it remains constant below 350 m depth during all the month of June.

v. Bottom parameters

The fact that there is a lack of site-specific bottom parameters lead us to consider, in this study, a generic bottom description. Based on previous studies of Soares *et al.*[7] and Maglio *et al.*[16] a two layer bottom model composed of a fluid sandy sediment layer over a rocky semi-infinite sub-bottom as described in Table 2, was adopted.

Table 2: Assumed seabed parameters.[7,16]

Model Parameter (units)	Value
Sediment speed (m/s)	1650
Sediment density (g/cm^3)	1.9
Sediment attenuation (dB/λ)	0.8
Sediment thickness (m)	10
Sub-bottom speed (m/s)	1800
Sub-bottom density (g/cm^3)	2.8
Sub-bottom attenuation (dB/λ)	0.2

vi. Surface wind generated noise

The wind contribution for the total underwater sound level present in a given area can not be neglected, specially considering the frequency range at stake. In order to be able to make a fair comparison between measured and modelled sound level, surface generated noise sets a lower bound or a background level in the absence of ship noise sources. Depending on the amount of ship noise and wind action on the sea surface, the relevance of surface noise increases with the decrease of ship noise level with frequency with a cross-frequency that varies between 400 and, say, 1000 Hz.[17]

Throughout the years, several models were proposed to represent wind generated noise at the sea surface.[18–21] In this work Wilson[21] model was adopted. According to that approach surface noise is represented by a uniform sheet of geographically distributed point acoustic sources.

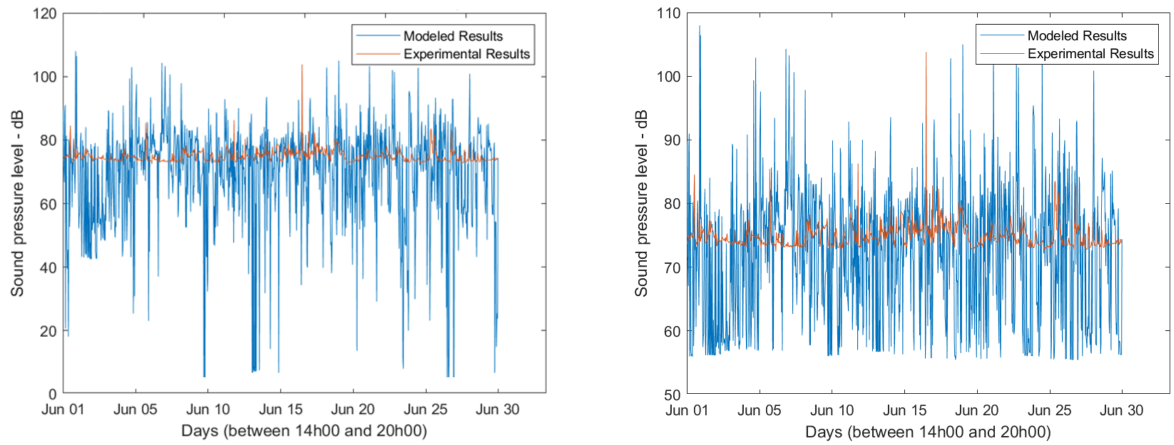
For our purpose, the area was divided in 10$\times$10 km cells and each source was randomly placed inside each cell for each snapshot, taken every 45 minute. A constant contribution of each source was considered taking into account a wind speed of 10 knot during the month of June 2018. Each source was placed at 0.1 m depth. Then a statistical post processing was implemented taking into account the percentile 50 over a 3 days moving window (96 snapshots).

3. RESULTS AND DISCUSSION

This section presents the comparison between the experimental measurements and the numerical underwater noise model results as direct sound pressure level and as statistical indicators for three hydrophones (CA, IN and MG), taking into account the frequencies of 63 and 126 Hz.

A. SOUND PRESSURE LEVEL COMPARISON

The comparison of SPL values can be made at two different phases: first comparing the experimental and numerical levels along the month of June 2018; and then comparing, for the same period of time, the



(a) Without wind noise *(b) With wind noise*

Figure 6: Numerical and experimental SPL at CA location considering the 63 Hz frequency band without wind noise (a) and with wind noise (b).

effect of adding the surface generated wind noise model in the numerical model.

Since the available data was recorded in the time interval between 14:00 - 20:00 UTC each day, the shipping noise predictions were filtered for that time window as well.

Comparing the experimental and the numerical results without surface generated wind noise as shown in Fig. 6a for CA location, it may be observed that the numerical results present a much higher amplitude variation through time than the experimental results, with values ranging from 4 up to 110 dB. This behavior can be seen in all three hydrophones. In fact, lower values are due to low or far away ship traffic, since this is the only source of noise taken into account. The numerical model used to compute the predicted SPL sets a lower bound of 4 dB when no ship is present.

The effect of adding the surface generated wind noise is shown in Fig. 6b for the CA site, where now the lower bound is oscillating through time at an SPL of approximately 55 dB, depending on the wind noise generation model output. It is also noted (but not shown) that the lower SPL values were registered at the IN hydrophone at both frequencies of 63 and 125 Hz. This was expected and is possibly related with its location, since IN is located in the middle of the channel, while CA and MG are located near the coast with nearby ports and traffic lanes. On the other hand, a lower variability was observed in the experimental results.

B. STATISTICAL COMPARISON

The statistical comparison was performed for the frequencies of 63 Hz and 126 Hz only.

i. Percentiles

In this study only the percentiles 5, 50 and 95 were considered as representative for evaluating the differences between experimental and numerical results and the influence of surface generated wind noise, as shown in table 3.

It is observed that when the surface generated wind noise is not considered the biggest differences between experimental and modeled results occurs when considering percentile 5. In this case, the difference is between 15 and 35 dB, while the CA location showed the largest difference. Taking into account percentile 95, the differences between experimental and modeled are centered between 7 and 12d̃B. Taking into account

Table 3: Experimental/numerical percentile comparison

	Exp. 63Hz	Mod.w/o wind 63Hz	Mod. w/ wind 63Hz	Exp. 126Hz	Mod. w/o wind 126Hz	Mod. w/ wind 126Hz
			Percentile 5			
CA	71.9	39.8	56.2	75.5	40.3	58.5
IN	69.4	53.6	55.5	73.5	55.0	58.7
MG	73.7	50.7	54.0	77.4	49.8	56.7
			Percentile 50			
CA	74.9	73.9	73.9	77.2	78.3	78.4
IN	71.3	75.7	75.7	75.5	78.1	78.2
MG	75.9	74.4	74.4	79.2	79.3	79.3
			Percentile 95			
CA	78.9	88.7	88.7	83.4	95.2	95.2
IN	75.7	86.5	86.5	84.0	92.4	92.4
MG	79.9	86.9	87.0	88.3	96.7	96.7

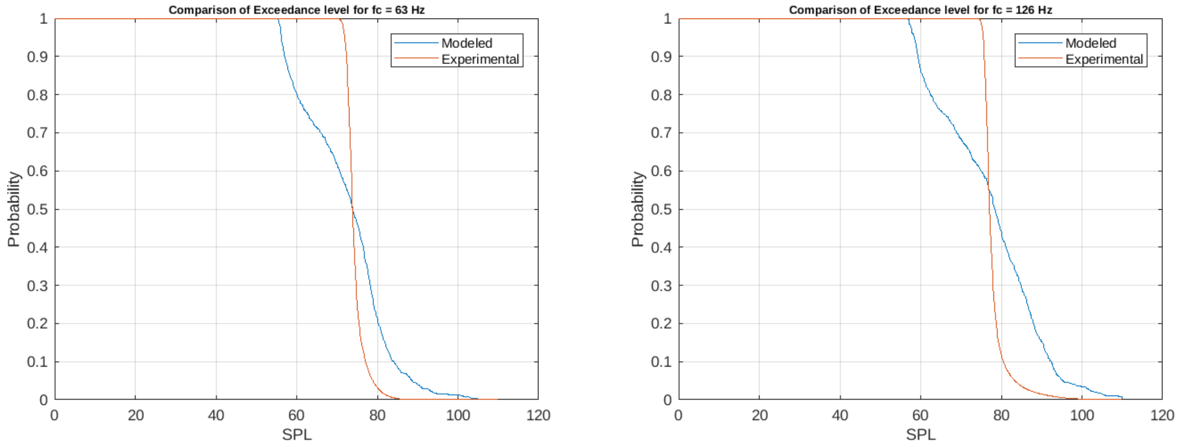
the percentile 50, it was observed minimal differences between experimental and modeled results, oscillating between 1 and 4 dB.

As expected when adding the modelled surface generated sound due to wind, the differences between experimental and modeled results reduce significantly. For percentile 5, a difference between 14 and 21 dB still exists but for percentiles 50 and 95 the coincidence between experimental and modelled results is now statistically perfect.

ii. Exceedance level

In order to evaluate the proportion of time that one specific sound pressure level is exceeded, the exceedance level was calculated, and shown for the CA site in Fig. 7, as an example.

Confirming previous findings it was, again, possible to note the low experimental results variability at both frequencies. The results obtained with the surface generated wind noise showed a better curve fitting to the experimental results than the modeled result without. However this fitting is better for high SPL values than for lower ones. Additionally, two considerations may be made: the IN shows the better fitting between experimental and numerical results and also where the SPL values are the lowest.



(a) *(b)*

Figure 7: Exceedance levels for CA site at 63 (a) and 126 Hz (b).

4. CONCLUSION

There is an important cetacean community in the Azores archipelago which rely on sound on their daily existence. Whether increasing human activity and ship traffic will lead to an increasing impact on cetaceans is the question we address in this work.

The Marine Strategy Framework Directive (MSFD) for underwater noise has suggested several strategies for performing ocean monitoring to attain the Good Environmental Status. One of them includes ocean noise prediction using numerical models, over extensive areas and time periods where no direct observations are possible.

This study compares the numerical results with *in-situ* noise measurements for three hydrophones deployed on the southern part of the channel between the islands of Faial and Pico in the Azores, at the frequencies of 63 and 126 Hz which cover the vocalization frequency band of fin and blue whales (20-200Hz).

In order to ensure a better fitting between numerical and experimental results, the influence of surface generated wind noise was considered by including results predicted with the Wilson wind noise model. This fact allowed to obtain a better fit and to show the importance of surface generated sound on sound maps.

The results suggest a favorable comparison between numerical and experimental results, showing a mean difference of 1 to 4 dB at 63 Hz and 1 to 2 dB at 126 Hz. The larger difference observed at 63 Hz could be explained by the possible existence of an implicit high pass filter at 50 Hz on the recording equipment, which may have a minor influence on the considered frequency. Another fact that may corroborate to this is the smaller variability observed in the experimental data, which was unexpected.

Turning to the main question of the title of this study, it is possible to state that the developed numerical model provided satisfactory predictions of the underwater noise in the area, which means that this could be a useful risk assessment tool for cetacean in Azores archipelago. Future work will be centered on the assessment of the excess noise level, *i.e.* the noise level above the natural sound level, in order to evaluate and quantify the direct impact that it may have on the cetacean population of the area.

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