

Shipping noise predictions from AIS in the Faial-Pico area, Azores archipelago

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Abstract—The Azores archipelago, lying on the North Atlantic (NA) ocean, hosts one of the greatest diversities of cetaceans, and is an important habitat for several resident and migratory species. However, this unique diversity may be at risk due to the ocean noise generated by increasing commercial and recreational vessel traffic in the area. AIS shipping distribution and water column variability, together with suitable numerical propagation models were used to generate noise level maps for the area around Faial-Pico-São Jorge Islands, during June 2018. The generated noise level time-space distribution generally agrees with detected environmental variability and known navigation in the area, namely ferries between islands and fishing patterns.

Index Terms—anthropogenic ocean noise, marine mammals, noise mapping, Azores archipelago.

I. INTRODUCTION

In the last decades, there is an increasing awareness of underwater noise pollution due to human activity and the impact it may have in ocean biodiversity. Sources of underwater noise may be classified in three categories: environmental (wind, rain, waves, earthquakes and ice), biological (vocalization of marine mammals, fish and invertebrate) and anthropogenic (shipping, offshore construction, seismic surveys, etc) [1]. Marine mammals in particular, rely on sound to forage, communicate, navigate and perceive their environment. Recent studies indicate that their behavior and physiology may be affected by anthropogenic ambient noise. These include: increased stress levels in NA right whales [2], changes in mating and foraging behavior of humpback whales [3], changes in harbor porpoise behavior [4], changes in calling behavior and masking reduction in communication space [5]. The Azores archipelago, lying on the North Atlantic ocean, hosts one of the greatest diversities of cetaceans including resident and migratory species [6]. However, this unique biodiversity may be at risk from increasing commercial and recreational vessel traffic (*e.g.* tankers, containers, ferries, etc) contributing to an overall background sound pressure level reported to be as high as 80 to 90 dB // $1\mu\text{Pa}^2/\text{Hz}$ in the 10 - 100 Hz band [7].

One way to predict the underwater noise resulting from anthropogenic sources, is by generating numerical noise maps [8]. Numerical noise maps stem from the idea of propagating the noise source pressure level at one point in space and time to every other point in the area of interest using a numerical propagation model, setup with the space-time variable

environmental properties of the area. The process is repeated for every known noise source and the resulting noise power summed up to form the noise map. Soares *et al.* [9] developed a noise mapping tool for shipping noise prediction, based on Automatic Identification System (AIS) data information for gathering ship type and spatial distribution.

The objective of the present work is to show preliminary results of shipping noise predictions around the Azorean islands of Pico, Faial and São Jorge through realistic noise maps based on the actual AIS distribution, bathymetry of the area and incorporating water column variability covering a period of 30 days during the month of June 2018.

This paper is organized as follows: section II describes the data sets used and methods implemented in this work; section III shows and discusses the results obtained and IV gives some conclusions and perspectives for further work.

II. MATERIALS AND METHODS

The present study takes into account the area between the Azorean Islands of Pico, Faial and São Jorge. This section describes six main input data sets required for underwater noise prediction: Automatic Identification System data, source level, bathymetry, water column data, seafloor acoustic parameters and then the actual acoustic field computation.

A. AIS data

The AIS is an automated tracking tool primarily used as anti-collision system. Among other information, AIS shows ships' type, position, speed and draught, which are relevant for the purpose of noise mapping.

Independently of vessel type, propeller cavitation is the main source of noise caused by vessels, followed by flow noise and noise due to machinery. For this reason, in numerical models, the depth of the propeller is an important input. The problem is that this parameter is frequently not available on ship data bases and also depends on ship load. Based on this reality, for numerical purposes, Scrimger and Heitmeyer [10] proposed an interval between 7 m to 14 m depth for the propeller position. In this work a propeller depth of 8 m was used throughout.

The AIS data used in this study was provided by MarSensing Lda. as a data sharing agreement with AIS Hub

(www.aishub.net), for the whole month of June 2018. The AIS archival data was segmented in 10 minute slots (4320 time frames). The anchored ships or ships not underway with engine were excluded from the data set.

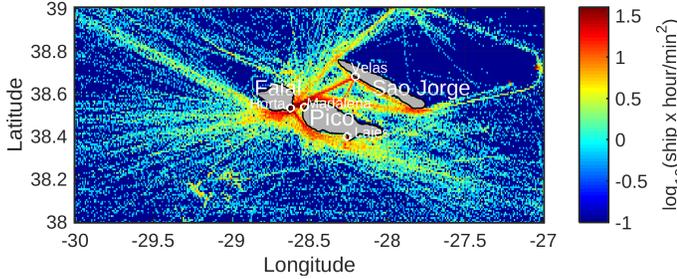


Fig. 1: Cumulative shipping density based on AIS data collected from the 1st to 30th of June 2018.

Fig. 1 shows the ship occupation hours in logarithmic scale (ship x hour/min²) in order to illustrate the importance of this area in terms of shipping routes. 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 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. Fig. 1 clearly identifies the main shipping lanes between these three islands and those running out of the box to/from other locations. The connections between Faial (at Horta port) and Pico (at Madalena and Lages ports), between Faial (at Horta port) and São Jorge (at Velas port) and between Pico (at São Roque port) and São Jorge (at Velas port) have very intense occupation which is mainly related with the fact that there are ferries making these connections every day, several times a day during the summer time. It is also possible to observe an intense shipping lane coming from Horta and crossing to the south-east side of São Jorge. Since there is no port on that part of the São Jorge island, we believe that this traffic intensity is related with the shipping lanes going towards Terceira island, which is located at north-east of São Jorge (out of the map). Another busy route connects the port of Horta through the west of São Jorge to the island of Graciosa to the north (also out of the map). As a curiosity the north-east side of São Jorge is almost empty from ship traffic.

B. Source level

It is not sufficient to know the position of ships, their type and their propeller depth. We also need to know the emitted source level, which is the major parameter for weighting each source contribution to the total noise field. Since this information is not readily available for the data set and period at hand, the approach taken here follows that of previous studies [9], [11] that use generic source levels measured in previous experiments for each ship type. In this work, the results obtained by McKenna *et al.* [12] were used, and are shown in Fig. 2 for a meaningful frequency band.

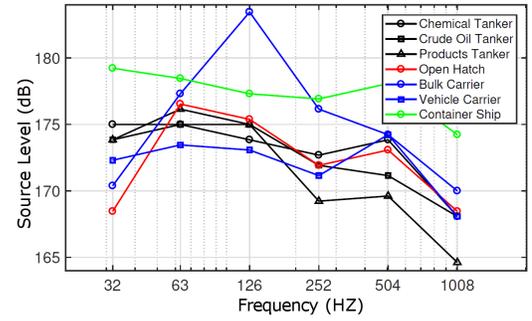


Fig. 2: One-octave band mean experimental source levels for different ship types (from [12]).

C. Bathymetry

The bathymetric data of the surrounding region of the islands of Pico, Faial and São Jorge was taken from the General Bathymetric Chart of Oceans (GEBCO) (www.gebco.net). It was used a GEBCO 2019 Grid Version with 15 arc-second interval generated by the assimilation of heterogeneous data, all referred to mean sea level [13].

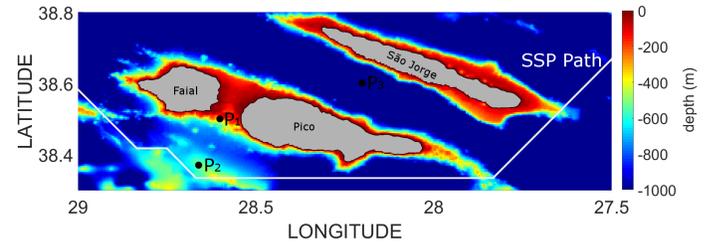


Fig. 3: Faial, Pico and São Jorge islands surrounding area bathymetry. White line indicates the coordinates along which water column variability is shown in section II-D. Pre-determined locations are shown as P_1 , P_2 and P_3 .

As shown in Fig. 3 the topography of the area is highly variable, especially around the islands with very steep section that easily reach a depth of 1000 m or more. One particularity of this region is the Faial - Pico channel, which shallowest part is only 50m deep and the deepest is not more than 200m. Another particularity of this region is the existence of several seamounts, mainly in its southwest part, which strongly contributes to the overall topographic variability. São Jorge has a relatively constant depth all around.

D. Sound speed profile

The sound speed profile depends on water temperature, salinity and depth [14] so, it is variable in time, in the horizontal plane and particularly along the vertical depth axis. The water-column was parameterized based on temperature and salinity models provided by the Copernicus database (www.copernicus.eu), from which sound speed was calculated

with the approximated Mackenzie [15] nine-term equation. To illustrate water column variability, Fig. 4a shows the sound speed variation obtained at P₂ (38°37.00N and 28°66.00W) of Fig. 3 during the whole month of June 2018, while Fig. 4b shows the spatial variation of sound speed along SSP Path of Fig. 3 on day June 15th, 2018.

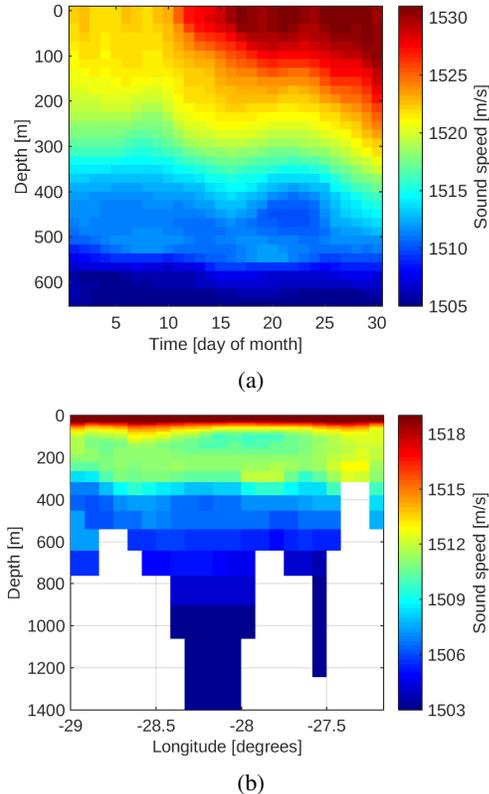


Fig. 4: Sound speed profile during the month of June at P₂ (a) and sound speed profile along SSP Path during June 15th, 2014 (b). Point P₂ and SSP are shown in Fig. 3.

Fig. 4a shows that the sound speed increases to the end of the month for depths lower than 300 m. Beyond 300 m, the sound speed remains approximately constant during the whole month. Fig. 4b shows that the sound speed spatial distribution is uniform along the SSP path, suggesting a modest influence of the bathymetry in the propagation of sound in the deep waters of the southern area of the islands and specially if compared with its major influence in shallow water.

E. Bottom parameters

Accurately describing seabed properties is a great challenge, due to the unknown bottom composition that may vary from one location to another. A lack of data made us assume a generic bottom description, considering a two layer bottom composed of a fluid sandy sediment layer over a rocky infinite sub-bottom [9], [14] with the values shown in Table I.

It is important to refer that although bottom parameters may have an influence in the numerical results for shallow water, in our case and except in the channel between Faial and Pico,

TABLE I: Assumed seabed parameters [9], [14].

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

most of the area is deep water, hence the seafloor properties should play a minor role in the sound propagation due to reduced interaction of the sound with the sea bottom.

F. Sound field computation

Sound field computation proceeds in two steps. In the first step, KRAKEN propagation model [8], [16], [17] is setup with the water column, bathymetry and seafloor parameters described above, and used to calculate the transmission loss (TL) from the n th AIS ship position to every point in a spatial grid defined by a disc of variable range R_r and azimuth θ_r for a fixed depth, so that the received rms power spectral density $Y_n(R_r, \theta_r)$ is given by

$$Y_n(R_r, \theta_r) = \sqrt{\sum_{k=1}^K |S(\omega_k)|^2 |\text{TL}_n(\omega_k, R_r, \theta_r)|^2}, \quad (1)$$

where the summation is performed over a given discrete number of frequencies K , at which the TL (in rms power units) is calculated, and where $S(\omega_k)$ is the power spectrum of the n th ship as defined in section II-B. In a second step the range-azimuth discs for each ship are converted to latitude-longitude-depth coordinates, say (x, y, z) , and then summed over all N source ships present in the area at any given time, to obtain actual sound pressure level (SPL)

$$\text{SPL}(x, y, z) = 10 \log_{10} \sum_{n=1}^N |Y_n(x, y, z)|^2. \quad (2)$$

These steps are then repeated along time throughout the whole period of interest at a rate of 10 min interval. In our case the spatial grid is set up with a resolution of 500m. The bathymetric map is set up to every 15 arc-second latitude - longitude squares and for two depths of 20 and 100 m.

III. RESULTS AND DISCUSSION

This section shows and discusses the predicted noise maps covering the Azorean Islands of Pico, Faial and São Jorge for the month of June 2018.

A. Noise level assessment

The following noise level assessment will be based on the exceedance level (EL) for two frequencies (63 Hz and 126 Hz) and at two depths (20 m and 100 m). EL is meaningful in terms of percentage of time, as it is equivalent to determining a given percentile for all available SPL predictions over a given area and time interval. In order to define the lower

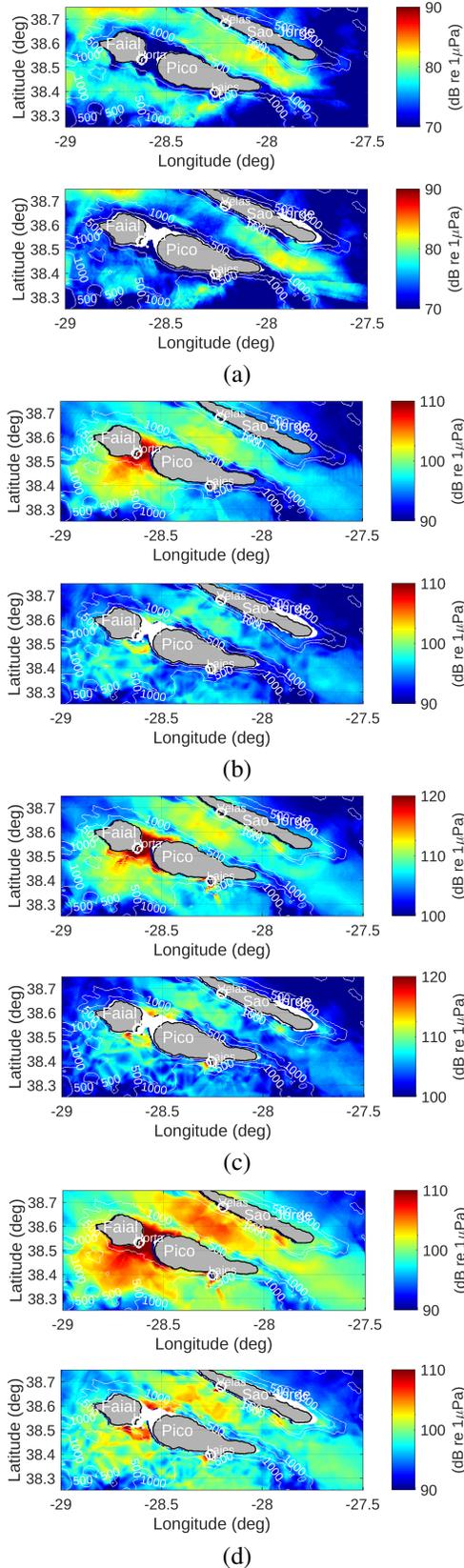


Fig. 5: Exceedance level at 20 m (above) and 100 m (below) for percentiles: 95 (a), 50 (b), 5 (c) and overall mean (d).

and upper boundaries of EL, 5% and 95% percentiles are considered. Figure 5 shows the EL pairs at 20 and 100 m depth for 95%, 50%, 5% proportions of time, and the overall mean from (a) to (d), respectively. Plot (a) obtained for EL 95% clearly shows that the most sensitive area is that located between Pico and São Jorge islands. The maximum noise level is not significantly different between 20 m and 100 m depth, although the area exceeding 75 dB is larger at the former than at the latter. The white colored area shown in the 100 m depth figure relates to the fact that this area is shallower than 100 m.

The EL of 5%, shown in plot (c), clearly reflects the effect of the bathymetry in the propagation of the noise. At 20 m depth the channel between Faial and Pico is considered as a critical area in terms of noise levels registered, which are higher than in other areas. In this area, the noise level reaches 120 dB. In deeper areas, the noise level decreases, as expected. Analysing the EL of 5% at 100 m depth one can observe that the noise level barely reaches 110 dB. The only exception is in the southern part of Horta port which is, again, a bathymetric effect.

The EL of 50% was used as an indicator yielding values close to average, with the advantage of reducing the role of outliers frequently observed in the average figure. According to this it is possible to observe that the EL of 50% yields lower noise levels in a wider area than the average both for 20 m and 100 m depth. This fact is specially true in the southwest side of Faial island and the area between Pico and São Jorge islands. Additionally, due to the sensitivity of the average to outliers, it is possible to distinguish some shipping lanes coming from Velas and Lages ports in São Jorge and Pico islands, respectively.

B. Analysis at discrete positions

After considering a global analysis in the surrounding area of Faial, Pico and São Jorge islands, it is now important to focus on some specific spots to have an idea of the actual noise level variation through time.

Three locations were selected at the following coordinates: P_1 (38.50N;28.60W), P_2 (38.37N; 28.66W) and P_3 (38.60N; 28.20W) as shown in Fig. 3. P_1 was defined to evaluate the noise level in the south side of the canal due to its particular topography and intense ship traffic. Location P_2 was chosen to illustrate the noise level at the outer south side of the canal and attempt to understand how far the canal topography may influence noise propagation. At this location the water depth is approximately 400 m while the ship traffic is less intense than in P_1 . Finally P_3 is a deep water location between Pico and São Jorge islands, and it was defined in order to evaluate the underwater noise propagation near one intense traffic shipping lane.

Table II shows the EL for the mean, 5%, 50% and 95% percentiles for the two depths of 20 and 100 m.

One can remark that the noise level average at 20 m depth is 6 dB higher than that at 100 m for P_1 . For P_2 and P_3 this difference is not significant. Comparing the results at 20 and 100 m depth, the differences between P_2 and P_3 mean values

TABLE II: Exceedance level at three specific coordinates.

Depth (m)	Position	Mean	p ₅	p ₅₀	p ₉₅
20	P ₁	111.3	68.8	107.5	118.0
20	P ₂	103.9	78.9	101.8	109.5
20	P ₃	104.1	80.1	101.9	112.6
100	P ₁	105.4	63.3	98.8	112.0
100	P ₂	102.3	75.6	99.7	108.2
100	P ₃	103.0	75.8	99.0	109.6

are very small, on the order of 1.6 dB for P₂ and 1.1 dB for P₃. If the outliers are not considered (percentile 50), the difference between 20 and 100 m depth for point P₁ increases by 8.7 dB. Comparing points P₂ and P₃ at 20 and 100 m depth, this difference is once again very small, on the order of 2.1 and 2.9 dB for P₂ and P₃, respectively.

Comparing points P₁, P₂ and P₃ one may remark that P₁ presents always the highest score independently of the depth considered. However, the differences between P₁ and the other two points is not significant at 100 m depth. This fact reflects the effect of the bathymetry for noise propagation since P₁ is located in a shallow water area and P₂ and P₃ in deep water. Fig. 6a and 6b show curves of the percentage of time for

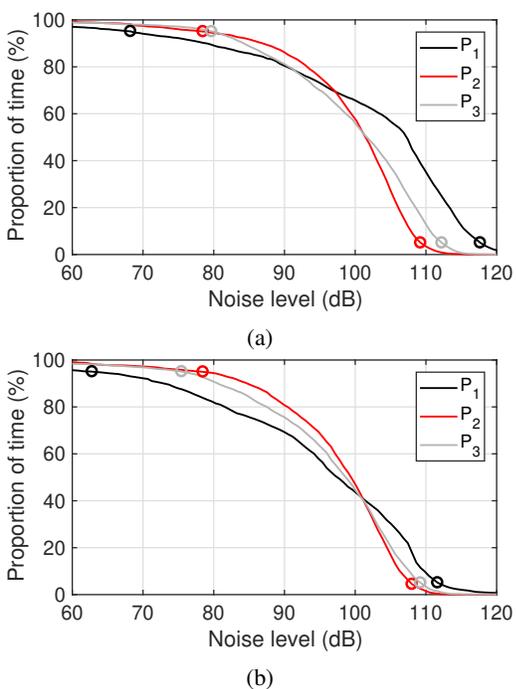


Fig. 6: Discrete analysis for points P₁, P₂ and P₃ at two different depths: (a) - 20 m and (b) - 100 m.

which a given level is exceeded for the same three locations. Point P₁ shows the highest EL, above 100 dB both for 20 and 100 m depth. This was expected due to its location at the border of the channel, near Horta port, and therefore in the vicinity of intense shipping.

Locations P₂ and P₃ have more or less the same behavior till an EL of 80 dB for both depths. Beyond 80 dB an higher EL is obtained at P₂ than at P₃ up to 100 dB at both depths.

At this point, the behavior is reversed since P₂ attains a lower EL than P₃, up to a maximum of 120 dB for both depths. This behavior may be explained by the fact that P₃ is located at a deeper site than P₂ but also by the fact that P₃ is located near the shipping lane that connects the busy ports of Horta and Velas, in São Jorge.

C. Time series analysis

The predicted noise level time series during the last seven days of June at 20 m depth is compared for the three locations P₁, P₂ and P₃ in figures 7a, 7b and 7c, respectively.

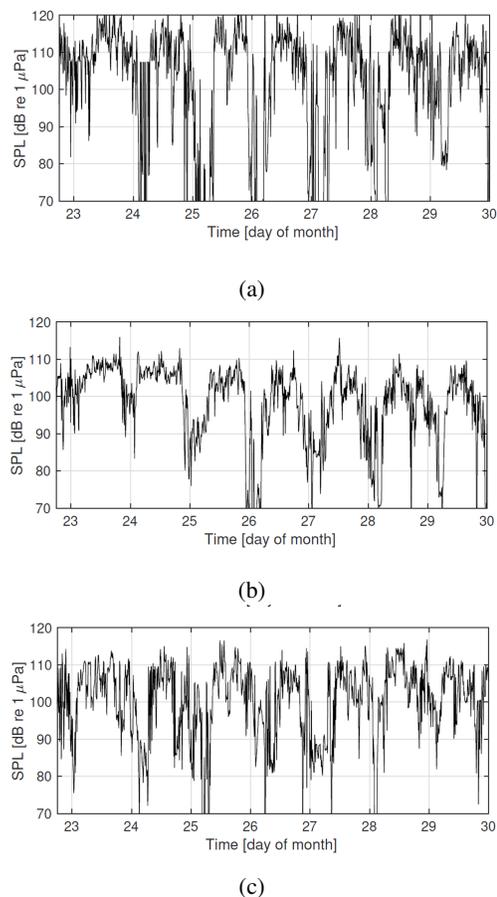


Fig. 7: Time series of predicted noise level for location points P₁, P₂ and P₃ during the last seven days of June 2018, at 20 m depth.

As expected, location P₁ has the highest noise levels and P₂ the lowest. This fact was expected since P₁ is en route to Horta harbour and consequently is where all vessels (recreational vessels, containers and cargo ships) cross to dock. The lowest noise levels (+/-70dB) were recorded near mid-night and the highest (+/-110/120dB) between 10:00 and 12:00. The diel periodic behavior can be clearly identified and somehow expected, since during the night there are much less frequent ferries and in generally also less fishing boats, as well as other vessels around the islands. Around 2:00 fishing activity increases and around 7:30 ferries also start crossing between

islands more frequently. Clearly, these activities increase the noise level at these two locations.

Additionally, the 23rd and 24th of June were Saturday and Sunday, respectively, and in opposite to what might have been expected, no significant difference can be seen in terms of noise level for points P_1 and P_3 . This fact indicates that it is not possible to identify any week/weekend pattern during the month of June in this area. We believe that this is also related to the fact that during summer time, weekends are considered as normal (or even busier) days for ferries but also that during the weekends there are no cargo ships in the area. At location P_2 we note that during the weekend the noise level does not decrease as much as during the week. To hypothesize which

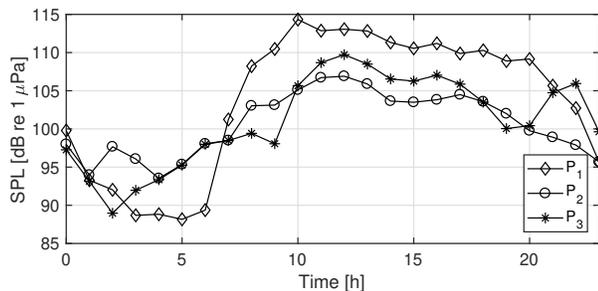


Fig. 8: Level of exceedance during the month of June as function of the hour of the day.

are the main noise level contributors at the various locations, the 50% EL observed during the month of June was extracted for its variation per day hour at 20 m depth and shown in Fig. 8. We believe that P_1 suffers the influence of ferries connecting the islands but fishing boats and large vessels as cargos, containers and tankers, P_2 mainly suffers the influence of fishing boats and P_3 is dominated by ferries connecting the islands of Faial and São Jorge.

IV. CONCLUSION

Shipping noise predictions based on AIS, bathymetry and variable water column properties was used to evaluate noise level in the surrounding area of Azorean islands of Faial, Pico and São Jorge. This study aims at contributing to the understanding of underwater noise levels in this region since, despite the importance of Azores in terms of cetaceans, to our best knowledge, this is the first time noise maps were generated for this area. This study was undertaken to present the predicted noise levels due to shipping at two depths: 20 m and 100 m. Mean noise level maps show an overall agreement with the known ferries and fishing patterns in the area. The statistical analysis over time periods and at selected locations are in line with expected results. However, one of the highest contributors of underwater noise near cetaceans locations, the whale-watching boats, is not taken into account since these boats do not carry AIS transponders and therefore they are not included in this study. The fact that the channel between Faial and Pico has no more than 50 m water depth and intense shipping activity largely contributes to the higher noise levels observed in this area. To increase the performance of the used

prediction tool and refine the parameters introduced in our model it is planned, as future work, to compare numerical and experimental results obtained in the surrounding area of Azorean islands of Faial, Pico and São Jorge.

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