DOI: 10.61782/fa.2023.1205

ANALYSIS OF THE AMBIENT NOISE AT THE SCALE OF THE BAY OF BISCAY MARINE SUB-REGION

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ABSTRACT

The impact of human activities on marine ecosystems has become a major international concern. In the waters of the European Union, the Marine Strategy Framework Directive (MSFD) is in charge of assessing the Good Environmental Status (GES). Based on a 6-year cycle, the GES is assessed through 11 pressure and status descriptors and is supported by data acquisition programs aiming to monitor marine environments. In France, a dedicated monitoring network (MAMBO), focuses on the underwater ambient noise level monitoring, particularly its continuous component related to maritime traffic in two targets frequency bands (one-third octave bands centered on 63 Hz and 125 Hz). A specific algorithm has been developed for background noise estimation without *a priori* in adverse marine environment. The algorithm enables to deal with complex and non-stationary noises as well as to ensure transient signal rejection. In order to make a proper estimation of the contribution of the man-made ambient noise to ambient noise budget, we quantify the oceanic ambient noise, i.e. without any identifiable source, and determine the traffic close to the monitoring station. A statistical study of the ambient noise is then performed in regard with the environmental conditions in order to analyze meteorological contribution.

Keywords: *MSFD, Bay of Biscay, traffic noise, detection algorithm*

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1. INTRODUCTION

Since the 1960s, the growth of maritime industries and the resulting increase in maritime traffic have resulted in the emergence of underwater noise pollution [1]. In certain ocean basins, there has been a noticeable rise in noise levels of 10 dB per decade within the main frequency band of noise emitted by ships [2]. At present, sea transportation accounts for over 80% of global trade by volume [3]. Underwater noise pollution is a significant environmental concern, as it can adversely affect marine life, particularly marine mammals. It can have several detrimental effects, such as masking communication signals [4], [5], [6], causing prey to flee [7], or inducing stress and disorientation [8]. The increased awareness of these risks has led to the implementation of conservation policies for species sensitive to underwater noise [9]. Thus, at the European level, the Marine Strategy Framework Directive 2008/56/EC was implemented on June 17, 2008 (MSFD) through 11 descriptors [10]. This directive applies to all European countries with a coastline. In France, it applies to metropolitan marine waters. It is through descriptor 11 (D11), defined as ”The introduction of energy, including underwater sound sources, is carried out at levels that do not harm the marine environment” of the MSFD that underwater noise of human origin is treated as a pollution with the need for a monitoring programme. MSFD establishes an obligation to maintain good sound status in metropolitan marine waters in regard to ambient noise. D11 is divided into two categories, namely D11C1 and D11C2. D11C2 refers to the pressure levels of continuous low-frequency sounds in the one-third octave bands centered on 63 Hz and 125 Hz. The selection of these specific frequency bands for D11C2 was based on their well-established relationship to shipping noise, as determined by the MSFD and supported by studies [11], [12]. A program has been introduced and approved at the national level in France, which focus is to monitor anthropogenic noise in metropolitan waters. The primary objective of this program is to collect the necessary data and information to develop indicators that meet the two criteria outlined in the directive. In the context of the study, our focus is on criterion D11C2. The former is concerned with gathering maritime traffic data through the Automatic Identification System (AIS) to model ambient noise at the scale of the Exclusive Economic Zone (EEZ), while the latter aims to establish a network of monitoring stations for acoustic measurements in metropolitan waters and to collect opportunity data through the MAMBO network - Acoustic Monitoring and Noise Measurements on Opportunities [13] (figure 1) .

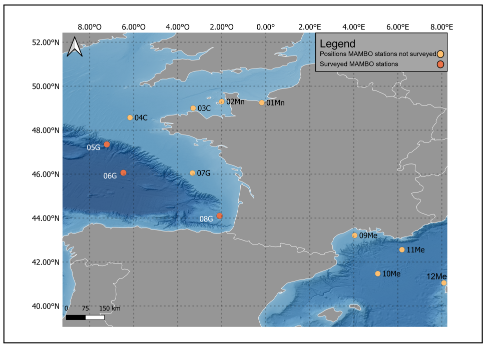

Figure 1. Map of the MAMBO network - Acoustic Monitoring and Noise Measurements on Opportunities. The positions of the different MAMBO moorings used in this study are shown in dark orange.

The purpose of this preliminary study is, from the acoustic data acquired in the framework of the ambient noise monitoring program, first to quantify the oceanic ambient noise, i.e. without identifiable sources, and secondly, to determine the traffic close to the monitoring station. A statistical study of the ambient noise is then performed with respect to environmental conditions in order to analyze the contributions of oceanic and meteorological variables.

2. MATERIAL AND METHODS

2.1 Data

The acoustic database consists of data acquired over several months at three mooring stations, all equiped with four sensors immersed at different depths (between 30 and 300 m). These stations are distributed on several strategic points off the French Atlantic coasts. Complementary data consists of environmental data from the Copernicus Marine Environmental Monitoring Service (CMEMS), the Copernicus Atmospheric Monitoring Service (CAMS) and AIS data provided by ExactEarth® and the Directorate of Maritime Fisheries and Aquaculture (DPMA).

2.1.1 Acoustics data

Acoustic data recordings from the mambo network, a network of 12 stations scattered in the French EEZ (Figure 1). The stations are located in or near areas of ecological interest. Among the three stations that will be analyzed (05G, 06G and 08G), station 05G is located in the vicinity of shipping lanes, and at the same time, close to the continental slope, such that both traffic noise and marine mammals vocalizations are present in the data. It has optimal low-frequency acoustic propagation conditions as it is placed in deep water environment. For each mooring, the hydrophones operate in pairs, one relaying the other when the batteries are discharged (pre-programmed mode). In total, the moorings are operational for around 150 days, as shown in table 1. Each hydrophone records the underwater soundscape at a sampling rate of 39 kHz on a 30 min.h^{-1} duty cycle, in an effective bandwidth between 10 Hz and 17 kHz.

Table 1. Information on the depth and duration of the different sensors of the studied stations.

Station (days)	Sensor	Depth	Duration
O5G (178 days)	22	300	16/05 - 25/07
	23	150	09/03 - 25/03
	24	80	16/05 - 25/07
	25	30	17/02 - 06/05
06G (143 days)	1	110	27/06 - 04/09
	2	160	29/09 - 12/12
	3	230	27/06 - 04/09
	4	380	29/09 - 12/12
08G (147 days)	18	60	28/06 - 12/09
	19	110	28/09 - 08/12
	20	180	28/06 - 12/09
	21	330	28/09 - 07/12

2.1.2 AIS data (Automatic Identification system)

The Automatic Identification System (AIS) data facilitates the exchange of information between ships and maritime traffic surveillance systems via VHF radio link (Very High Frequency). As a result, the AIS provides access to various information about vessels, including its MMSI number (Maritime Mobile Service Identity), name, position at a specific time, and characteristics such as length. Multiple data providers offer AIS data. The AIS data emitted by the boats were acquired from ExactEarth® and the DPMA on a fee basis. For the study, the data on a grid of one degree of longitude and latitude of the anchorage, i.e. an area of approximately 100 km2.

2.1.3 Environmental data

The meteorological variable analyzed in this study is the wind. The wind speed observation data ($\mathrm{m\,s^{-1}}$) are produced by Ifremer, from the EU Copernicus maritime service and available at https://marine.copernicus.eu. These data have 0.25° spatial resolution and are sampled and averaged every 6 hours. This variable is retrieved at a grid of one degree of latitude and longitude around the mooring point.

2.2 Data processing

2.2.1 Ambient noise estimation

For the purposes of the MSFD, ambient noise levels were previously calculated in the frequency bands characteristic of noise generated by maritime traffic, i.e. the two third octave bands centered on 63 Hz and 125 Hz. Ambient noise, unlike ocean noise, includes only the stationary noise over periods beyond the estimation time window. The estimation of the ambient noise is obtained from the Percentile Controlled Recursive Averaging (PCRA) method, an algorithm developed by the Naval Hydrographic and Oceanographic Service (SHOM) underwater acoustics department team [14]. It is a recursive Bayesian method that produces simultaneously, from the spectrogram of the acoustic data, a time-frequency mapping of the ambient noise and of the signal presence probability (SPP) used for the detection of transient signals. At each time step, the method estimates a set of parameters that includes the SPP, which is used to weigh the noise estimates from previous time steps and the spectral content at the current time step. If a signal is present at a given frequency, the estimation of the noise level is dominated by the contributions of previous time steps to prevent the signal from biasing the noise level estimation. Conversely, if a signal is weak or absent, the noise estimation is updated at the current step. This ensures continuous operation without information loss while minimizing the contribution of the signal on the ambient noise level estimation quality. However, due to the recursive estimation process, the algorithm preserve the contributions of shippping to ambiant noise. The algorithm assumes that the ocean noise is stationary over periods of time during which the background noise statistics, excluding transients, vary slightly. The noise level is estimated from the spectogram's statistics. Although the estimation is done at the resolution of the spectrogram, only the 10-second averaged outputs are retained since the focus is on activity tracking rather than individual signals. The signal-to-noise ratio (SNR), which is the ratio of the signal to the background noise, can be obtained from the noise level estimation.

2.2.2 Automatic detection and association of acoustic data with AIS data

The soundscape measured by the hydrophones is made up of multiple unknown sources that can be near or distant. The recorded signal $e(t)$ can therefore be decomposed according to formula (1).

$$\begin{aligned} e(t) =& x_{an}(t) + \delta_{ship}(t) * x_{ship}(t) + \\ & \delta_{bio}(t) * x_{bio}(t) + \delta_{env}(t) * x_{env}(t) \end{aligned} \tag{1}$$

Where $e(t)$ represents the recorded signal and x those components described in the following paragraph. All variables are time dependent. The ambient noise (x_{an}) corresponds to ambient noise including distant traffic noise. The transient signals are produced by the occasional and irregular sources (nearby ship (x_{ship}), biological organisms (x_{bio}) and meteorological noise (x_{env})). Since these are occasional signals, we use the coefficient δ which corresponds to the Dirac distribution taking for value 0 or 1 corresponding respectively to the presence or absence of the transient signal. It is then necessary to quantify the ambient noise in the area and determine the contribution of vessels transiting nearby the sensor to the overall statistics of the measurement. This leads to the implementation of an acoustic detection algorithm for vessels near the acoustic mooring. This algorithm, by associating AIS data, makes it possible to identify the source of the noise (x_{ship}) and its characteristics (size, speed, motorization, etc.). Then, by identifying the nearby passing ships and excluding the transient sources, it is possible to estimate the distant component from the PCRA noise levels estimates or noise from sources whose contributions are not distinguished by the algorithm (x_{env}), i-e, the slowly varying persistent background noise. The estimation of the contribution of environmental variables on the ambient noise have been be made from tis component.

The detections were made on daily step on the noise levels of the two MSFD frequency bands and in the ship-specific band. They are characterized by an energy peak in the noise level. The moving average is calculated to smooth the raw data. This smoothing results in a linear signal consisting of occasional peaks corresponding to ship passages (figure 2).

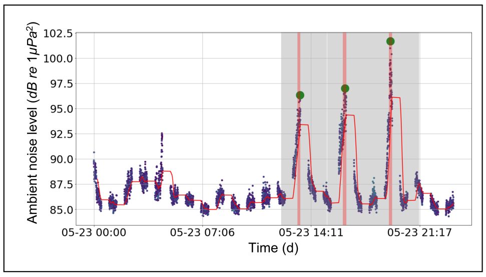

Figure 2. Representation of the daily signal (ambient noise level calculated in the third octave band centered on 63 Hz as a function of time). In red, the signal averaged over 45 min, with three energy peaks.

From the ship passage detection algorithm, it is then possible to estimate the acoustic level generated by the maritime traffic. Indeed, using the AIS data, the position of each ship is acquired every 10 to 20 minutes. For each position, several information are provided, including the time t when the data were transmitted. The hypothesis is that the acoustic passage detected corresponds to the vessels present during the passage and which have their position at the CPA (Closest Point Approach). It is then necessary to determine the exact position of this point and the corresponding time. All the positions obtained for each acoustic detection have been gathered by corresponding vessel using its MMSI. It is possible to find several AIS positions (with different MMSI) in the time interval of a single passage detected in the acoustic data. The calculation of the CPA is then performed for each MMSI if at least two AIS positions were recorded. The position and time at CPA are obtained in 5 steps:

1. Calculate the distance to the acoustic mooring for each AIS position for each vessel identified by its MMSI;
2. Find the two positions closest to the acoustic mooring;
3. Calculate the distance between the two positions to estimate the average speed. This speed provides an estimation of the CPA time;
4. In order to find the position of the CPA, we must first calculate the line equation D that passes through the two points, and then from this line D, find the line equation d that corresponds to the shortest distance from the line D on the buoy position. The position of the CPA is obtained from the two line equations D and d (figure 3 a);
5. Calculation of the time at the CPA: There are two cases that lead to 4 situations (figure 3 b), these two cases, the boat can go in either direction (case $*$ or $**$). The time difference Δt will then be different in each case (formula (2)) :
   (a) In the first case (i) we have the position of the CPA which is between the two MMSI points
   (b) In the second case (ii) the position of the CPA is outside the CPA but is still at a closer distance to the MMSI 1 because it has the closest position to the buoy.

$$\Delta t = \frac{t_{MMSI2} - t_{MMSI1}}{|t_{MMSI2} - t_{MMSI1}|} = \begin{cases} -1 & \text{Case } (*)\ t_{MMSI2} < t_{MMSI1} \\ 1 & \text{Case } (**)\ t_{MMSI2} \geq t_{MMSI1} \end{cases} \tag{2}$$

Finally the CPA time can be obtained using the equations according to the corresponding case, case (i) (formula (3)) and case (ii) (formula (4)) :

$$t_{CPA} = t_{MMSI1} + \Delta t * \frac{a}{v} \tag{3}$$

$$t_{CPA} = t_{MMSI1} - \Delta t * \frac{a}{v} \tag{4}$$

with :

- a the distance according to figure 3 b;
- v the speed between the two points;
- Δt the time difference calculated with the equation.

It is possible that several ships are identified for the same acoustic passage. A probability calculation (P) (formula (5)) on the source emitting the acoustic peak is performed according to several criteria such as the distance of the vessel from the mooring, the speed of the vessel and its length. A weight (w) can be applied for each of the criteria (2.2.2). The effective contribution of a vessel to the measured noise can be more dependent on its distance

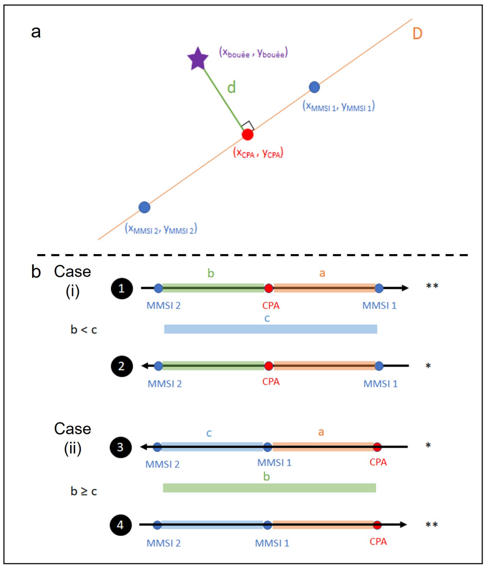

Figure 3. Diagram representing (a) a case for obtaining the CPA position, (b) different cases for obtaining the time at CPA.

than on its emitted level. Thus, the weight for distance is 0.5, speed and length each contribute a weight of 0.25.

$$P_i = \sum_j w_j c_i^j \tag{5}$$

with :

- i vessel's index;
- j criterion index (distance to buoy, speed and length of vessel).

Table 2. Example of application with 3 criteria and the weights attributed for each.

Notation	weight (w)	criteria (c)	probability
c_i^1	0.5	distance	$\frac{min(d)}{d_i}$
c_i^2	0.25	speed (v)	$\frac{v_i}{max(v)}$
c_i^3	0.25	length (l)	$\frac{l_i}{max(l)}$

2.2.3 Consistency of environmental data and ambient noise levels

Since the environmental data (wind speed) is 6-hour averaged data, the noise level was also averaged over 6 hours. An initial investigation of the Pearson correlation coefficient r was done to summarize the strength of the linear relationship between the two data samples, between wind speed on integrated noise levels at the two frequency bands targeted by the MSFD. A correlation analysis was also done between wind speed and integrated noise levels on all other 1/3-octave bands to understand the behavior of noise under different wind regimes and find the maximum correlation. Then, a cross-covariance analysis or cross-correlation was used to measure the similarity between the noise level time series and the wind speed time series.

3. RESULTS

3.1 Study of the traffic in the measurement area: detection and characterization of sources

The automatic detection algorithm was able to dissociate the detectable sources from the overall ocean noise and associate the noise levels above the baseline with one or more vessels. For the different acoustic recorders, 80% to 90% of the detected sources could be associated with specific AIS emissions .

For all acoustic recorders in both study areas, the proportion of single vessel detections is much lower than the proportion of multiple vessels for the same acoustic passage (high level in the ambient noise time series). This is because it is possible that the CPA time for multiple vessels was obtained in the same time interval of the detected passage. Several vessels may contribute to the acoustic peak, but since the peaks have a well-localized maximum (not several), it is possible to assume that there is one vessel whose contribution dominates. The probability calculation from the vessel characteristics is useful to obtain the most likely vessel at the acoustic emission. This calculation could be performed for the associations at station 05G. Keeping the vessel with the highest probability of being the main contributor to the observed acoustic peak, no particular relationship exists between vessel distance and noise level (figure 4). Many detections are located in the same area, between 10 and 15 km from the buoy, at the level of the shipping route to be exact, which does not allow for an objective result.

It was also found that, for each recorder, the number of detections of acoustic events related to passing vessels and associations with AIS data is somewhat greater in the higher MSFD frequency band (at 125 Hz). For station 05G, recorders 22 and 24 operating together do

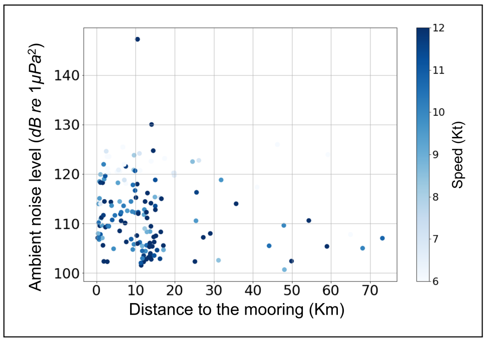

Figure 4. Graph showing the wideband noise level in the frequency band centered on the third octave 125 Hz obtained at a depth of 30 m as a function of the distance from the mooring 05G

not have the same number of acoustic detections. Indeed, there is more detections for the recorder located at 80 m depth than at 300 m. The association with AIS data is also slightly higher. This difference associated with depth is also observed for station 08G between recorders operating in tandem. It should be noted that the association is much lower for recorder 25 at 30 m due to lack of AIS data for 2 weeks.

3.2 Impact of wind on the measurement of ambient noise.

The stations have a prevailing wind regime characterized by calm and light winds. An initial correlation analysis between wind speed and noise level on the two MSFD bands over all depths for each station was performed. There is a significant moderate positive Pearson correlation greater than 0.5 (r= 0.54, p-value < 0.05) for station 05G at 30 m depth on the frequency band centered at the third octave on 63 Hz. A non-negligible negative correlation was also observed for station 06G at the sensor located at 160 m (r = - 0.413, p-value < 0.05). Figure 5 shows the Pearson correlation between the different wind speed measurements and noise levels with their different center frequencies for recorder 25 (station 05G at 30 m). It was found that the strength of correlation between wind speed and noise level follow the pattern of the model of Wenz which for the very low frequencies would come from a contribution of the swell [15], [16], for the high frequencies to the breaking winds and in the middle an absence of correlation corresponding to the band of predominance of maritime traffic which would explain the minimum correlation. A linear regression allowed to understand that 30% of the noise level could be explained by wind speed in the frequency band centered at 63 Hz. Then, it is possible to draw a model of linear dependence between the wind speed and the noise level in the bay of Biscay. Finally, the cross-correlation highlighted the existence of a 12-hour phase shift between the wind speed and the noise level.

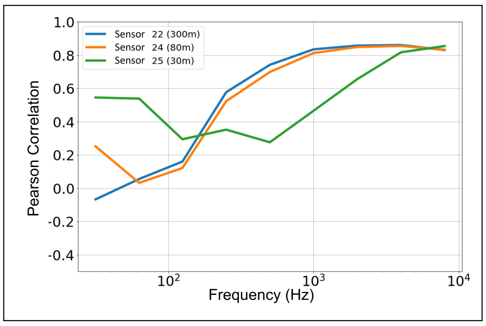

Figure 5. Pearson correlation between wind speed $m.s^{-1}$ and wideband noise level over all frequency bands centered at the third octave.

4. DISCUSSION

4.1 Limitations of the automatic detection algorithm

There are several limitations to the proper functioning of the automatic ship passage detection algorithm. First, a systematic study of the acoustic passages detected on 51 days was carried out. 160 vessels were acoustically detected out of a total of 193 passages that should have been detected . The performances are given according to 2 parameters, the probability (or percentage) of detection (number of passages detected on total number of passages) here 83%, and of false alarm (number of detection when no passage/number of observation without detection. The 17% that were not detected were largely caused by the breakdown of the analyses on daily base. Indeed, the splitting accounts for 50% of the undetected runs . In total, the true missed detections represent only 8% of the 193 runs.

Regarding the association with AIS data, it should be noted that the noise emmited by ships comes from hydrodynamic sources and vibroacoustic sources [17]. There are several reasons for a stronger association between AIS data and acoustic detected events in the 1/3 octave band centered at 125 Hz. First, some studies point to the difficulty in characterizing all ship noise for the one-third octave band centered at 63 Hz [18]. This is because some classes of vessels emit in higher frequencies [19]. Second, the propagation conditions according to the environmental conditions will significantly modify the signal reception. At station 05G, a study of transmission loss on the two MSFD bands was conducted over 40 km from the mooring at different seasons. There is a greater loss at certain depths. A difference of more than 10 dB exists between the two bands recommended by the MSFD.

4.2 Relationship between wind speed and noise level

The effect of wind is local and previous studies show that the noise level depends on the wind speed in the receiver's vicinity [15], [20]. When the wind speed is less than $5m.s^{-1}$, there is very little wave breaking at the ocean surface, and the contribution of wind to the ambient noise level is small. Therefore, it is not easy to obtain an acoustic measurement of wind speed [21]. The one-third octave bands centered on 63 Hz and 125 Hz are used by the MSFD as indicators of shipping noise, as they contain maximum anthropogenic contributions and minimum natural contributions [22]. However, the results of the present study suggest that natural sources and propagation characteristics can also influence sound levels in these bands (figure 5). This suggests that when comparisons are made between sites, or between seasons, it should be done with knowledge of local environmental contributions, including depth, bathymetry, weather conditions, and the presence of biological sources that produce low-frequency sound. In addition, ship noise contributes to underwater soundscapes at frequencies ranging from 10 Hz to 10 kHz [23], depending on the size and speed of the ship [24]. Tracking at higher frequencies, as proposed [25], is attractive but we must be able to separate natural from anthropogenic noise, which is not straightforward and makes tracking more complex.

In conclusion, the algorithm for automatic detection and association of acoustic data to AIS data is a first approach to understand the contribution of nearby traffic to the overall noise environment. It was possible to quantify the background noise and determine the contribution of ships transiting near the sensor to the overall measurement statistics. It allowed to dissociate the detectable sources from the global ocean noise and to associate the nearby source to one or more ships. The detection algorithm failed to detect all passages (8% missed). There are several sources of error, one of which is particularly important: the recording cycle (30 $min.h^{-1}$). To distinguish this sampling bias from the missed profiles, the test should be done on a station that records continuously. The association with AIS data is 80% satisfactory. This phase of acoustic detection could be improved by looking for specific characteristics of the noise radiated by ships (low frequency lines, or interference patterns, etc.). The analysis on ocean noise then showed that wind speed, depending on the area and depth of the sensor studied, can be a significant contributor to the noise level in the 1/3-octave bands centered on 63 Hz and 125 Hz used by the MSFD as indicators of shipping noise. Therefore, the environment should be considered when implementing regulatory measures to limit the level of ambient man-made noise.

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