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Monitoring Long-Term underwater acoustic pollution in Mediterranean Sea waters

Rodrigo-Saura, F. J.[1]
Sociedad Anónima de Electrónica Submarina (SAES)
30205 Ctra. de la Algameca, S/N. Cartagena, Murcia (Spain)

Poveda, P[2]; Carbajo, J[3]; Ramis, J[4]
University of Alicante
03080 Ctra. San Vicente del Raspeig, Alicante (Spain)

ABSTRACT

Anthropogenic noise is a growing threat to marine life. The human interaction with the marine environment is entailing a continuous growth in the Ambient noise levels. This effect is particularly noticeable in shallow water areas which are characterized by concentrating a high level of activity in a wide range of fields such as fishing, tourism, sailing, and renewable energy generation. The International Community is increasing concern on the effects of the acoustic pollution on marine life as reflected in the Marine Strategy Framework Directive (MSFD) of the European Union. In order to establish the underwater noise levels and therefore allow the evaluation of the impact of the acoustic pollution in the marine life, it is necessary to study the acoustic noise evolution, in particular during long time intervals. This paper presents an analysis of the underwater Ambient noise in the Mediterranean Sea, focusing primarily on the variation patterns both daily and throughout the annual seasons. The study includes different parameters from the Descriptor 11 of the MSFD as well as other acoustic indicators.

Keywords: Shipping Noise, Ambient noise, underwater acoustic pollution, long term monitoring.

I-INCE Classification of Subject Number: 56

1. INTRODUCTION

Urick [1] defined ambient noise as the part of the total noise background observed with a non-directional hydrophone, which is not due to the hydrophone and its manner of mounting (self-noise), or to some identifiable localized source of noise. Anthropogenic sounds, called anthrophonies by Farina [2], are any sounds that originate from human activity. Humans produce underwater sounds both intentionally as well as unintentionally as a side-product of for example shipping.

[1] f.rodrigo@electronica-submarina.com
[2] pedro.poveda@ua.es
[3] jcarbajo@ua.es
[4] jramis@ua.es

Wenz [3] established curves of underwater Ambient noise for different sea conditions and ship traffic density. The curves provided by Wenz have been widely adopted by the underwater acoustic community. The underwater Ambient noise has increased significantly with the increment of the intensity of ship traffic. Andrew et al. [4] determined that in locations with high-intensity ship traffic, the ambient sound levels had increased 3 dB per decade. Ross [5], McDonald et al [6] and Chapman and Price [7] confirmed the increase in low frequency ambient noise. Bjorno [8] indicated that since World War II, the average level of the ambient noise increased by 12-15 dB.

The effects of underwater sound on the marine fauna greatly depend on the character of sound, distinguishing between impulsive and continuous noise. In this way, in Europe, the Commission Decision 2010/477/EU on criteria and methodological standards on Good Ambient Status (GES) of marine waters defined the descriptor 11 with two indicators: loud, low and mid frequency impulsive sounds, and continuous low frequency sound.

In this work, acoustic measurements performed at Cartagena port were analysed in order to provide relevant information about the increment of acoustic noise levels due to the ship traffic. To do this, the campaign of measurements was divided into: Shipping noise (i. e. acoustic measurements performed while a ship is navigating close to the sensor), and Ambient noise (i. e. acoustic measurements performed in absence of ships navigating close to the sensor). The study includes the analysis of the low frequency continuous noise due to the absence of impulsive noise sources in the area during the campaign of measurements.

The results of the statistical continuous noise analysis indicate that the control of the radiated noise by ships is a relevant issue to reduce the underwater acoustic pollution.

2. MATERIALS AND METHODS

2.1. Study area

The study area chosen was the port of Cartagena located in the southeast coast of Spain. This area has an intense anthropogenic activity, with a relevant merchant, passenger, fishing and recreative maritime traffic. Additionally, in Cartagena there is one of the most important naval bases of the Spanish Navy. Measurements of navy ships were not performed.

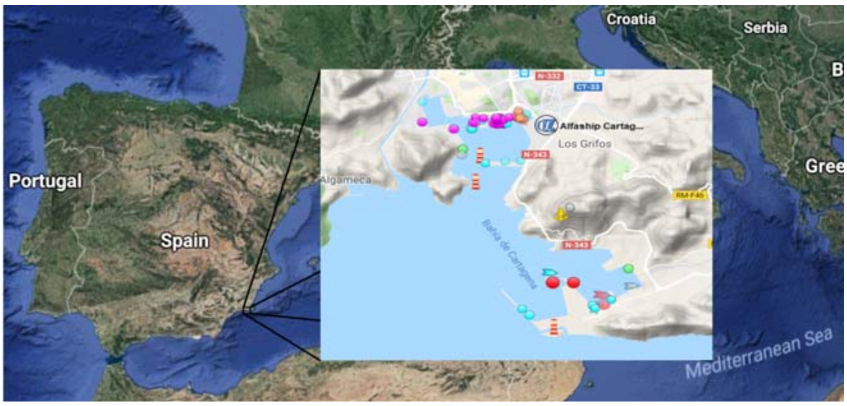

Figure 1. Study area: Cartagena Port (Mediterranean Sea).

2.2. Data measurement

The measurements were collected using underwater multi-influence sensor manufactured by the Sociedad Anónima de Electronica Submarina (SAES). Figure 2 shows the underwater multi-influence sensor. This sensor has the capability to measure magnetic, electric, pressure, seismic and acoustic signals simultaneously. The acoustic measurements were performed by means an omnidirectional hydrophone with a measurement range of acoustic data of up to 8 kHz. The sensor was deployed at sea bottom at 15 meters depth in shallow waters.

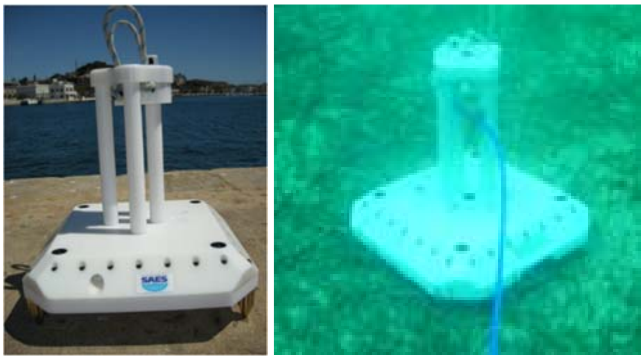

Figure 2. Sea bottom underwater Multi-Influence sensor.

The acoustic measurements were performed during one year, from January to December of 2014. During August the system was stopped and therefore measurement data for this month are not available. The acquisition system was working automatically for 24 hours per day.

An Automatic Identification System (AIS) was integrated with the acquisition system in order to detect the presence of ships close to the sensor and thus start the measurement and record the information of these. Besides, once a measurement of a ship was done, and five minutes after that, an automatic measurement of the Ambient noise was performed. Therefore, the dataset is composed of measurements with Shipping Noise superimposed on Ambient noise, and measurements with Ambient noise only.

2.3. Acoustic data analysis

The acoustic parameters included in the study were the unweighted Sound Pressure Level (SPL), unweighted Mean Square Pressure Spectral Density Level (MSP-SDL), and the mean square pressure in 1/3 octave bands. The acoustic quantities and units used are defined in Ainslie [9] and de Jong et al. [10].

The unweighted Sound Pressure Level is defined as follows

$$SPL = 10log_{10}\frac{1}{T}\int_0^T \frac{p(t)^2}{{P_{ref}}^2}dt \; [dB\; ref.1\; \mu Pa^2] \quad (1)$$

where $p(t)$ is the instantaneous sound pressure, P_{ref} the reference sound pressure and T the averaging time interval.

The unweighted Mean Square Pressure Spectral Density Level (MSP-SDL) is defined as follows

$$MSP - SDL = 10log_{10}\frac{Q(f)}{\frac{{P_{ref}}^2}{f_{ref}}} \; [dB\; ref.1\; \mu Pa^2/Hz] \quad (2)$$

where $Q(f)$ is the unweighted root mean square sound pressure density, which stands for the contribution of the mean square pressure per unit of frequency bandwidth. f_{ref} is the reference frequency 1 Hz.

The 1/3 octave band is a frequency band whose width is one-tenth of a decade and whose centre frequency is one of the preferred frequencies listed in IEC 61260:1995 [12].

The 1/3 octave bands used for analysis of the of the mean square pressure were those defined in the international standard IEC 61260:1995 [12]. The centre frequencies of the bands described in the Commission Decision 2010/477/EU [11] (i.e. 63 and 125 Hz), are nominal. The signal analysis of the mean square pressure in 1/3 octave bands used a Hann window and an overlapping of 50%.

2.4. Marine traffic

The information of the vessel under measurement was collected along the campaign by means of an Automatic Identification System. The used information of each passing ship was the Maritime Mobile Service Identity (MMSI) number, the type of vessel, the tracking of its positions and the heading and speed during the measurement. The recorded data set was composed of Shipping Noise and Ambient noise. Table 1 shows the number of measurements per month for Shipping Noise and Ambient noise.

Month	Shipping Noise	Ambient noise
January	342	267
February	143	116
March	176	146
April	202	178
May	456	327
June	456	364
July	102	89
September	284	19
October	315	236
November	363	304
December	455	391
Total:	**3294**	**2437**

Table 1. Number of measurements of shipping and Ambient noise per month.

The types of ship under measurement were extensive, including cargo, fishing, passenger, pleasure, tug, sailing and others. Table 2 shows the number of Shipping Noise measurements for each type of ship.

Cargo	Fishing	Passenger	Pleasure	Tug	Sailing	Others	Total
353	644	94	666	308	313	916	**3294**

Table 2. Number of Shipping noise measurements for each type of ship.

2.5. Statistical analysis

The statistical analysis is extended to measurements with Shipping Noise and Ambient noise so as to study the variations of the acoustic noise when a ship is navigating close to the sensor.

The 1/3 octave bands were calculated for the entire duration of each measurement. For each measurement, the maximum, mean and minimum values of each 1/3 octave band were computed. The Commission Decision 2010/477/EU defines in the Descriptor 11 the average temporal evolution of the 63 Hz and 125 Hz 1/3 octave bands. In order to study the monthly average variation of 1/3 octave bands at 63 and 125 Hz, the mean values of the maximum, mean and minimum values for all measurements performed during the same month were computed. The study of the 1/3 octave bands variation includes a time-dependent average analysis dividing the day into three temporal intervals defined as: 07:00-15:00 (morning), 15:00-23:00 (evening) and 23:00-07:00 (night) hours.

In order to verify the assessment of the defined bands in Descriptor 11, the statistical analysis included the study of the distribution of the energy on the 1/3 octave bands taking into account the number of times that a band had the maximum average level per measurement.

The unweighted SPL and MSP-SDL levels were calculated according to Equation 1 and Equation 2, respectively, for the entire duration of each measurement. To study the monthly average variation of the SPL and MSP-SDL levels, the mean, median and 75th, 25th, 5th and 95th percentiles were provided. The statistical analysis included the monthly average variation of the maximum, mean and minimum values of these indicators of all measurements performed during the same month. Additionally, the study of the variation of the SPL and MSP-SDL levels included the time-dependent analysis by dividing the day into three temporal intervals.

3. RESULTS AND DISCUSSION

The study of the continuous low frequency sound includes the analysis of the 1/3 octave bands and the unweighted SPL and MSP-SDL levels.

3.1. Analysis of 1/3 Octave Bands

Figure 3 shows the maximum, mean and minimum values of 1/3 octave bands computed for set of measurements of Shipping noise and Ambient noise per day.

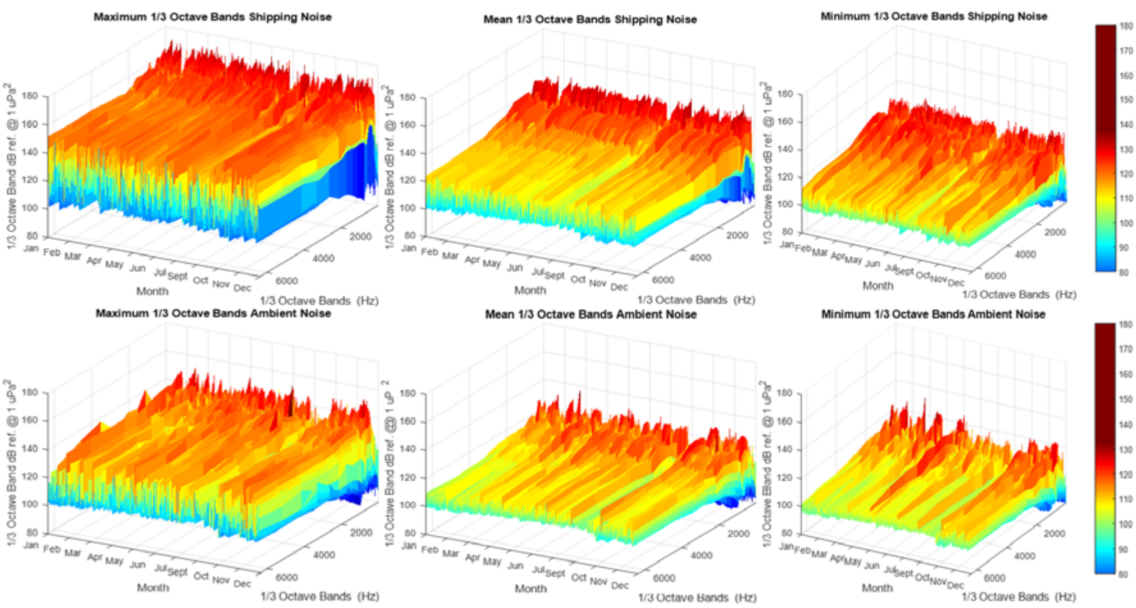

Figure 3. Daily evolution of the maximum (left), mean (centre) and minimum (right) of the 1/3 octave bands of Shipping Noise (upper row) and Ambient noise (lower row).

Following to the Commission Decision 2010/477/EU on criteria and methodological standards on Good Environmental Status (GES) of marine waters, the average temporal evolution at 63 Hz and 125 Hz 1/3 octave nominal bands were calculated.

Table 3 shows the monthly average of the maximum, mean and minimum values at 63 and 125 Hz 1/3 octave bands computed for measurements of Ambient Noise.

Ambient noise 1/3 octave band dB ref. @ 1μPa^2						
Month	**63 Hz**			**125 Hz**		
	Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
January	105.5	97.9	91.7	105.4	100.3	95.9
February	109.8	101	94.6	108.5	101.8	97.2
March	111.5	103.3	96.1	110.5	103.7	98.5
April	110.6	101.1	93.7	110.3	102.6	97.4
May	110.6	98.3	91.5	109.7	101.7	96.6
June	114.2	99.17	92	111.3	102.2	97
July	115.7	103.3	94.7	114.2	103.6	97.4
September	112.8	103.1	94.9	114.6	103.9	97.1
October	110.9	101.8	94.3	111.1	103.3	97.7
November	108.3	100.4	93.7	108.6	101.7	96.4
December	105.9	98.4	92.1	106.6	100.4	95.6
Average	**110.5**	**100.7**	**93.6**	**110.1**	**102.3**	**96.9**
Standard Deviation	**3.14**	**2.05**	**1.53**	**2.81**	**1.26**	**0.8**

Table 3. Monthly average evolution of the maximum, mean and minimum of the 1/3 octave bands at 63 and 125 Hz of Ambient noise measurements.

Both 1/3 octave bands indicator bands demonstrated low average levels of variation, with the greatest variation exhibited by 63 Hz band, with maximum values ranged from 115.7 dB on July to 105.5 dB on January. An increasing trend in both 1/3 octave bands was identified from winter, with minimum values on November, December and January, to summer with highest values on June, July and September. This trend is typical on areas with high recreational and tourist activities. The mean values of both 1/3 octave bands were similar. Table 4 shows the monthly average of the maximum, mean and minimum values at 63 and 125 Hz 1/3 octave bands computed for measurements of Shipping Noise.

Shipping Noise 1/3 octave band dB ref. @ 1μPa^2						
Month	**63 Hz**			**125 Hz**		
	Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
January	129.8	112.9	98.26	133.7	114.6	101.3
February	135.7	118.5	102.4	139.7	119.9	104
March	139.9	122.4	105.8	141.6	122.3	106.5
April	133.2	115.6	100.6	135	116.8	104.1
May	126.5	109.6	96.9	128.3	110.9	100.8
June	130.9	112	97.8	131.7	113.4	101.7
July	130.2	112.8	98.6	132.1	113.5	100.5
September	124.5	108.9	96.3	127.2	110.1	99.5
October	126.6	111	98.6	128.7	111.4	100.7
November	127.7	111.7	98.5	130.9	113.3	101.6
December	127.9	110.6	96.9	132.5	112.9	100.5
Average:	**130.3**	**113.3**	**99.15**	**132.8**	**114.5**	**101.9**
Standard Deviation:	**4.52**	**4.06**	**2.8**	**4.52**	**3.78**	**2.07**

Table 4. Monthly average evolution of the maximum, mean and minimum of the 1/3 octave bands at 63 and 125 Hz of Shipping Noise.

For shipping noise measurements, both 1/3 octave bands demonstrated high average variation with the greatest variation exhibited by 125 Hz band, with maximum values ranged from 141.6 dB on March to 128.3 dB on May.

The presence of a ship passing close to the sensor increases the maximum average level up to 20 dB at 63 Hz and 23 dB at 125 Hz.

The statistical analysis includes the time-dependent monthly average. Figure 4 shows the time-dependent average monthly variation of the maximum, mean and minimum values of measurements of Shipping noise at 63 and 125 Hz bands.

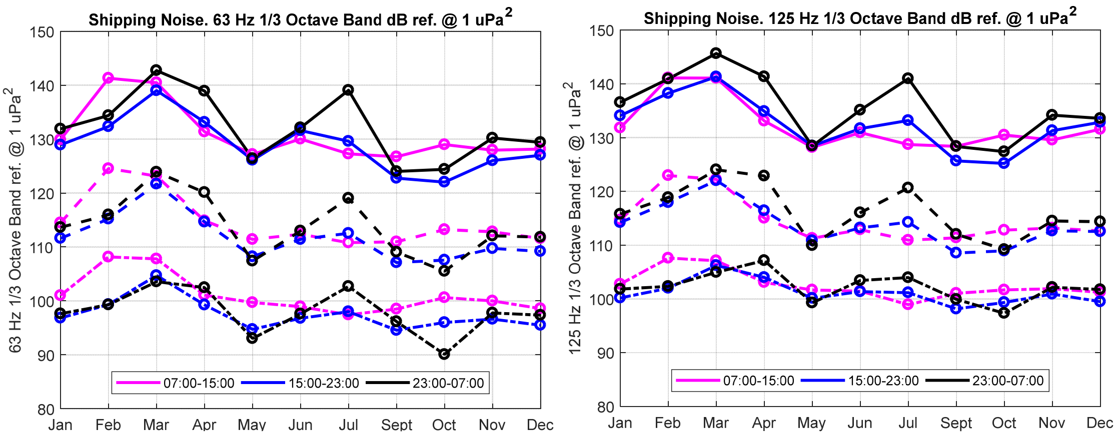

Figure 4. Monthly average evolution of the maximum (- solid line), mean (-- dashed line) and minimum (-. dash-dot line) of the 1/3 octave bands at 63 Hz (left) and 125 Hz (right) for three-time intervals of measurements of Shipping noise.

There is a high activity during the night due to the traffic of fishing ships. During the morning the activity is concentrated around the shipyard and container dock. Lower levels appear during the evening when only recreative activities are carried out.

In order to establish the good assessment of the evolution of the low frequency continuous noise based on the monitoring of the 1/3 octave bands at 63 Hz and 125 Hz, Shipping noise the number of times that each 1/3 octave band has the highest level of average acoustic energy for the entire set of measurements is shown in Figure 5.

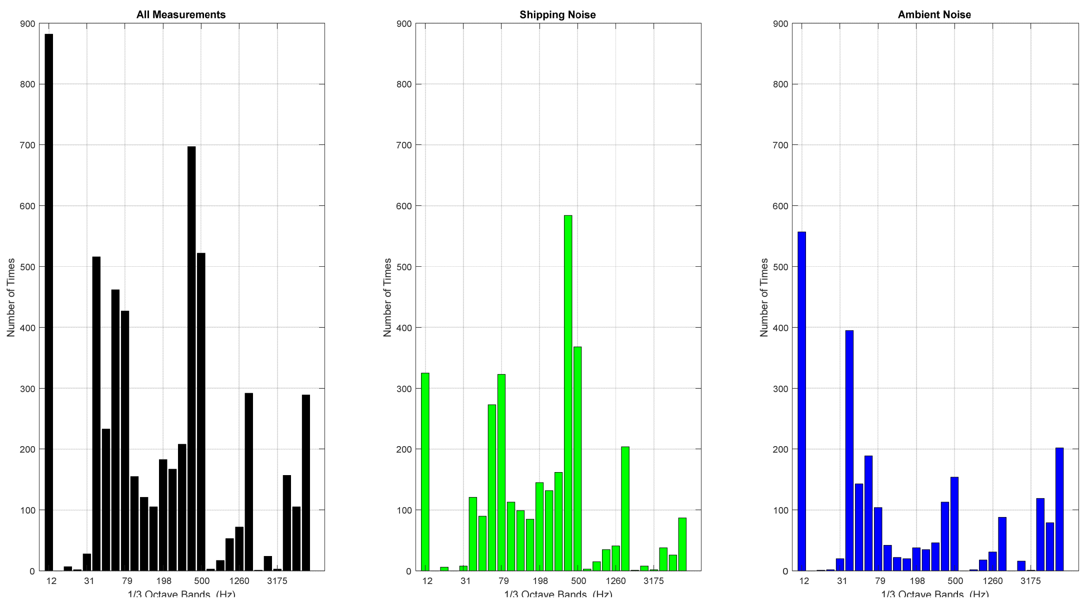

Figure 5. Evaluation of the 1/3 octave bands with higher energy for all measurements (left), Shipping noise (centre), and Ambient noise (right).

It can be seen that the acoustic energy is concentrated in the 1/3 octave band from 40 to 500 Hz. For Shipping noise, the bands with maximum average energy was 400 Hz, whereas for Ambient noise, it was 40 Hz Ambient noise. The bands with lower energy are from 15.5 to 32 Hz regardless the type of measurement. Therefore, the 1/3 octave bands defined by Commission Decision 2010/477/EU are in the bandwidth with maximum acoustic energy but not in the bands with highest levels.

3.2. Analysis of unweighted Sound Pressure Level (SPL) and unweighted Mean Square Pressure Spectral Density Level (MSP-SDL)

Figure 6 shows the monthly variation of the mean, median, the 75th, 25th, 5th and 95th percentiles of the unweighted Sound Pressure and Mean Square Pressure Spectral Density levels calculated over measurements of Shipping noise and Ambient noise. Note than the y axis is displayed from 105 dB.

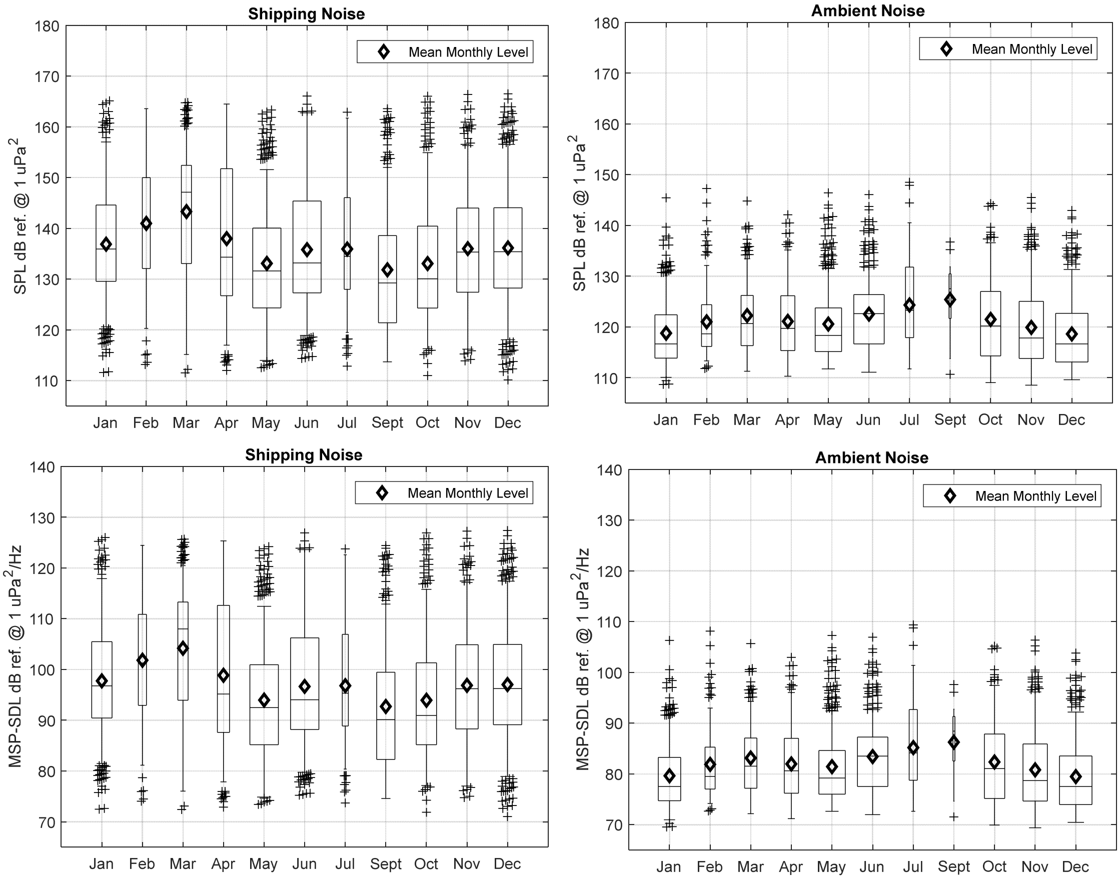

Figure 6. Mean and median monthly evolution of SPL level (up) and MSP-SDL (down) for measurements of Shipping noise (left) and Ambient noise (right). The median is given by the centre of the box. The 25th and 75th percentiles are given by the upper and lower bounds of the box. The width of the box indicates the relative number of measurements per month. The 5th and 95th percentiles are given by the bottom and up bar respectively. Data points are outliers with values lower or higher than the percentile 5th or 95th respectively.

The presence of shipping noise increased the values of the SPL and MSP-SDL levels and their monthly variation. The patterns of the variation of the Ambient noise and Shipping noise were different. The louder month in presence of Shipping noise was march while the louder month in absence of Shipping noise was July. Notice that both months are typical holidays time and therefore the recreational and tourist activities were higher. There was not a correlation between the number of measurements and the levels. This was expected due to the levels depend on the type of ship under measurement and the human activity at harbour.

Table 5 and Table 6 show the maximum, mean and minimum unweighted SPL and MSP-SDL levels, respectively, computed for measurements of Ambient and Shipping Noise.

Unweighted SPL levels in dB ref. @ 1µPa²						
Month	**Shipping Noise**			**Ambient noise**		
	Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
January	165.1	136.9	111.6	145.4	118.8	108.7
February	163.6	141	113.2	147.3	121	111.8
March	164.8	143.3	111.5	144.8	122.3	111.3
April	164.5	138	112	142.1	121.1	110.3
May	163.3	133.1	112.6	146.4	120.6	111.8
June	166.1	135.8	114.4	146.1	122.5	111.1
July	162.9	136	112.9	148.5	124.3	111.8
September	163.6	131.8	113.7	136.8	125.4	110.7
October	166.1	133.1	111	144.3	121.5	109.1
November	166.4	136	113.9	145.5	119.9	108.5
December	166.5	136.2	110.2	143	118.6	109.6
Average:	**164.8**	**136.5**	**112.4**	**144.6**	**121.4**	**110.4**
Standard Deviation:	**1.33**	**3.39**	**1.31**	**3.15**	**2.1**	**1.27**

Table 5. Monthly average evolution of the maximum, mean and minimum of the SPL levels for measurements of Shipping noise and Ambient noise.

Unweighted MSP-SDL levels in dB ref. @ 1µPa²/Hz						
Month	**Shipping Noise**			**Ambient noise**		
	Max	**Mean**	**Min**	**Max**	**Mean**	**Min**
January	126	97.75	72.48	106.3	79.65	69.55
February	124.5	101.8	74.05	108.1	81.89	72.69
March	125.7	104.2	72.41	105.7	83.13	72.16
April	125.4	98.85	72.89	103	81.98	71.18
May	124.2	93.97	73.42	107.3	81.44	72.63
June	126.9	96.67	75.23	106.9	83.41	71.97
July	123.8	96.82	73.72	109.4	85.2	72.63
September	124.4	92.71	74.59	97.62	86.26	71.56
October	126.9	93.95	71.87	105.2	82.36	69.92
November	127.2	96.88	74.76	106.4	80.79	69.4
December	127.4	97.03	71.02	103.8	79.48	70.48
Average:	**125.7**	**97.33**	**73.31**	**105.4**	**82.3**	**71.28**
Standard Deviation:	**1.31**	**3.38**	**1.3**	**3.16**	**2.1**	**1.26**

Table 6. Monthly average evolution of the maximum, mean and minimum of the MSP-SDL levels for measurements of Shipping noise and Ambient noise.

The Ambient noise measurements exhibited higher monthly variation with maximum SPL levels ranged from 136.8 dB on September to 147.3 dB on February and with maximum MSP-SDL levels ranged from 97.62 dB on September to 109.4 dB on July.

The presence of ships navigating close to the sensor increased the maximum SPL and MSP-SDL levels up to 20 dB. There were not clear identifiable monthly evolution patterns for both types of measurements due to the obtained high levels and low average variation. The mean SPL and MSP-SDL levels of Ambient noise increased during summer time and decreased during winter while the mean SPL and MSP-SDL levels of shipping noise increased during February and March.

Figure 7 shows the time-dependent monthly average statistical analysis of the unweighted SPL and MSP-SDL levels.

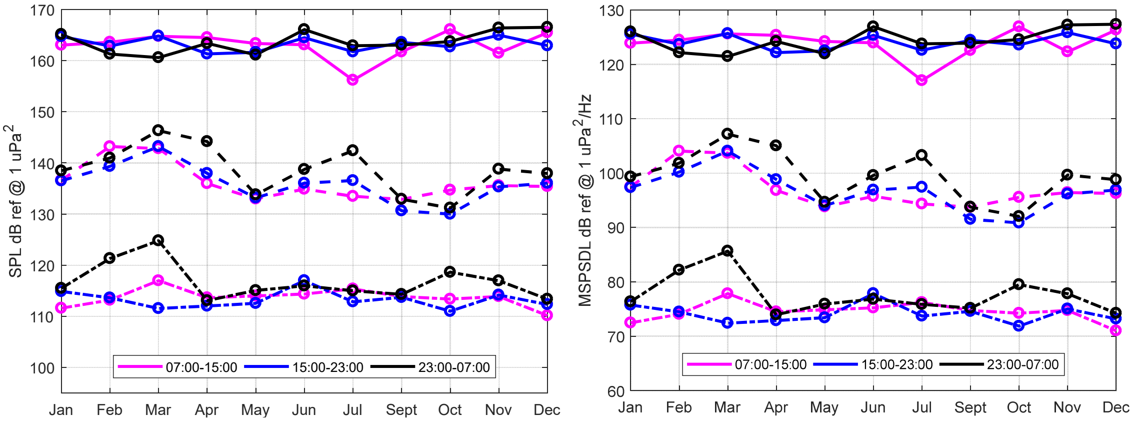

Figure 7. Monthly average evolution of the maximum (- solid line), mean (-- dashed line) and minimum (-. dash-dot line) of SPL level (up) and MSP-SDL level (down) for measurements of Shipping noise.

The highest levels of SPL and MSP-SDL appeared during the evening and morning schedule due to the fishing ships and shipyard activities, respectively, on March and July.

4. CONCLUSIONS

In this research, an analysis of the one-year variation of the underwater noise in the port of Cartagena in the Mediterranean Sea has been presented using a data set composed by 5731 acoustic measurements. In order to evaluate the impact of the noise generated by ship traffic, the measurements were divided into two groups: measurements in the presence of ships navigating close to the sensor (Shipping noise), and measurements without the presence of navigating ships (Ambient noise).

The analysis was focused on the continuous low-frequency noise because sources of impulsive noise were not working in the area during the measurement campaign. To quantify the noise generated by ships, the 1/3 octave band, the SPL and the MSP-SDL were analysed. In addition, and following the Commission Decision 2010/477/EU, the average temporal evolution at 63 Hz and 125 Hz 1/3 octave nominal bands were also calculated. The statistical analysis was based on the monthly average of the maximum, mean and minimum values of the acoustic indicators defined in the descriptor 11 and the SPL and MSP-SDL levels. Additionally, the statistical analysis of the SPL and MSP-SDL levels included the calculation of the percentiles 5th, 25th, 50th, 75th and 95th.

The 63 Hz and 125 Hz 1/3 octave bands exhibited average levels higher than the provided in Garret et al. [13] due to the lower depth of the sensor deployment. By other hand, the highest monthly variation was found in the 63 Hz such as in Garret et al. [13] and van der Schaar et al. [14]. The presence of a ship passing close to the sensor increased the maximum average level up to 20 dB at 63 Hz and 23 dB at 125 Hz, hence the maximum average levels increasing up to 130 dB and 132 dB respectively.

The Commission Decision 200/477/EU defines the nominal 1/3 octave bands at 63 and 125 Hz as indicators to monitor the underwater pollution. The study of the 1/3 octave bands over a bandwidth up to 8 kHz shows that the bandwidth with maximum acoustic energy is from 40 to 500 Hz nominal bands. For Shipping noise measurements, the band with maximum average energy was 400 Hz, whereas for Ambient noise it was 40 Hz. The bands with lower energy are from 15.5 to 32 Hz independently of the type of measurement. Therefore, the 1/3 octave bands defined by the Commission Decision 2010/477/EU are included in the bandwidth with maximum acoustic energy but these are not the bands with highest levels.

The study of the low frequency continuous noise is completed with the analysis of the monthly average of the unweighted Sound Pressure Level (SPL) and Mean Square Pressure Spectral Density Level (MSP-SDL).

The unweighted SPL levels of the Ambient noise measurements were found higher than the recommended limits, reaching monthly maximum average levels up to 144 dB, increasing up to 20 dB due to the ship traffic. The analysis of the unweighted MSP-SDL levels revealed the same conclusions. The MSP-SDL levels of the monthly maximum average Ambient noise measurements reached monthly maximum average levels of up to 125 dB, increasing up to 20 dB due to the ship traffic.

In summary, the presented study shows that Ambient noise has increased in the area under study due to ship traffic. Therefore, the control of the underwater radiated noise by ships is a critical issue in order to preserve the marine life.

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