Baseline assessment of underwater noise in the Ria Formosa

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Contents

List of Figures

Glossary

Ambient noise - Background noise in the environment without distinguishable sources.
Attenuation - Decrease of sound pressure levels / acoustic energy.
Bandwidth - Range of frequencies of a given sound.
Decibel (dB) - The logarithmic measure of sound intensity/pressure. The decibel value for sound pressure is $20 \log 10(\frac{P}{P_0})$ where P is the actual pressure and P_0 is the reference pressure. In underwater acoustics the reference pressure is 1 μPa.
Hertz - The unit for frequency where 1 Hz = 1 cycle per second. One Kilohertz (kHz) are 1,000 cycles per second.
Impulsive sound - Transient signals emitted in brief sequences (pulses) with short duration and often high peak sound pressure levels.
Micro Pascal (μPa) - Reference pressure for underwater sound. 1 $\mu\text{Pa} = 10^{-5}\mu\text{bar}$.
Octave band - Interval between two discrete frequencies having a frequency ratio of two.
1/3 octave band - frequency band whose upper band-edge frequency is the lower band frequency times the cube root of two. **1/3 octave level** - sound level obtained as the integration of the acoustic power contained in a 1/3 octave band. **Pascal** - Unit of pressure equal to one Newton per square metre.
Propagation loss (Transmission loss) - Loss of sound power with increasing distance.
Spectral density - plot showing spectral power amplitudes of a signal as a function of frequency.
Source level - Acoustic pressure at a standard reference distance of 1 m. Unit in dB re 1 μPa at 1 m (sometimes given as: @ 1 m).
Sound pressure level (SPL) Expression of the sound pressure in decibel (dB).
Time-frequency distribution - plot showing spectral power amplitudes of a signal as a function of time and frequency.

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1 Introduction

The SCORE project aims at testing a tidal turbine, floatable tidal energy converter (TEC), in a 1:10 scale at one of the main inlets of the Ria Formosa coastal lagoon. The main objectives of the project are to analyse the energy extraction efficiency of the device and the eventual impacts on ecological communities and physical settings. The latter objective includes noise monitoring aiming at the assessment of the eventual amount of acoustic energy introduced by the TEC in the marine environment during operation.

TECs are mechanical devices with parts that rotate for generating electric current. This operation can produce noise that may propagate across the adjacent area. So far, the information on the noise produced by this type of devices is scarce or nonexistent, and therefore, studies aiming at the evaluation of this descriptor of environmental performance are required as generic practice of the offshore renewables industry.

As a partner of this project consortium, CIMA (Universidade do Algarve) has hired MarSensing Lda. to carry out a baseline assessment of underwater noise in the TEC's deployment area. This study is part of *Task 3.2.3 - Reference Situation Environmental Assessment*. On 19 January 2017 a team of CIMA divers has deployed an autonomous hydrophone provided by MarSensing on a tripod structure at the TEC's deployment site. The device was programmed to perform a 90 seconds recording every 10 minutes, which allowed for approximately 2 weeks of acoustic data recordings under this configuration.

In the actual report acoustic data acquired over 13 full days are analysed (approximately 50 hours of data). The data analysis consists in obtaining estimates of sound pressure level (SPL) over the entire acquisition period, mainly based on statistical indicators both for broadband SPL and frequency levels.

The results indicate that the overall variability is relatively high due to two prevailing factors, boat traffic which are time discrete transient noise sources, and tidal currents whose speed peaking can induces a significant increase in noise level.

2 Acoustic acquisition setup

The objective of the noise monitoring procedure was to establish a baseline measurement at the site. The acoustic data was collected with an autonomous hydrophone, the digitalHyd SR-1, over a period of approximately two weeks in the Ria Formosa coastal lagoon, at one of the inlets, at latitude N36.9749 and longitude W7.8753, where the average water depth is approximately 11 m. Figure 1 shows the hydrophone mooring, made of a tripod structure deployed on the seabottom. The mooring was deployed on January 19, 2017, and recovered on February 14.

The SR-1 autonomous hydrophone is a cylindrical device with a 50 mm diameter and 323 m length, when operating with a single battery. The device is equipped with SensorTech SQ-26 transducer (sensitivy si -194 dB re 1 V /1 μPa), followed by a 32 dB pre-amplifier, and a programmable gain amplifier (PGA) with selectable gains from $1\times, 2\times, 4\times, \ldots, 64\times$. The availale sampling rates are 52734 or 105468 samples per second (sps).

In the actual experiment the SR-1 hydrophone was equipped with an add-on battery pack containing five 18650 LiIon batteries, completing a capacity of 18 Ah at 3.7 V, in order to extend its autonomy. Concerning the relevant settings, the PGA was set to a gain of $16\times$, rendering an overall sensitivy of -143 dB re 1 V / 1 μPa; the sampling rate was set to 52734 sps and amplitude resolution was to 24 bits; the acquisition was programmed to

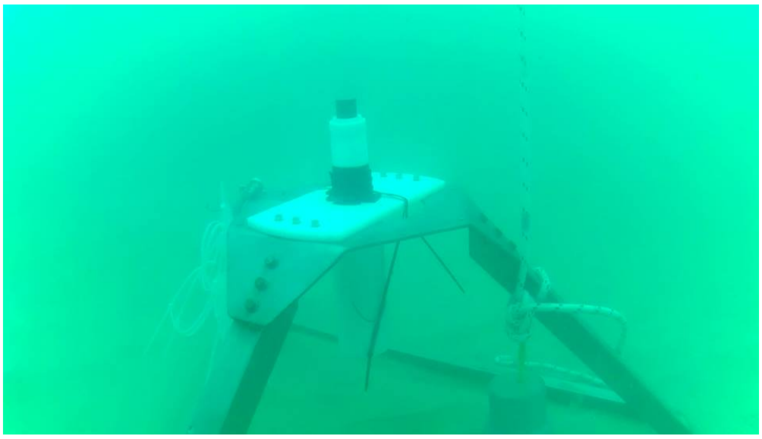

Figure 1: *Autonmous hydrophone mooring made by means of a tripod structure. The structure was deployed for approximately three weeks.*

start at 12:00 a.m. of January 19 (day of deployment), and to restart every 10 minutes for 90 seconds, i.e. a duty-cycle of 15%. For each acquisition interval a WAV file is generated. The total effective acquisition time was approximately 50 hours.

3 Acoustic data analysis

This section reports on the acoustic data analysis. The data analysis carried out herein takes into account for the fact that the acoustic observation was carried out over a relatively long time period at a single position (approximately two weeks), and that the anthropogenic contribution to the total noise budget comes mainly from boats passing in the neighborhood of the deployment position. That gives rise to the possibility to different regimes, as for example over day and night, and business days and weekends.

3.1 Methodology

The data analysis carried out herein is based on Frequency Analysis or Fourier Analysis. The time series made of acoustic data samples is divided in segments of K samples. To each segment a Hanning observation window is applied, followed by the computation of the Discrete Fourier Transform (DFT) by means of a FFT algorithm. The Fourier transform of each segment of samples is called periodogram. For spectral estimation purposes, in order to reduce the statistical variance of the spectral components obtained in each periodogram, the Bartlett method is employed. The Bartlett method is a classical spectral estimation method, which consists in the following steps:

- divide a series of N data samples in L segments of K samples;
- compute the DFT of each;
- compute the square of the K spectral magnitudes;
- average the L squared periodograms.

The result of this algorithm is an estimate of the power signal spectrum called Power Spectrum Density (PSD).

f_{min}	f_c	f_{max}	f_{min}	f_c	f_{max}
35	39	44	1114	1250	1403
44	49	55	1403	1575	1768
55	62	70	1768	1984	2227
70	78	88	2227	2500	2806
88	98	110	2806	3150	3536
110	124	139	3536	3969	4454
139	156	175	4454	5000	5612
175	197	221	5612	6300	7071
221	248	278	7071	7937	8909
278	312	351	8909	10000	11225
351	394	442	11225	12599	14142
442	496	557	14142	15874	17818
557	625	702	17818	20000	22449
702	787	884			

Table 1: Fraction 1/3 octave bands used for spectral analysis.

Simply stacking the periodograms provides a time-frequency representation of the acoustic signal, i.e., the signal spectrum is observed as a function of time. This is the so-called spectrogram. Spectrograms permite the observation of changes in the spectral contents over time. Acoustic transients can be found by visual inspection of a spectrogram.

While the PSD derived directly from windowing provides a frequency resolution of $2/T$, where T is the length of the observation window, the frequency resolution is often reduced to fractional octave band analysis, commonly 1/3- or 1/12-octave bands, wherein the frequency range of the band is directly proportional to the centre frequency. The spectral slope of the fractional octave band levels differs from the PSD, as the bands are scaled logarithmically with frequency, meaning that the bands widen with increasing frequency, and therefore higher frequency bands integrate energy over larger frequency ranges. For example, PSD and 1/3-octave band analysis cannot be directly compared due to differing frequency bands used to integrate the energy. The PSD uses only one frequency bin for each spectral component, while the fractional band analysis integrates (or sums) the energy of multiple frequency bins, depending on the width of the fractional band. Table 1 shows the 1/3 octave bands with the centre frequency and minimum and maximum frequency of each.

The data analysis is carried out as follows. First, the DFT over the complete data set was computed with segment length of 4096 (equivalent to approximately 0.077 s) samples windowed with a Hanning window. This output is a time series of instantaneous acoustic spectra, which shall be subject to further analysis, such as broadband sound pressure level (BB SPL) analysis, spectral analysis, 1/3 octave band analysis, and statistical analysis. Spectral analysis is carried out by means of the Welch method. A statistical analysis is given for the BB SPL and for the 1/3 octave band frequency analysis, including mean values and percentiles. Historically, the root of mean squared (rms) level is the most prevalent metric. However, it is strongly influenced by the highest instant sound levels and should be used carefully with transient sound sources (such as boats passing occasionally at the measurement position). Therefore a statistical analysis is performed as a complement to rms levels. The computation of empirical distributions give an idea of prevalent sound levels, both over frequencies or in terms of BB SPL. Percentile levels are estimated across frequency and time. Percentiles are used for the assessment of levels in proportion of time, or to assess the distribution of acoustic energy and level distribution across the frequency band.

4 Data analysis

4.1 Time series analysis

The analysis of the complete time series can provide a rough idea of the frequency discrete events and the variability of the SPL over time. The spectrogram is widely used in time series aalysis, allowing for the observation of variations of the sound level with time at each frequency. Visual inspection allows for the detection or even identification of discrete sound sources such as boats passing near or vocalisations of animals, as each type of sound source may show distinct spectral contents. Figure 2 shows the time-frequency analysis (spectrograms) for the complete acquisition period considered, from 20$^{\text{th}}$ January to 1$^{\text{st}}$ of February. In order to provide the outstanding of these noise events from background noise, curves of BB SPL as a function of time are shown in tandem. These curves allow for the observation of the variability of the full SPL from floor sound level to amplitude peaking caused by transient events. The time is in days of the month, and the ticks coincide at time 24:00 (midnight). The data has been processed indepently for each 90 s period, where data was first segmented into 4096 samples sequences for processing (DFT and BB SPL computation), whose result is then averaged over that period. This means that the results shown in Figure 2 are average values over each 90 s period, which causes the observations to be smoothed out. In other words, instant SPL values within a segment would vary over a broader interval. A more detailed analysis is provided by a statistical analysis shown below.

The site of deployment is close to a traffic route leaving or entering the Ria Formosa, and therefore idle and busy periods were expected *a priori* to occur. In terms of discrete acoustic events, it is quite apparent that there are busy periods alternated with idle or relatively idle periods. The idle periods are centered at midnight, which is particularly true at times 22/01 (Saturday to Sunday) and 23/01 (Sunday to Monday). Approximately the same observation is made one week later, where a similar level of activity takes place, and approximately the same sound level was received. The quietest periods have BB SPL as low as 87 to 90 dB. For other nocturne periods some discrete events are observed, as the received power rises over the whole spectral interval.

While discrete events are quite obvious, other variations in the time-frequency and broadband SPL plots are visible. Variations in background noise can be related to natural phenomena such as wind, waves and water current speed. Figure 3 shows the absolute value of current speed recorded with an ADCP during the acoustic deployment. The current velocity is related to the tide cycle that causes water flow through the channel. It is seen that the velocity peaks attain about 0.4 m/s during date 20/01, from which the peak speed progressively increases to 1.1 m/s. A few examples in particular can be analysed.

The absence of discrete events during the night from 21 to 22 of January enables one to observe some variability in the level of background noise. It is apparent that about midnight the level of background noise is maximized and after it progressively reduces until the first discrete events occur at time 05:15. This observation is in agreement with the peak in current velocity attained just after midnight and the minimum speed achieved at time 04:45. Also over the night from 22nd to 23rd January a similar phenomena is observed where a maximum velocity occurs before midnight and another after midnight, and a minimum

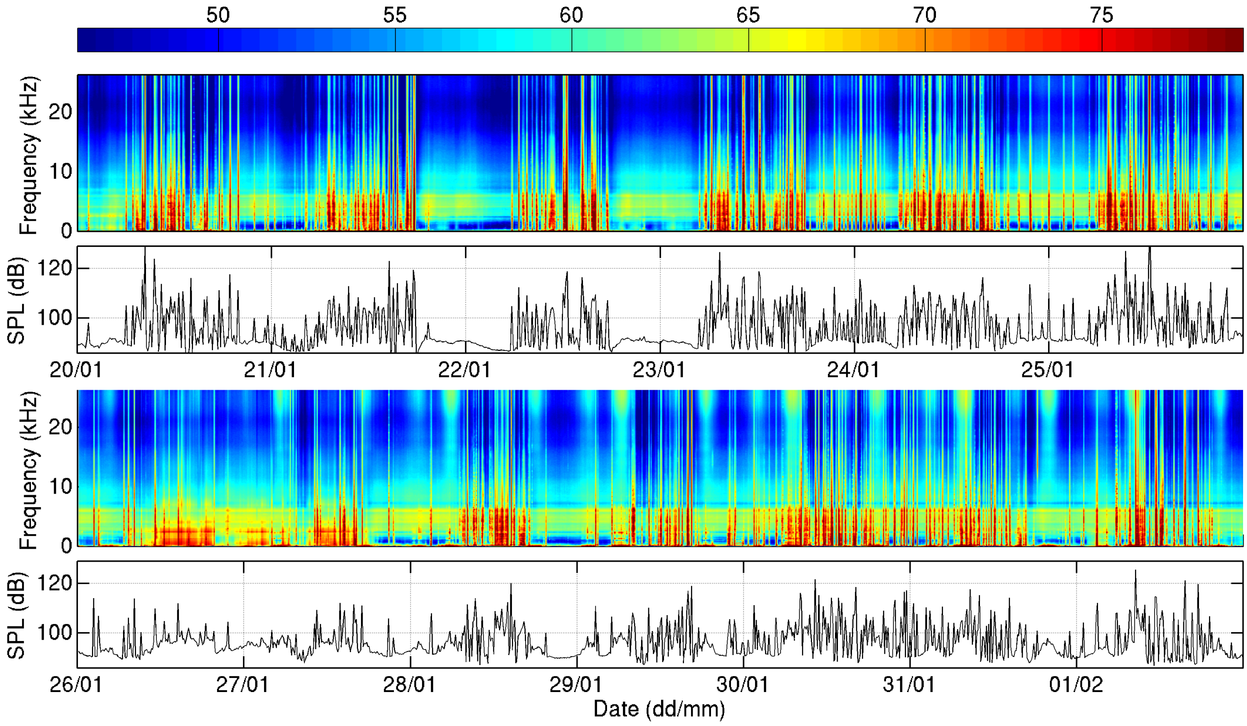

Figure 2: *Time series analysis of acoustic acquired with an autonomous hydrophone over the entire acquisition period in Ria Formosa, Faro, in January 2017. Time-frequency analysis spectrograms and respective broadband SPL are shown. The time is divided among the two panels: 20 to 25 January (top panel); and 26 January to 01 February (bottom panel). The analysis has been performed using observation windows of 4096 samples (≈ 0.077 s) which have been averaged to 90 s using the Welch method.*

velocity at about midnight. In the spectrogram it is clear that the noise level is minimised, in particular for frequencies below 2 kHz. From 26th January onwards the contribution of current velocity to the received noise becomes even more evident, as the variations in background noise are significantly broader in terms of frequency band, as the complete band is spanned. There are spots of energy above 20 kHz coincident with velocity peaks which are quite evident from 27th January onwards. At time 06:26 of 29th January a maximum in SPL of 100 dB is observed, while apparently no ship was passing near. This compares to the lowest levels of 87 to 90 dB observed during days 22, 23, and 24 of January. Altough it is evident that the variation in background noise is correlated to current velocity, it is not known how much flow noise induced on the acquisition device is contributing to the observed variations.

Also wind was analysed, as wind may contribute with noise induced at water surface. Table 2 shows the average wind speed over intervals of the day. The upper part of the table considers 4 hours intervals of the day, and the lower part of the table considers diurne and nocturne periods (based on idle and busy periods). Higher wind speed occured during the day, from 4.6 to 4.9 m/s with, however, a relatively low difference of average wind speed. During the night average wind speeds from 3.6 to 3.9 m/s were observed. Similar values are observed when only diurne and nocturne periods are considered. The visual analysis of the spectrograms does not provide a discrimination of significant contributions of windspeed to the received noise level.

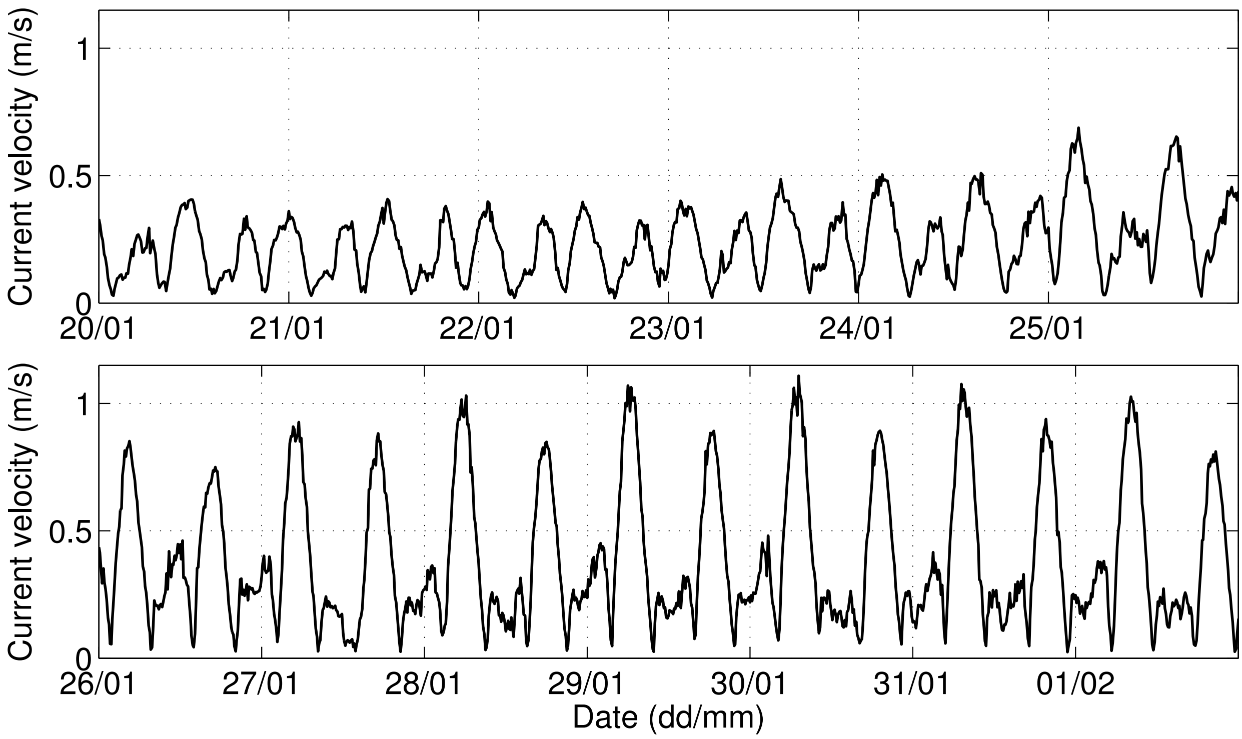

Figure 3: *Current velocity as function of time during the acoustic acquisition period from 20th of January to 1st of February.*

Time (hh:mm)	Wind speed (m/s)
00:00 to 04:00	3.9
04:00 to 08:00	4.1
08:00 to 12:00	4.9
12:00 to 16:00	4.6
16:00 to 20:00	3.6
20:00 to 24:00	3.6
07:00 to 17:00	4.6
17:00 to 07:00	3.8

Table 2: Average current speed from 20th April to 1st February over time intervals of 4 hours (upper part) and over idle and busy boat traffic periods (lower part).

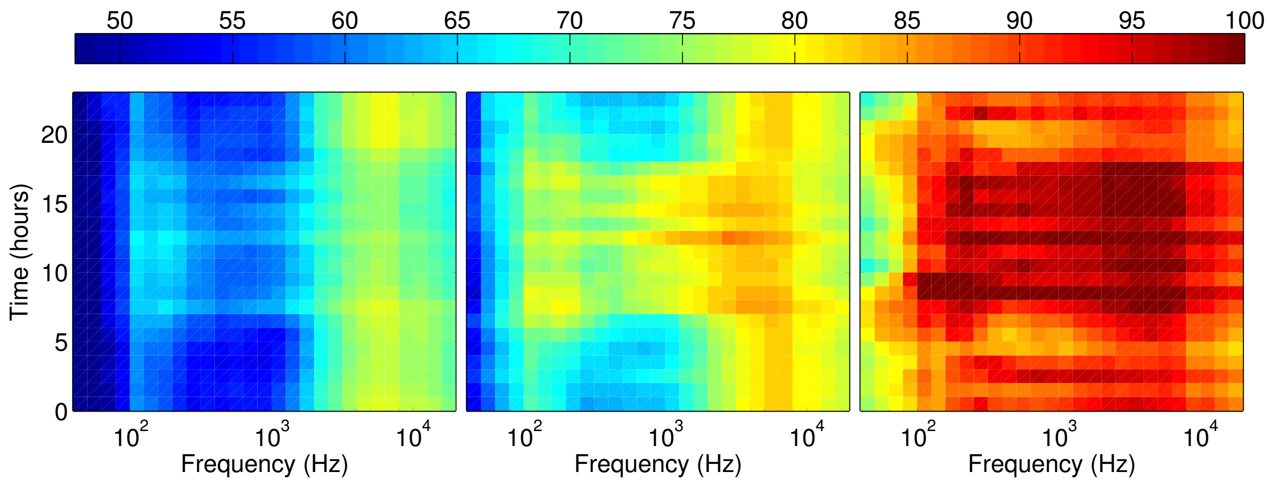

Figure 4: *Percentiles for 1/3 octave level for each hour of the day for the entire acoustic acquisition interval: percentile 5 (left) median (middle) percentile 95 (right).*

The visual analysis clearly suggests that there two regimes, a diurne regime where a significant number of transient acoustic events are noticed. The majority of such transients are related to boat traffic that mostly operates during the day. However, this technique is insufficient for the accurate discrimination of the two time intervals of the day. In order, to determine the idle and the busy period in terms of noise level, a statistical analysis on the 1/3 octave bands spectrum has been carried out. Figure 4 shows percentiles obtained for 1/3 octave bands bins over 1-hour intervals for the complete acquisition period. For each 1-hour interval all instantaneous 1/3 octave bands spectra were computed (no averaging), and percentiles obtained. The left panel is percentile 5, the middle panel is percentile 50, and the right panel is percentile 95. The meaning of the percentiles is the exceeded level in proportion of time. For example percentile 5 indicates the level that has been exceeded during 95% of time. This analysis clearly allows for the discrimination of the idle period from the busy period. In particular, percentile 50, seems to separate the two periods almost free of ambiguity, since there is a step of 10 to 15 dB in the intermediate region of the time axis. For percentiles 5 and 95 the step is less pronounced, with a difference of 5 to 10 dB. This analysis indicates that the busy period is from times 07h00 to 17h00 of the day, and the rest of the time can be considered the idle period.

The separation of idle and busy period might be important for comparison purposes. Assuming that a new observation is to be made with the tide turbine operating on site, the idle period shall be used to assess the contribution of the turbine to the total noise, or in an attempt to characterize the acoustic signature of the turbine.

4.2 Statistical analysis

This section provides a statistical analysis of the acoustic data, in opposition to the time series representation given above. In general, statistical analysis are more suited to characterising variability and comparing soundscapes at different times or locations, while time series representations are more suited to show discrete events and describing trends in sound levels.

4.2.1 Broadband noise levels

This section provides an analysis on broadband noise levels. Throughout this text broadband level refers to the sound level integrating all power contained from 35 Hz to 22449 Hz, which is the range of frequencies given in table 1, more specifically, the frequency band that goes from the lower frequency bound of the first 1/3 octave band to upper frequency bound in the last 1/3 octave band considered herein. In this way coherence between the broadband SPL and 1/3 octave level analyses is maintained.

Figure 5 shows Level Exceedance in Proportion of Time. This indicator represents the SPL exceeded during a given percent of time. To calculate level exceedance, the instantaneous SPL observations obtained from data windowing for a given interval of the day were collected and sorted in ascending order as to obtain the percentiles from zero to 100 with a resolution of 1. Then the percentile was simply reversed and converted to percent, in order to obtain the proportion of time instead percentile. For example, percentile 5 SPL corresponds to the SPL exceeded during 95% of the time. This analysis was obtained for the full acquistion time (gray curve), and for the two comparison intervals, from times 7h00 to 17h00 (blue curve), and from times 17h00 to 07h00 (black curve). For the sake of easy comparison markers at 95% and 5% of the time have been included. It is seen that the variability over the diurne period is higher then over nocturne period, since the curves cross at 80% of time, which means that in proportion of time both the lowest and highest sound levels can be observed during the diurne period. For 95% of the time the exceeded level is 86 dB during the diurne period and 87.5 dB during the nocturne period. This behaviour could be somewhat unexpected, but one should account that not only man-made noise contribute for the total noise budget - also natural factors may contribute.

In section 4.1 average values for wind speed were given, whereas wind speed was higher during the diurne period, and therefore this reason can be discarded, since noise is induced by increasing windspeed. It was observed that current speed was a prevalent factor regarding noise level, as in the visualization of the time series as a spectrogram, periods of increased ambient noise could be matched with periods of increased current speed. Current speed evolves over time according to the tide cycle, with amplitude modulation leading to significant amplitude variation over a time span of weeks. A simple comparison of the current speed can be carried out by computing the rms speeds [1] over diurne and nocturne periods, for the entire acquisition period. The rms speed for the diurne period was 0.36 m/s and for the nocturne period it was 0.42 m/s. As a prevalent factor on the noise level, it is acceptable to infere that current speed establishes the lower boundary in the measured noise level, i.e., the minimum received noise level is a function of currents speed (among others). Therefore, it shall be concluded that current speed was the cause for lower boundary of noise level to be higher during the idle period than for the busy period. Note that this particularity may be unrepeatable, as in a future acoustic data acquistion may occur at a different tide fase.

On the upper end (towards 0% of the time) the comparison result is within the expectations, according to the time series observation in section 4.1, whereas the diurne period (busy period) is louder than the nocturne period. The level exceedance for 5% of the time is 112 dB for the diurne period (blue), 107 dB for the nocturne period (black), and 109 dB overall (gray). The curves for diurne period and total period show a long tail since there is a long interval from the 5% markers to the end of the scale (approximately 30 dB). This is caused by the fact that the noise sources are discrete in time with relatively short transient

[1] root mean square (rms) is defined as the square root of mean square. By applying the root the original units are preserved (m/s).

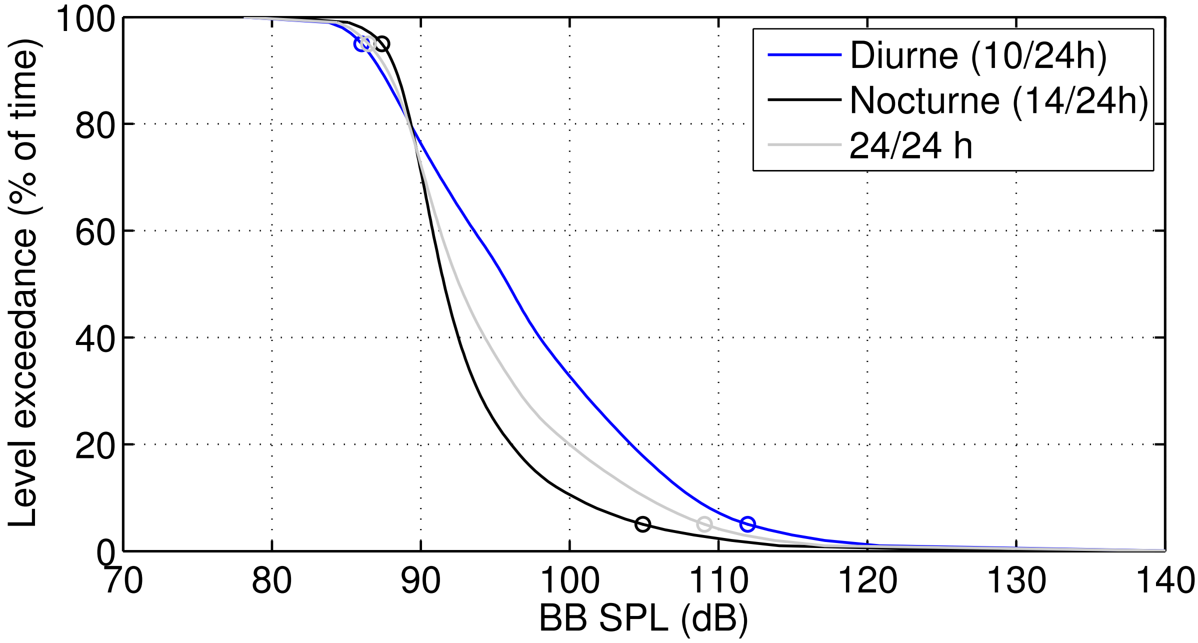

Figure 5: *Sound level exceedance in proportion of time from 20th January to 1st February. Diurne intevals from 07h00 to 17h00 (blue); nocturne intevals from 17h00 to 07h00 (black); all data (gray). The circle markers indicate level exceedance for 95% and 5% of the time.*

periods, and with levels significantly outstanding from ambient noise.

As a complementary analysis in the time domain, and to assess the diel variability of BB SPL, Figure 6 shows a boxplot for 1 hour intervals over the entire acquisition period. The black mark is the median, box edges are the first and third quartiles, and the blue circles indicate percentiles 1 and 99 (whiskers). This result highlights the dependence of the noise level with time of the day, as a result of the boat traffic nearby. There is a high degree of skewness for times in the nocturne interval, where percentile 1 to median interval amplitude ranges from 3 to 6 dB, which is likely to be related to a relatively low number of time discrete transient events and noise induced during peaking of current speed. The skewness is significantly releaved from time 07h00 onwards until 17h00, where the percentile 1 to median interval amplitude ranges up to 13 dB. The third quartile is stable below 94 dB from times 20h00 to 6h00. From 6h00 onwards it steadily rises and reamains relatively steady above 10 dB until it starts to reduce from 17h00 onwards. This observation is reinforced by percentile 99 which also has well defining period of high values, from 7h00 to 18h00, and low values during the remaining time. This plot contributes for understanding the noise floor observed during level exceedance analysis. Percentile 1 (bottom blue circles) has most lowest values within times from 8h00 to 19h00, at times reaching values as low as 82.1 dB. From 19h00 onwards the percentile 1 values rise to values close to 87 dB. All percentiles and mean value over 1 hour intervals for BB SPL are provided in table 4 of the appendix.

Table 3 summarizes the statistical results on broadband SPL by means of percentiles and rms levels for the three analysis intervals. Concerning the percentiles, this is table reflects the information given in the form of level exceedance in proportion of time in Figure 5.

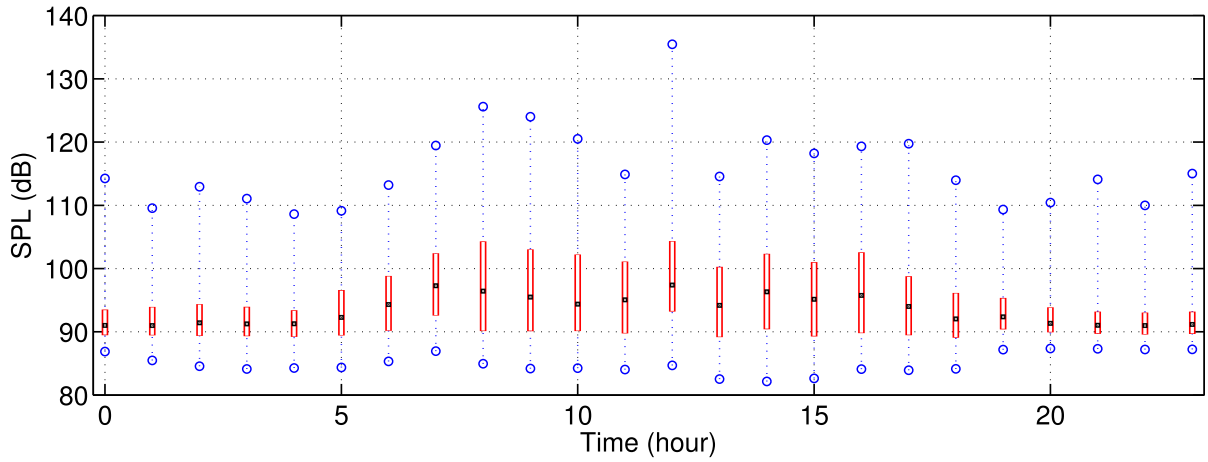

Figure 6: *Boxplot for broadband SPL over 1 hour intervals of the acoustic data acquired from 20th January to 1st February. The black mark is the median, box edges are the first and third quartiles, and the blue circles indicate percentiles 1 and 99.*

	p_1	p_5	p_{25}	p_{50}	p_{75}	p_{95}	p_{99}	rms
All time	84.4	86.5	89.7	92.6	98.0	109.1	117.1	94.7
Diurne interval	83.8	86.0	90.3	95.9	102.4	112.0	120.8	97.0
Nocturne interval	85.1	87.4	89.7	91.6	94.8	104.9	114.1	93.2

Table 3: Broadband sound pressure level: statistical analysis summary for the three intervals. Percentiles and rms values are given in decibel.

4.2.2 Frequency domain analysis

Boxplots can be computed in the frequency domain for the assessment of the variability over significant spectral bands. Figure 7 shows boxplots for the three analysis intervals over 1/3 octave bands. The frequencies are the center frequencies of 1/3 octave bands, whose width increses logarithmically with frequency. This should be accounted for, since the plotted amplitudes represent the power integration over the respective 1/3 octave band.

The boxplot for the nocturne interval in Figure 7(top) indicates that for frequency bands with center frequencies up to 110 dB have evenly distributed sound levels (low degree of skewness), while the skewness is high for the remaining frequency bands. In the interval from 125 to 1250 Hz, the degree of skewness is high since 74% of the realizations are contained in a 20 dB interval and the remaining 25% in a interval exceeding a 30 dB amplitude. For frequencies above 2500 Hz the skewness becomes even more accute, since the boxes have amplitudes varying from to 2 to 5 dB, while 74% of the realizations are contained in a 10 dB interval, and the remaing 25% are contained in intervals with amplitudes up to 20 dB.

For the diurne interval no significant change is observed for frequencies up to 78 Hz. In comparison to the nocturne period, the most significant increase in noise level occurs in the frequency band 248 t0 1575 Hz, where, at the same time, the skewness is signifcantly releaved. The first quartile is moved by 5 to 9 dB upwards and the third quartile is moves 9 to 11 dB. Above 1575 Hz, the first quartile have changes from 3 at 1984 Hz to -3 at 20 kHz, while the third quartile changed 8 dB at 1984 Hz to 2 dB at 20 kHz. For this frequency range percentile 1 changed from -1 to -3 dB, while the change for percentile 99 was 5 to 6 dB. In general, from the nocturne to the diurne interval there has been clearly a broadening effect in the variability of noise level caused by the prevalence of current speed

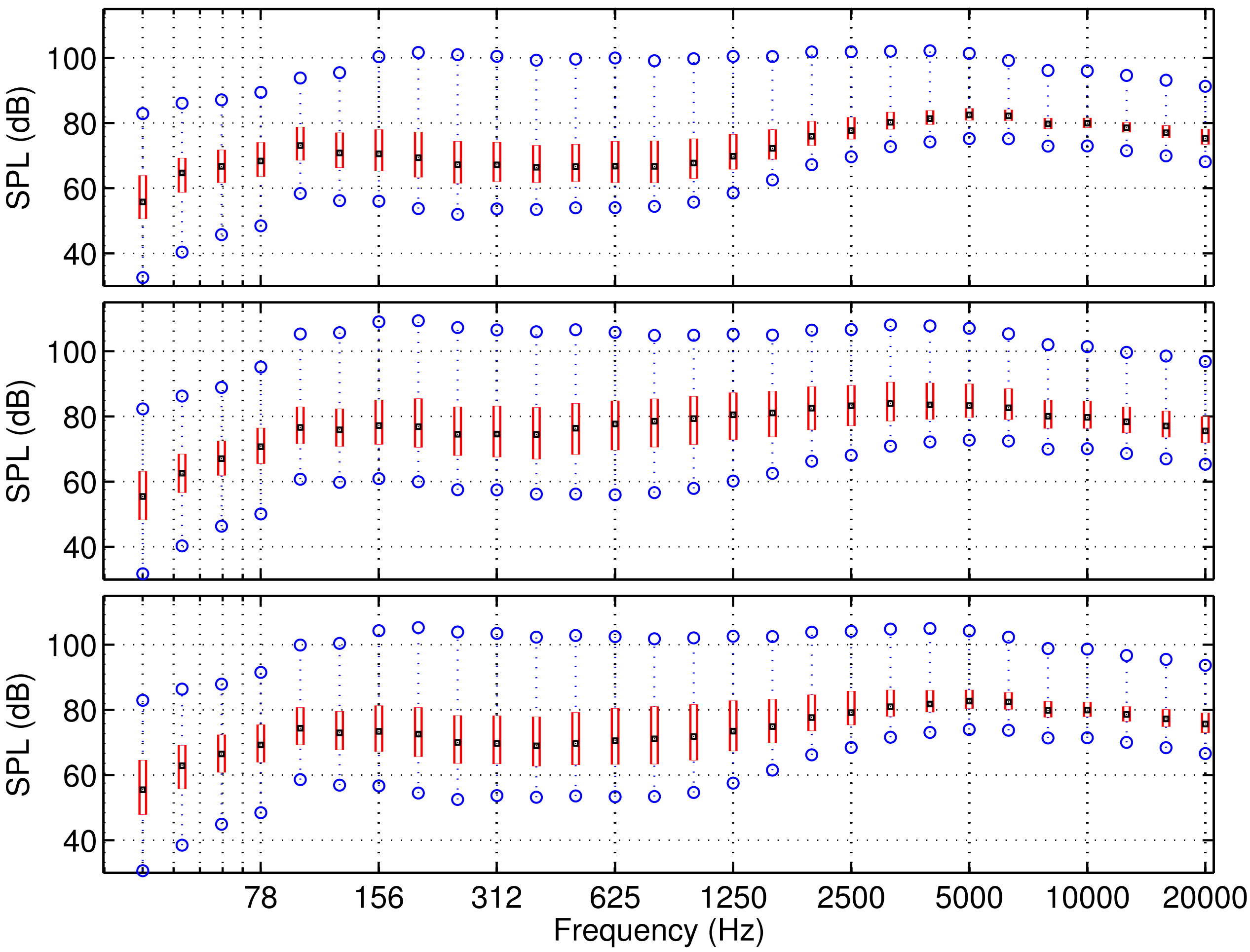

Figure 7: *Boxplot of 1/3 octave bands for nocturne interval (top); diurne interval (middle); and all time (bottom) of the acoustic data acquired from 20th January to 1st February. The black mark is the median, box edges are the first and third quartiles, and the blue circles indicate percentiles 1 and 99 (whiskers).*

on noise level for the lower SPL boundaries, specially at the upper frequency range, and on the upper SPL boundary for the increased boat traffic in the diurne period, specially in the middle frequency range, while in the upper frequency ranges contributions from both noise sources are received.

Figure 7(lower) shows the boxplot for all data, and is therefore a combination of the other two. At this point no further comments are provided on this analysis. All percentiles and mean value over 1/3-octave bands are provided in tables 5, 6, and 7 of the appendix.

Figure 8 shows the spectral probability density (SPD), whereby the empirical probability of sound levels in each frequency band is presented, with superimposed percentile curves across the frequency band for percentiles 1, 5, 50, 95 and 99. The top panel shows the SPD for the nocturne intervals (times 07:00 to 17:00), the middle panel shows the SPD for the diurne intervals (times 07:00 to 17:00), and the bottom panel shows the SPD for all time (24 hours per day). This analysis can reveal multi-modality in the received sound level. It is clear that the measured noise has a unimodal characteristic, since for each frequency only a single distribution peak exists over the entire frequency band. These empirical distributions can complement the frequency boxplot as it clearly reveals how the noise levels distributed.

For example, the noise in the frequency band above 2 kHz is very stable since the distribution is very compact. It also reveals that the boat radiated noise dilutes the distributions over the frequency band, including the upper frequency interval, indicating that boat noise has spectral contents well spread over the entire acquisition band.

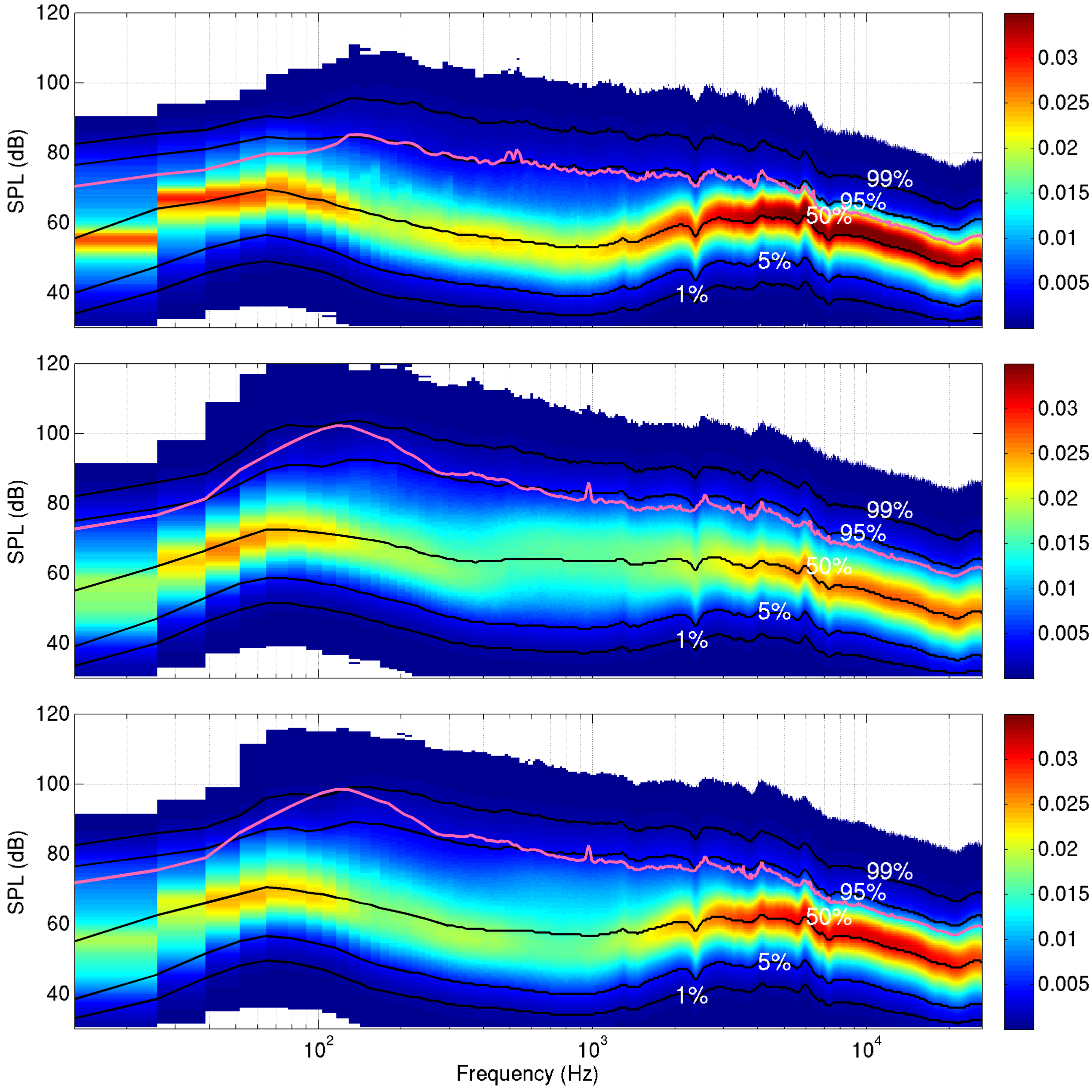

Figure 8: *Spectral Density Probability of noise level as a function of frequency with percentiles (black curves) and PSD (pink curve): nocturne interval (top); diurne interval (middle); all data (bottom).*

The SPL interval goes well beyond the 1% and 99% percentile boundaries over most of the frequency band, indicating contents of some outliers. Hence, this also indicates that the acoustic recorder self-noise did not limit the observation of the lowest sound levels. These plots reveal with increased detail the distribution of sound observed above with boxplots. It is seen how skewness varies and how the noise level speads over the frequency band. The pink curve shows an estimate of the average PSD estimated by integrating the SPL over the probability distribution at each frequency. For the nocturne interval (Figure 8(top)) mean PSD tends to superimpose the percentile 95 from 100 to 6000 Hz, while during the diurne interval the mean PSD attains percentile 99 at its peak and coincides with percentile 95 over most of the band (Figure 8(middle)). Sound level in rms values must be analysed carefully:

since these values are provided in a logarithmic scale, outliers may contribute on the upper end of the distribution and significantly contribute for the average level.

5 Conclusions

Acoustic data has been acquired from 20 January to 1 February 2017 at an inlet at Ria Formosa coastal lagoon with an autonomous hydrophone moored by means of a tripod structure deployed on the seabottom at an average water depth of approximately 11 m. The deployment site is an inlet of the lagoon system Ria Formosa through which water flows at significant speed due to tidal cycles and serves as passage of local boats.

During the analysis of the actual data set it was concluded that these two factors are prevailing to the variability in the noise level. It is clearly observed that the current speed induced a significant increase on broadband noise level, specially during the second week when current speed peaked to its maximum values measured during the acoustic acquistion time interval. It was concluded that this factor imposes the lower bound on noise level when it observed that noise floor during the busy period (diurne interval established from times 07h00 to 17h00) was lower that the noise floor during the idle interval (nocturne interval established from times 17h00 to 07h00) due to increased rms current speed during the nocturne interval. The diurne and nocturne intervals were acoustically established from percentiles of 1/3-octave levels after visualization of the spectrogram of the complete time series, where it was evident that periods of idle or reduced boat traffic at night were interchanged with busy boat traffic during the day.

The data analysis was based on a statistical analysis of the data from the established diurne and nocturne intervals, and 24-hours interval, including percentile analysis in the time and frequency domains, and a spectral probability analysis, on broadband levels and spectral levels. This analysis conducted to a clear distinction between two acoustic regimes induced by the aforementtion factors.

Future work shall include a new deployment once the tidal turbine is in operation, in order to assess the possible contribution of that device as a noise source.

A Statistical results in tabular format

This section provides tables with results obtained from the statistical analysis in sections 4.2.1 and 4.2.2.

Time (HH:MM)	p_1	p_5	p_{25}	p_{50}	p_{75}	p_{95}	p_{99}	rms
00:00-01:00	86.9	87.8	89.5	91.0	93.5	106.8	114.2	92.6
01:00-02:00	85.5	87.3	89.4	91.0	93.9	104.0	109.5	92.4
02:00-03:00	84.6	86.3	89.3	91.4	94.4	108.3	112.9	93.0
03:00-04:00	84.1	85.7	89.3	91.2	94.0	104.7	111.1	92.4
04:00-05:00	84.3	85.6	89.2	91.3	93.4	100.5	108.6	91.8
05:00-06:00	84.4	86.1	89.4	92.3	96.6	104.7	109.1	93.4
06:00-07:00	85.3	86.9	90.1	94.3	98.8	105.8	113.2	95.0
07:00-08:00	86.9	88.5	92.6	97.3	102.4	110.5	119.5	98.1
08:00-09:00	85.0	86.5	90.1	96.4	104.3	116.7	125.6	98.2
09:00-10:00	84.2	85.9	90.1	95.5	103.0	111.6	124.0	97.1
10:00-11:00	84.2	85.9	90.1	94.4	102.2	112.5	120.5	96.5
11:00-12:00	84.0	85.9	89.7	95.1	101.1	109.0	114.9	95.9
12:00-13:00	84.7	86.6	93.2	97.4	104.4	113.6	135.5	99.0
13:00-14:00	82.5	85.3	89.1	94.2	100.3	108.9	114.6	95.2
14:00-15:00	82.1	85.8	90.4	96.3	102.3	113.1	120.3	97.2
15:00-16:00	82.6	85.4	89.3	95.1	101.0	111.2	118.2	96.1
16:00-17:00	84.1	85.9	89.8	95.8	102.6	111.5	119.3	96.8
17:00-18:00	83.9	85.4	89.4	94.0	98.8	111.9	119.7	95.2
18:00-19:00	84.2	85.8	89.1	92.0	96.2	104.9	114.0	93.2
19:00-20:00	87.2	88.3	90.4	92.4	95.4	101.2	109.3	93.3
20:00-21:00	87.3	88.3	89.9	91.3	93.9	102.4	110.4	92.7
21:00-22:00	87.3	88.2	89.7	91.0	93.2	107.3	114.1	92.9
22:00-23:00	87.2	88.0	89.6	91.0	93.0	103.7	110.0	92.3
23:00-24:00	87.2	88.1	89.7	91.2	93.2	101.2	115.0	92.3

Table 4: Percentiles for broadband sound pressure levels over 1-hour slots for all data. Levels are given in decibel.

f (Hz)	p_1	p_5	p_{25}	p_{50}	p_{75}	p_{95}	p_{99}	rms
39	30.7	38.0	47.8	55.5	64.6	76.9	82.9	56.3
49	38.5	45.9	55.7	62.8	69.2	80.1	86.3	62.7
62	44.9	52.2	60.8	66.4	72.4	81.9	87.9	66.6
78	48.4	55.6	63.9	69.2	75.5	84.9	91.5	69.7
98	58.6	63.0	69.2	74.4	80.8	90.8	99.9	75.4
124	56.9	61.3	67.6	72.9	79.6	90.6	100.4	74.1
156	56.7	60.6	67.1	73.4	81.3	94.4	104.3	75.0
197	54.5	58.3	65.6	72.5	80.8	95.7	105.3	74.1
248	52.5	56.4	63.5	70.0	78.3	94.0	103.9	71.8
312	53.7	57.1	63.4	69.7	78.2	93.5	103.4	71.7
394	53.2	56.5	62.7	68.9	77.9	92.6	102.3	71.1
496	53.6	56.7	63.1	69.7	79.2	93.1	102.8	71.8
625	53.3	56.4	63.2	70.5	80.5	93.3	102.4	72.3
787	53.4	56.7	63.3	71.1	81.1	93.5	101.8	72.7
992	54.7	58.2	64.5	71.8	81.7	94.3	102.1	73.6
1250	57.5	61.4	67.3	73.5	82.9	94.9	102.6	75.5
1575	61.5	64.9	69.8	74.9	83.3	95.0	102.5	77.0
1984	66.2	69.3	73.5	77.6	84.7	96.4	103.8	79.8
2500	68.5	71.3	75.3	79.1	85.8	96.3	104.1	81.1
3150	71.6	74.3	77.9	80.9	86.2	97.4	104.8	82.8
3969	73.1	75.6	79.3	81.8	86.0	97.2	105.0	83.5
5000	74.0	76.6	80.4	82.7	86.2	96.8	104.2	84.1
6300	73.8	76.4	80.1	82.4	85.4	95.1	102.3	83.5
7937	71.3	73.9	77.7	79.8	82.6	91.4	98.8	80.8
10000	71.5	74.1	77.8	80.0	82.4	91.3	98.6	80.8
12599	70.0	72.6	76.4	78.6	81.1	89.4	96.7	79.4
15874	68.4	71.0	74.8	77.2	80.2	87.8	95.5	78.0
20000	66.6	69.1	72.9	75.6	79.1	85.9	93.7	76.4

Table 5: Statistics for 1/3 octave levels for all data: percentiles and rms level as a function of frequency. Levels are given in decibel.

f (Hz)	p_1	p_5	p_{25}	p_{50}	p_{75}	p_{95}	p_{99}	rms
39	31.7	39.1	48.2	55.4	63.2	75.5	82.3	56.0
49	40.3	47.6	56.6	62.6	68.5	78.8	86.3	62.7
62	46.3	53.6	61.8	67.0	72.5	81.6	88.9	67.3
78	50.1	57.3	65.5	70.7	76.5	86.2	95.1	71.2
98	60.7	65.2	71.6	76.6	83.0	94.4	105.3	77.8
124	59.7	64.3	70.7	75.9	82.4	94.5	105.7	77.2
156	60.9	65.0	71.4	77.2	85.1	97.9	109.0	78.9
197	59.9	63.9	70.5	76.8	85.5	99.2	109.4	78.7
248	57.5	61.4	68.0	74.5	82.9	97.5	107.3	76.3
312	57.5	61.0	67.5	74.6	83.2	97.0	106.5	76.2
394	56.2	59.8	66.9	74.5	82.8	96.0	105.9	75.7
496	56.2	60.0	68.3	76.4	84.0	96.4	106.6	76.8
625	55.9	60.2	69.6	77.7	84.8	96.4	105.8	77.7
787	56.6	60.8	70.5	78.5	85.5	96.4	104.8	78.4
992	57.9	61.9	71.3	79.3	86.2	97.1	104.9	79.2
1250	60.1	64.1	72.8	80.5	87.3	97.6	105.2	80.4
1575	62.5	66.1	73.7	81.0	87.8	97.5	104.9	81.2
1984	66.2	69.6	75.8	82.5	89.2	99.1	106.5	83.0
2500	68.0	71.1	77.1	83.3	89.6	99.2	106.6	83.9
3150	70.9	73.6	78.5	83.9	90.6	100.2	108.0	85.1
3969	72.2	74.7	79.0	83.5	90.3	100.3	107.7	85.2
5000	72.8	75.6	79.6	83.3	90.0	99.9	107.0	85.2
6300	72.4	75.3	79.0	82.6	88.5	98.0	105.3	84.3
7937	70.0	72.7	76.3	80.0	85.1	94.1	102.0	81.3
10000	70.1	72.8	76.3	79.7	84.8	93.9	101.4	81.1
12599	68.6	71.4	74.9	78.3	82.9	91.8	99.6	79.5
15874	67.0	69.8	73.6	77.1	81.7	90.4	98.5	78.2
20000	65.3	68.0	71.9	75.6	80.0	88.4	96.8	76.5

Table 6: Statistics for 1/3 octave levels for diurne intervals (times from 07h00 to 17h00): percentiles and rms level as a function of frequency. Levels are given in decibel.

f (Hz)	p_1	p_5	p_{25}	p_{50}	p_{75}	p_{95}	p_{99}	rms
39	32.6	40.2	50.5	55.8	64.0	77.0	82.9	57.2
49	40.4	48.1	58.6	64.7	69.3	80.1	86.1	64.1
62	45.8	53.1	61.6	66.7	71.8	81.5	87.1	66.8
78	48.4	55.5	63.5	68.3	74.1	83.8	89.4	68.9
98	58.3	62.6	68.5	73.1	78.8	87.9	93.8	74.0
124	56.2	60.4	66.3	70.8	77.1	87.8	95.4	72.1
156	56.0	59.7	65.3	70.5	78.0	90.6	100.3	72.3
197	53.8	57.3	63.3	69.4	77.3	90.9	101.6	71.1
248	52.0	55.5	61.4	67.2	74.4	89.3	100.9	68.9
312	53.6	56.7	62.0	67.2	74.1	88.6	100.5	69.1
394	53.5	56.4	61.7	66.4	73.2	87.7	99.3	68.5
496	54.0	56.8	62.0	66.6	73.5	88.4	99.6	68.8
625	54.0	56.6	61.6	66.7	74.4	89.4	99.9	69.1
787	54.4	56.8	61.6	66.7	74.5	89.4	99.1	69.1
992	55.7	58.1	62.9	67.7	75.2	89.7	99.7	70.1
1250	58.5	61.2	65.8	69.8	76.6	91.1	100.4	72.2
1575	62.5	65.0	68.8	72.2	78.0	91.1	100.4	74.4
1984	67.2	69.7	73.0	75.9	80.6	92.4	101.8	77.7
2500	69.6	71.9	75.0	77.6	81.8	91.7	101.8	79.2
3150	72.7	75.1	78.0	80.2	83.4	92.5	102.0	81.5
3969	74.2	76.8	79.5	81.4	83.9	92.6	102.1	82.4
5000	75.2	78.1	80.8	82.5	84.5	92.1	101.4	83.3
6300	75.2	78.0	80.6	82.2	84.1	90.9	99.1	82.9
7937	72.9	75.5	78.2	79.7	81.5	87.6	96.1	80.3
10000	73.0	75.7	78.5	79.9	81.5	87.8	96.0	80.5
12599	71.5	74.2	77.1	78.5	80.2	86.3	94.6	79.1
15874	69.9	72.6	75.4	77.0	79.2	85.0	93.1	77.7
20000	68.1	70.7	73.4	75.3	78.2	83.6	91.3	76.2

Table 7: Statistics for 1/3 octave levels for nocturne intervals (times from 17h00 to 07h00): percentiles and rms level as a function of frequency. Levels are given in decibel.