25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0134
PASSIVE ACOUSTIC MONITORING OF UNDERWATER BUBBLE PLUMES

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Abstract. *One of the challenges in Carbon Capture and Storage (CCS) is guaranteeing minimum leakage condition in the reservoir as some researches indicate that even small leakage would impose a severe economic risk to the operation and harsh environmental damages. In order to assess those impacts, controlled leakage experiments were performed in the recent past; in some cases, those experiments also aimed in determining leakage detection capabilities. The use of passive acoustic monitoring is proposed as the first layer of alarms for gaseous leakages in underwater operations, as during the formation of gas bubbles in water, a known signal is generated. Nevertheless, no data is available to assist in the development of passive acoustic leakage detection methodologies. Aiming at this gap, our group planned and performed controlled leakage tests at Baia de Santos to obtain the audio signals for different leakage conditions and distances between leakage sources and sensors. This paper describes the experimental campaign design, its methodology, and the results that allow us to start understanding the acoustic emission behavior of bubble plumes.*

Keywords: *Underwater acoustics; Carbon Capture, and Storage; Leakage Detection, Bubble plumes*

1. INTRODUCTION

In the past years, CCS technology has advanced significantly. The adoption of this methodology as an effective climate change mitigation action is being considered, even resulting in the adoption of a European Directive on the subject legislation (European Parliament and the Council of the European Union, 2009). The main objective of CCS is the reduction of the atmospheric CO_2, therefore, as seen in (European Union, 2015) and (United States House of Representatives, 2019), governments are proposing legislation that induces economic impacts in companies. With this in mind, a rise in the number of operational CCS projects is expected, and the efforts to minimize all the uncertainties related to this technology are also augmenting, the capability to detect leakage occurrences is one of those aspects that still need development.

Monitoring the occurrence of leakages is necessary in order to guarantee the achievement of the objective aimed with CCS, therefore avoiding potential economic and environmental damages. The assessments of the several parameters that interfere in leakage patterns, and its environmental impact, have been done mainly by controlled leaks experiments, and as reported by (Roberts & Stalker, 2017), at least 27 of those tests were done, one of them performed in Brazil but focusing only on assessing leakage impact at onshore sites. Up to our knowledge, there was no offshore/underwater assessment of CO2 leakages focusing on the development of monitoring devices and techniques.

In the occurrence of a failure in the sealing rock, the greenhouse gases stored in offshore reservoirs will percolate through geologic structures and upon reaching the seafloor, this gas may form bubble plumes. As shown by (Minnaert, 1933), (Strasberg, 1956) and several others, the bubble formation produces a characteristic acoustic signal, that could be used to characterize the occurrence of an underwater gaseous leakage. Therefore, passive acoustic monitoring devices could be used as lead Our group has previously worked on underwater soundscapes, (Sánchez-Gendriz & Padovese, 2016) and (Hubert, Padovese, & Stern, 2018), the analysis of the signals obtained by passive acoustic on the monitoring leaks at offshore CCS sites became of interest. On this work we will discuss one of the first steps in the development of a leakage detection system, the construction of an experimental set-up for controlled gas leakage and measurement of the sound emitted during bubble formation.

2. LITERATURE REVIEW ON BUBBLE FORMATION EXPERIMENTAL WORKS

A great number of researchers studied, in the past, the bubble formation phenomenon in several aspects. Focusing on the works that analyzed the acoustic emission at the moment of a bubble formation we could cite (Di Bari &

Robinson, 2013), (Nicholas, Roy, Crum, Oguz, & Prosperetti, 1994), (Longuet-Higgins, 1990) and (Pumphrey & Ffowcs Williams, 1990). As observed in the bubble acoustics literature, the experimental set-up commonly used to acoustically observe gas bubbles in a liquid medium is mainly composed of two parts. The first is responsible for the data acquisition and the second part is responsible for the controlled release of the gas, in other words, the bubble generation apparatus. Figure 1, reproduced from (Leighton T. G., 1994), schematically shows the experimental set-up including both parts and three possibilities of bubble generation apparatus.

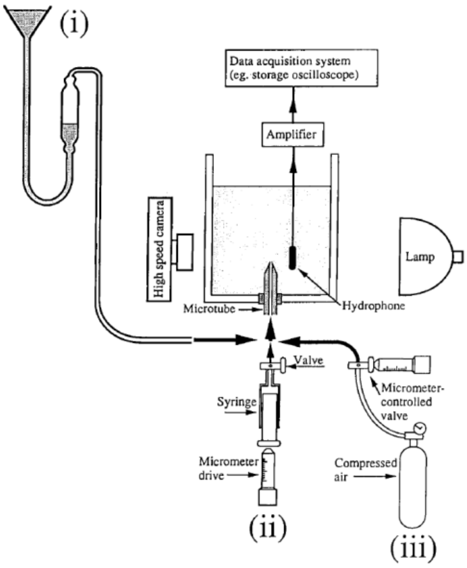

Figure 1 – Experimental set-up as exposed by (Leighton T. G., 1994). Showing Minnaert's (i), Leighton's (ii) and Longuet-Higgins (iii) bubble generation apparatus.

Regarding the data acquisition equipment, although some works used microphones outside the liquid container, the most adopted technique is the usage of hydrophones near the gas release nozzles to record the acoustic signal, as the sound emitted during bubble formation is first transmitted in the liquid medium. It should be also noted that some of the studies used high-speed cameras to obtain images of the bubbles and/or bubble plumes produced. Another relevant aspect is that, for the future analysis of the signals, these two sensors should be connected to recording equipment (Leighton & Walton, 1987), such as audio/video recorders, commercial audio interface, and data acquisition systems.

On the side of the bubble generation apparatus, there are at least three different forms of inducing a known gas volumetric flow to the liquid medium. The first method (i), by (Minnaert, 1933), uses a water stream as responsible for slowly displacing air from a tube into the liquid container. The second (ii) was reported by (Leighton & Walton, 1987) and uses hypodermic syringes, 3-way valves, and micrometric drives to push the gas towards the liquid. From (Longuet-Higgins, Kerman, & Lunde, 1991), the third possibility (iii) is to use compressed air infrastructure and flow control valves.

The methods proposed by Minnaert and Leighton are capable of good control of the volume displaced towards the liquid but they have an inherent limitation on the maximum possible displaced quantity. Therefore, they are only capable of producing small flow rates, being suited for the study of single bubbles. On the other hand, the method proposed by (Longuet-Higgins, Kerman, & Lunde, 1991) is capable of producing bigger volumetric flows at the expense of control capabilities, therefore being more suited to the study of gas plumes. The limitations on flow rates and flow control are imposed mainly by the compressed air infrastructure available.

Although these three possibilities, shown at Figure 1 in roman numerals, are the base to almost every experimental work discussed in the literature, it is important to note the huge variance on the flow values observed at various reported studies. As examples, we cite the works from (Di Bari & Robinson, 2013) on single bubble emissions, passing through the works of (Bergès, Leighton, & White, 2015) and (Fasham, Brown, & Crook, 2015) on small leakage flows, and up to the $8.3\ 10^{-3}$ m^3/s (500 L/min) leakages reported on (Miao, Liu, Qin, Chu, Wu, & Wang, 2018).

An important fact is that the great majority of the papers on the area could be classified into three different categories. The first comprises the works done in laboratories; it is focused on several aspects of the bubble formation phenomenon and its acoustics. The second category encompasses experimental works that were developed to record data produced on the field by natural bubble formations. Finally, the third group of articles is the ones related to field recordings that established acoustic emissions for controlled leakage scenarios. Table 1 shows in which category are the references listed in this article.

Table 1 - Summary of the three groups of experimental works found in the literature

Type of Experiment	Articles
Laboratory	(Minnaert, 1933), (Longuet-Higgins, Kerman, & Lunde, 1991), (Nicholas, Roy, Crum, Oguz, & Prosperetti, 1994), (Greene & Wilson, 2012), (Di Bari & Robinson, 2013), (Miao, Liu, Qin, Chu, Wu, & Wang, 2018)
Field experiments Natural bubble formation	(Leighton & Walton, 1987), (Leifer & Tang, 2007), and (Pumphrey & Ffowcs Williams, 1990)
Field experiments Controlled leakage	(Fasham, Brown, & Crook, 2015), (Bergès, Leighton, & White, 2015)

3. EXPERIMENTAL SET-UP DESIGN

Our objective with the experiments was to obtain the signals emitted by underwater gas leakages at controlled flow rates. Therefore, we focused on building a portable and interchangeable apparatus that could be easily used to simulate leakages occurring with different exhaust nozzle diameters and allowed easy changes in the distance between leakage source and hydrophones. In terms of allowing those sea measurements at several distances, the solution proposed was to use two separate boats, one containing the controlled gas release equipment and another for the hydrophones and data acquisition equipment. Our experimental set-up was built based on the work of (Longuet-Higgins, Kerman, & Lunde, 1991). The main reasons were the availability of compressed air infrastructure at the laboratory, achieving gas flows that form bubble plumes and our needs to also reproduce the experiments at sea. At this last case, the usage of diving breathing air cylinders is a widely available option.

At the moment, our experimental set-up is capable of producing leakages with pressures between 0,1 and 1 MPa (1 to 10 bar) and flows ranging from 1,67 10^{-8} to 16,67 10^{-5} m³/s (10^{-3} L/min to 10 L/min). For the flow control unit assembly, regular industrial compressed air parts, such as pressure and flow regulators and 8 mm external diameter PU hose, were used. Another important feature is the possibility to rapidly change the exhaust nozzle's inner diameter by simply connecting different fittings, as reducers and nipples. The inner diameters that are available for use are 2.5, 4.0, 6.0, 8.0 and 11.0 mm, allowing us to produce bubble plumes that have different flow geometries while maintaining the same volumetric flow. The sketch of our experimental set-up flow control unit (FCU) is shown in Figure 2

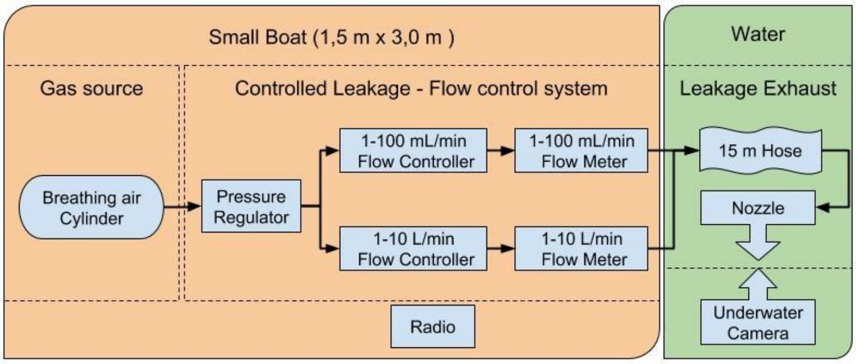

Figure 2 – Sketch of the Flow Control Unit (FCU).

Regarding the signal acquisition, hydrophones with a flat response between 20 Hz and 20 kHz were plugged to a TASCAM US-800 audio interface connected to a notebook via USB. This equipment is capable of recording up to 96 kHz sampling frequency in 32-bit WAV format using Reaper Digital Audio Workstation. The data acquisition set-up was calibrated at the laboratory in order to obtain the transfer functions for the conversion of the values in the .wav files to sound pressure values in Pascal. Figure 3 shows a sketch of our data acquisition hardware. It is important to notice that, according to the expression proposed by (Minnaert, 1933) our data acquisition equipment will be able to record the signals emitted by bubbles with radii between 0.1 mm and 100 mm.

4. PRELIMINARY EXPERIMENT – WHAT WAS RECORDED AND HOW IT WAS RECORDED

As mentioned earlier in this article, the final objective of the project is to develop a passive acoustic detection system for underwater gaseous leakages. In order to achieve it, our first action was obtaining the signals emitted by bubble plumes in controlled leakage conditions, meaning that the flow rates, water depth, gas pressures, and nozzle geometric configuration were well known. To obtain those leakage audio signals, we assembled the equipment, performed preliminary equipment tests at the laboratory and then proceeded to evaluate the signals from bubble plume formation in preliminary sea experiments.

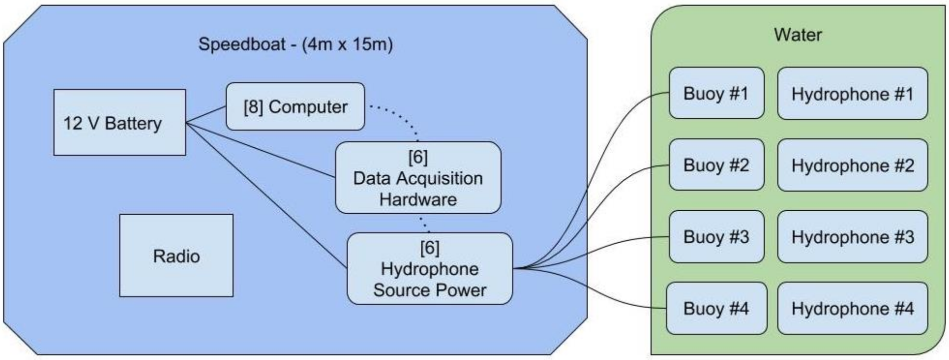

Figure 3 – Sketch of the data acquisition unit used to record the bubble plume signals.

On this first sea experiment, the focus was on setting the experimental apparatus, determining the best way to ensure the flow parameters, and observe the influence of the oceanic ambient noise on the recorded signal. On the side of assurance of the flow conditions, the parameters that are determined and observed are the gas inlet pressure, tubing, and nozzle internal diameters, nozzle depth and volumetric flow rates. On this first experiment, the only flow parameter that we varied was the volumetric flow rate. The signals recorded were for leakages with volumetric flow rates of 1.67, 3.33 and 16.67 10^{-5} m³/s (2, 5 and 10 L/min). As exposed by (Bergès, Leighton, & White, 2015), another important parameter is the tidal height. The external pressure that the gas leakage will oppose as it leaves the nozzle is a function of the water depths and will vary with tidal height. The values for all those parameters are shown in Table 2.

Table 2 – Adopted parameters/conditions for the experiment

Flow parameters					
Inlet Pressure [bar]	Nozzle Depth [m]	Nozzle Diameter [mm]		Hydrophone Depth [m]	Array Geometry
10	8	Outer: 16 / Inner: 11		6	3.7 by 5.7 Triangle
Variables					
Volumetric Flow [L/min]	0		2	5	10
Distances [m]	3		26	50	100
Oceanographic Conditions		Data acquisition parameters			
Tide Height	Water Depth	Number of Hydrophones	TASCAM Gains		Sampling Frequency
~ 0.5 m	~10 m	3	180 º / 270 º / 300 º		48 kHz

As we also needed to evaluate changes in the signal's energy related to the distance between nozzle and hydrophones, we recorded signals not only at constant distances but also the with the leakage source moving closer or apart from the hydrophones, therefore, making it possible to verify at which distance the signals were no longer perceivable. Table 3 summarizes the flow and movement conditions of each of the recordings done at Santos Bay

Table 3 Summary of the audio signals recorded on 28 of January 2019 at Santos Bay and respective figures

Audio Scenario	Time of recording	Distance [m]	Flow Rate [10^{-5} m³/s (L/min)]	Dinghy movement
#1	09h39min	3-100	16.67 (10)	Departing
#2	10h03min	100-3	16.67 (10)	Approaching
#3	10h19min	3-6	16.67 (10)	Anchored
#4	10h24min	3-6	3.33 (2)	Anchored
#5	10h27min	3-6	8.67 (5)	Anchored
#6	10h31min	3-100	8.67 (5)	Departing
#7	10h55min	100-26	8.67 (5)	Approaching
#8	11h03min	3-100	3.33 (2)	Departing
#9	11h26min	100-5	3.33 (2)	Approaching

5. DISCUSSION ON PRELIMINARY EXPERIMENT RECORDED DATA AND ITS ANALYSIS

The analyses of the recorded signals were done in the time and frequency domains. The first and simplest evaluation was to check if the signals' Sound Pressure Level (SPL) changed in the presence of the leakage. Using the signal in the time domain, we calculated the overall SPLs for 125 ms time windows, without any overlaps. The analysis showed that with the overall SPL it wasn't possible to observe changes in energy of the signal even in the recordings of leakages near the hydrophone. Therefore, overall SPL wasn't a good indicator of the presence of the leakages.

Our first attempt to overcome this issue was to perform frequency domain analysis and observe any changes in the spectral content in the presence of gas leakage. For this purpose, the signals were analyzed in terms of Short-Time Fourier Transforms (STFT) using 125 ms windows without any overlap, and then these STFTs were plotted as spectrograms. The results showed spectral changes at frequencies between 100-500 Hz in the presence of controlled leakages. In order to quantify the differences between each of the leakage flows, we used the STFTs to calculate the SPL on the bubble emission frequency band. In possession of these SPLs, a statistical analysis was done grouping 3 seconds of SPLs, mean SPLs and Standard deviations were calculated on these clusters.

For the 2 L/min recording, the leakage started around 45 seconds of recording. We observe changes in mean SPL in the order of 2 dB and a minor change in standard deviation. On the other hand, changes in spectral content are not very easily observed. Figure 4 shows the statistical analysis and the spectrogram of signal #4, recorded on hydrophone #3. At the 5 L/min recording, the leakage started around 25 seconds of recording. We observe changes in mean SPL in the order of 5 dB, and the standard deviation lowered to around 3 dB. Figure 5 shows both the statistical analysis and the spectrogram of signal #5, recorded on hydrophone #3. For the 10 L/min recording, the leakage started around 110 seconds of recording. We observe changes in mean SPL in the order of 8 dB, and the standard deviation lowered to about 2 dB. Figure 6 shows both the statistical analysis and the spectrogram of signal #3, recorded on hydrophone #3.

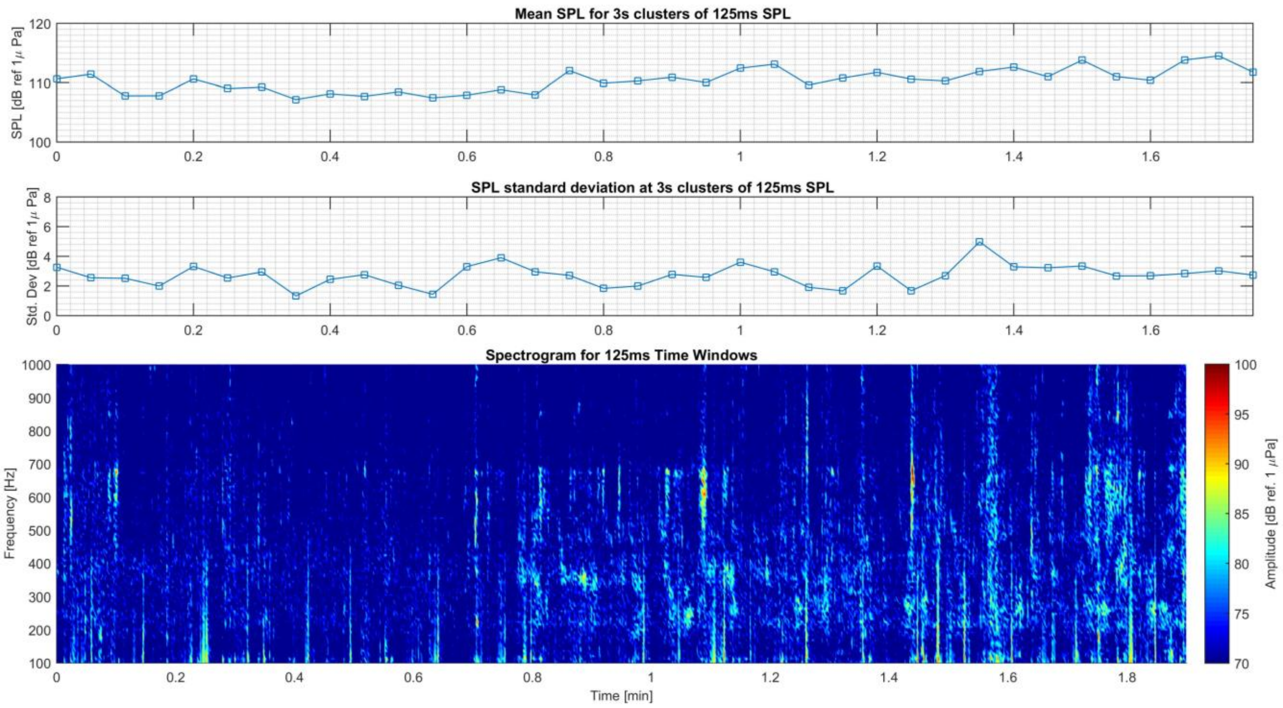

Figure 4 – Statistical analysis of 3-second clusters containing 24 SPL, 3.33×10^{-5} m³/s (2 L/min) flow rate. Mean values for SPL (top), standard deviations (mid) and spectrograms for frequencies between 100-1000 Hz (bottom).

In order to easily analyze the differences between those three leakage scenarios, we plot in Figure 7, mean SPL, standard deviations and calculated mean spectrum for the three recordings altogether. As can be observed in the figure, the statistical analysis of the 100-500 Hz band filtered SPL is capable of indicating the presence of leakages. During the presence of leakages, changes are seen both in mean value and standard deviation. In the presence of a leakage, the mean SPL augments whereas the standard deviation diminishes.

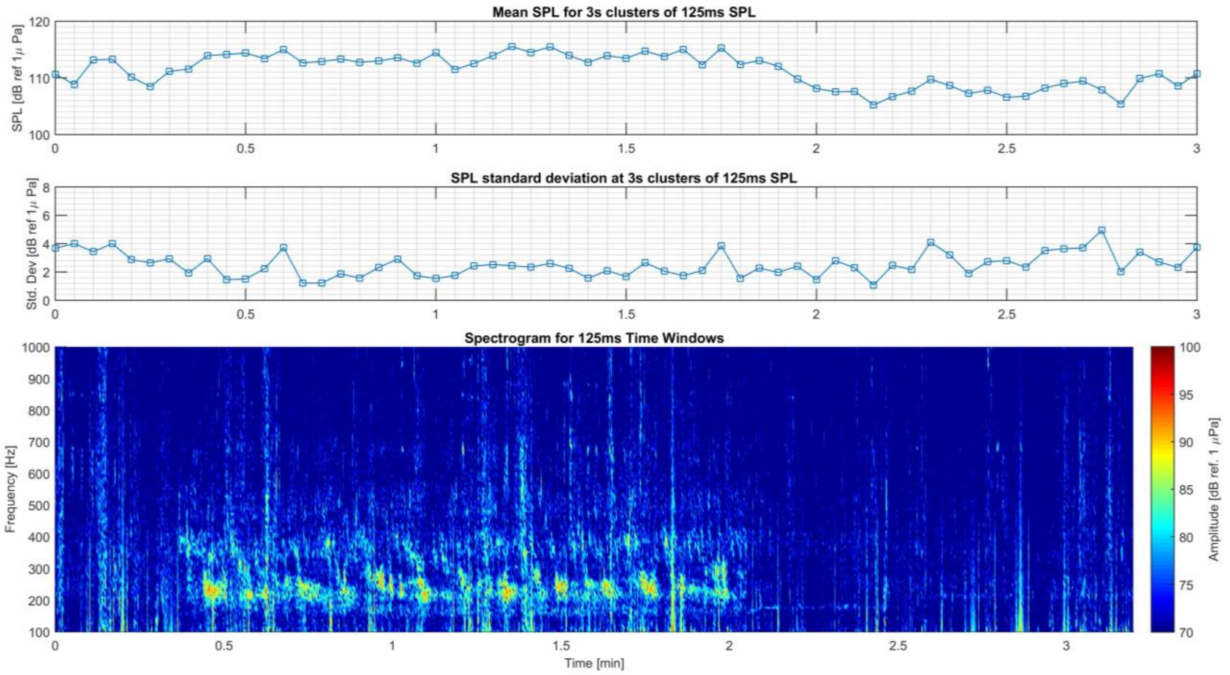

Figure 5 – Statistical analysis of 3-second clusters containing 24 SPL, $8.33*10^{-5}$ m³/s (5 L/min) flow rate. Mean values for SPL (top), standard deviations (mid) and spectrograms for frequencies between 100-1000 Hz (bottom).

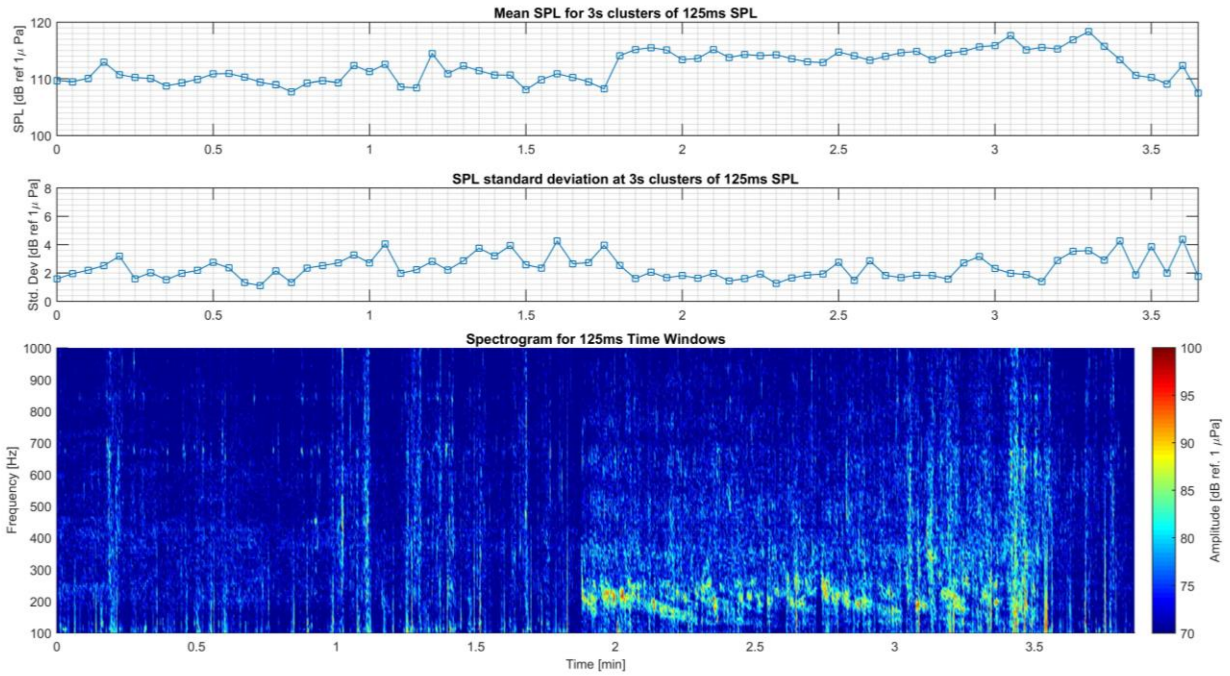

Figure 6 – Statistical analysis of 3-second clusters containing 24 SPL, $16.67*10^{-5}$ m³/s (10 L/min) flow rate. Mean values for SPL (top), standard deviations (mid) and spectrograms for frequencies between 100-1000 Hz (bottom).

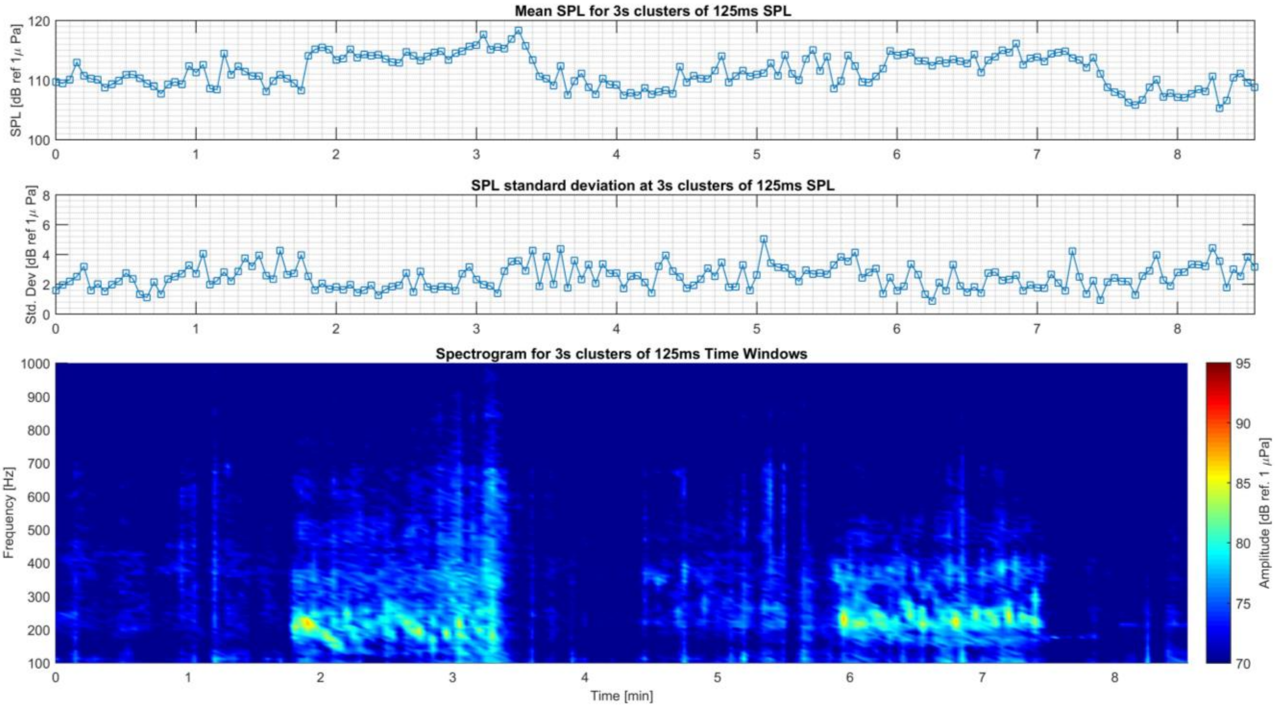

Figure 7 – Analysis for the three leakages, 10L/min leakage near minutes 2 and 3, 2L/min around 6 and 7 minutes, 5L/min leakage nearby 8 and 9 minutes.

Calculating mean and standard deviation values for each of the scenarios lead us to the values shown in Table 4. It can be seen that the 10 L/min leakage produced 111.3 dB band-filtered SPL at the hydrophone, the 5 L/min leakages produced a slightly lower SPL, 110.9 dB, and the 02 L/min leakage produced 107.5 dB. All those levels are above the 106.1 dB obtained for the periods without any leakage. Figure 8 summarizes the SPL mean values for the no leakage scenario and for the three leakage scenarios.

Table 4 – SPL means and standard deviation for each of the noise and leakage scenarios.

Scenario		Volumetric Flow rate [L/min]	Time		Sound Pressure Level [dB]	
ID	Condition		Starting Time	End Time	Mean Value	Standard Deviation
#3a	Noise	N/A	00min00s	01min48s	106.3	2.9
#3b	Leakage#1	10	01min48s	03min24s	111.3	2.6
#3c & #4a	Noise	N/A	03min24s	05min27s	105.0	3.1
#4b	Leakage#2	2	05min27s	07min06s	107.5	3.0
#4c & #5a	Noise	N/A	07min06s	07min48s	108.3	3.3
#5b	Leakage#3	5	07min48s	09min21s	110.9	2.3
#5c	Noise	N/A	09min21s	11min03s	104.7	3.0
Overall Noise		N/A	-	-	106.1	3.1

As seen in all cases, the SPLs observed during the occurrence of the leakages are consistently higher and the standard deviation of the levels are lower than the ones observed whenever there is only noise on the signal. Those results show that band-filtered SPL could be used as indicators to the occurrence of gaseous leakages in the aquatic environment. According to several of the articles already cited, the band of bubble occurrence is quite narrow, and therefore, the use of those band-filtered levels could lead to a good indication of the presence of the leakage, nevertheless, as there is no information about what caused the changes in SPL there is a need for some other signal processing techniques that could confirm that the type of signal observed is really related to gaseous bubble formation.

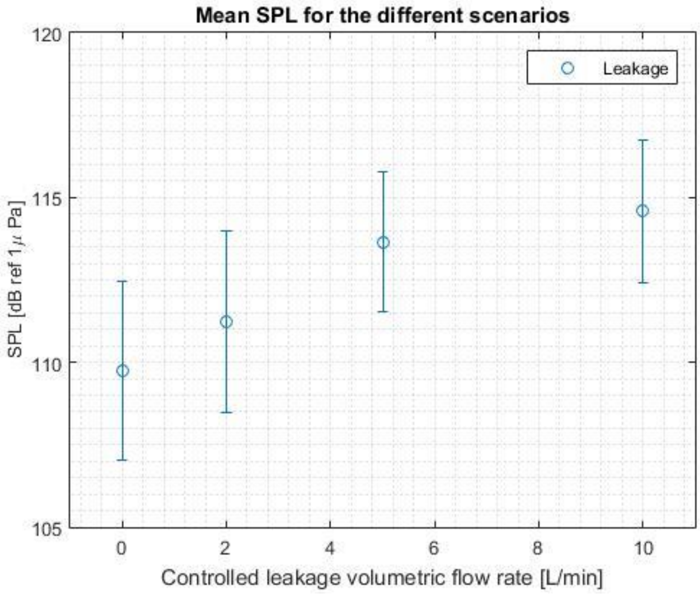

Figure 8 – Summary of the SPL mean (circle) and standard deviations (upper and lower limits) for the no leakage and leakage scenarios.

6. CONCLUSION

The experimental set-up proposed was successfully used both at the laboratory and in the open sea experiments, as both the data acquisition system and flow control unit worked as expected. Therefore, we were able to record the audio signals from bubble plumes in different scenarios. Our experimental set-up was capable of simulating underwater leakages with the controlled release of gas from single bubbles flows up to rates as high as $16.67\ 10^{-5}$ m³/s (10 L/min). The other experimental parameters that we are able to easily vary are the nozzle's inner diameters, the distance between hydrophones and leakage source, including also their positions relative to sea level.

Unfortunately, as expected for a preliminary experimental campaign, some minor details that could be improved were observed. The most easily identified problem was that, as the data acquisition system was placed in the main boat, a major influence of the boat-related noise was found in our recordings and several boat-water interaction events could be heard. Fortunately, these events are not in the frequency range excited by bubble plume formation at the conditions chosen for the experiment. Another problem found was that the correlation among noise greatly decreased our capability to correctly determine the presence of the bubble plume signal, i.e the passage of a ship produced similarities in the spectrums of different leakage and no-leakage scenarios. Therefore, performing the same leakage scenario with a time span that leads to different ambient noise sources in the signal is recommended. This would deteriorate the correlations not related to the leakage signal and augment the similarities exclusively related to the leakage signal.

The results shown in this article are for a single outlet with 11 mm inner diameter. The three flow rates used on the experiment were two, five and ten liters per minute and the distance between hydrophones and leakage source varied between three and one hundred meters. The acquired audio signals were analyzed in the time and frequency domains. The sound pressure spectrograms were obtained using short-time Fourier transforms. Therefore, changes in spectral content were observable during the occurrence of controlled leakages for some of the analyzed scenarios. Using these STFTs to compute the Sound Pressure Levels in the 100-500 Hz frequency band allowed us to readily observe rises in SPL means and decrease in SPL standard deviation that is closely related to the presence of leakages. Therefore, indicating that the filtered SPL could be used as a simple metric for leakage detection.

7. ACKNOWLEDGMENTS

The authors would like to thank Alexandra Chung, Paulo Hubert, Claudio Poggetto, and Orion Diver for their help during the experimental campaign at Baia de Santos and gratefully acknowledge the University of São Paulo and support from SHELL Brazil (subsidiary company of Royal Dutch Shell) and FAPESP, through the Research Centre for Gas Innovation (RCGI) hosted by the University of São Paulo (FAPESP Grant Proc. 2014/50279-4). We would also like to thank FAPESP and CNPq for their support, by grants number FAPESP 2016/02175-0 and CNPq 303992/2017-4.

8. RESPONSIBILITY NOTICE

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