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ACOUSTIC DETECTION OF SEABED GAS LEAKS, WITH APPLICATION TO CARBON CAPTURE AND STORAGE (CCS), AND LEAK PREVENTION FOR THE OIL AND GAS INDUSTRY: PRELIMINARY ASSESSMENT OF USE OF ACTIVE AND PASSIVE ACOUSTIC INVERSION FOR THE QUANTIFICATION OF UNDERWATER GAS RELEASES

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1 INTRODUCTION

The acoustic remote sensing of subsea gas leakage is becoming increasingly important. This includes the monitoring of underwater discharges from human related and natural sources, for the following reasons. First, as the oil and gas industry faces increasing regulation from authorities, there is a need to put more control in the industrial process and to assess the impact of activities on the marine environment [1]. The applications are diverse, including: early warnings of “blow-out” from offshore installations, detection of leaks from underwater gas pipelines, gas leakage detection from Carbon and Capture and Storage facilities (a process aimed at mitigating the release of large quantities of CO_2 in the atmosphere), and seabed monitoring (for the stability of civil engineering project and prediction of underwater landslip) [1,2]. Second, this technology has a role to play in oceanography for a better understanding of natural occurrences of gas release from the seafloor such as gas seepage or mud volcanoes. This is of major importance for the assessment of the exchange of gas between the ocean and the atmosphere with application to global warming. All those phenomena involved the formation and release of bubbles of different sizes (from tiny bubble streams to large bubble clouds). These can be detected acoustically (using passive and active acoustic techniques) because they are strong sources and scatterers of sound [3,4].

This paper reports progress to date on an ongoing two-phase study. This project is aimed at assessing the accuracy of active and passive acoustic techniques for the quantification of gas releases with application to methane seepage and gas leaks from pipelines.

First, water tank experiments consisting of the release of clouds of bubbles were undertaken in order to estimate acoustically the bubble generation rates and correlate the results with independent measurement of flow rates. The acoustic emissions are monitored using calibrated hydrophones and post processed signals are used to infer the bubble populations using the model derived by Leighton and White [5]. The results are compared to assess the application and the accuracy of the technique.

Second, a multifrequency inversion model of single beam echosounder data from bubbles is proposed. This model is applied to EK60 data collected during the JCR253 scientific cruise [6] that observed bubble plumes formed from methane seepage venting from the seabed of the West Spitsbergen continental margin.

2 PASSIVE ACOUSTIC INVERSION

2.1 Procedure

Measurements of passive acoustic emissions of bubble clouds were conducted in an 8 m x 8 m x 5 m deep test tank containing fresh water at 10°C. The bubble generation system used consisted on an arrangement of needles in circle on a plate. The spacing between them was approximately 3 cm and the size of each nozzle was 1.2 mm. A nitrogen gas cylinder was used to produce the gas for generating the bubbles. The output of the bottle was connected to a mass flow meter (Bronkhorst in-flow series, model F-111BI) adjusting the gas flow. The measurements of gas flow were recorded via a data acquisition system (DAQ). The bubble generation system was then connected to the end of the gas line and deployed at the bottom of the test tank.

For the acquisition of the acoustic signals, a calibrated T8105 B&K hydrophone was placed at a range of 5 meters from the base of the bubble cloud. This was connected to a B&K T2635 charge amplifier and a data acquisition unit.

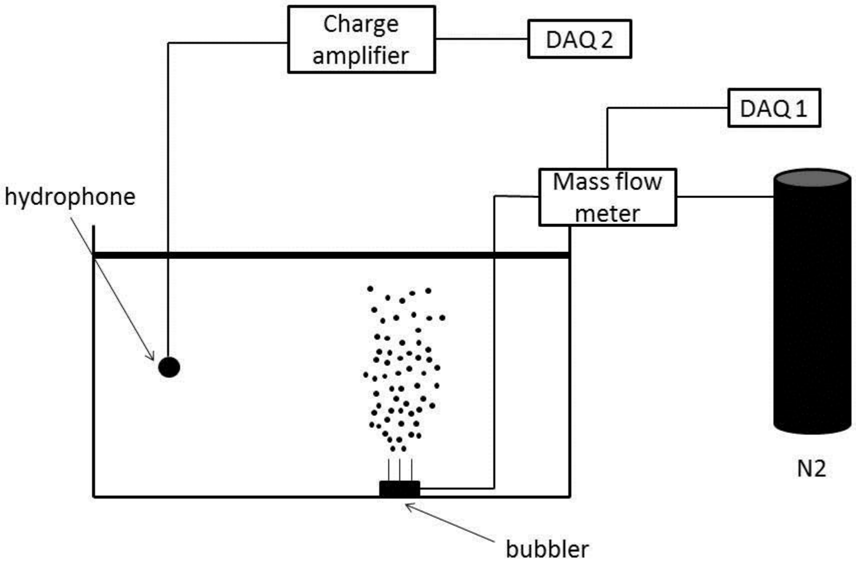


Figure 1: schematic of the experimental apparatus. Bubbles were released using a nitrogen gas bottle and a bubbling system composed of six needles. The acoustic emissions were recording using a calibrated hydrophone and the flow rate was acquired using a mass flow meter connected to independent acquisition units.

The recorded signals were bandpass filtered and corrected to account for the reverberation of the enclosure. This correction is based on the theory by Cochard et al. [7] that expresses the emission in free field from given measurements in a reverberant environment. For this experiment, the volume of the test tank is $V = 200\ \mathrm{m}^3$ and the reverberation time is $T_{60} = 192\ \mathrm{ms}$.

From the data collected by the hydrophone, the bubble size distributions are determined using the model by Leighton and White [5]. The power spectral density $S(\omega)$ of the signal can be expressed as:

$$S(\omega) = \int_0^{+\infty} D(R_0)|X_b(\omega, R_0)|^2 dR_0, \tag{1}$$

with $|X_b(\omega, R_0)|^2$ denoting the squared magnitude of the Fourier transform of the response of a single bubble of radius R_0. The quantity $D(R_0)$ is the bubble-emission size distribution as a function of R_0, defined such that $\int_{R_1}^{R_2} D(R_0)dR_0$ represents the number of bubbles generated per second with a radius in the range (R_1, R_2).

This problem can be solved numerically as the equation defines a Fredholm integral of the first kind that can be discretized [5]. The determination of the bubble distributions consists on solving the inverse problem expressed in matrix form as:

$$\boldsymbol{D} = \boldsymbol{X_b}^{-1}\,\boldsymbol{S} \tag{2}$$

The number of radius bins is chosen to be equal to the number of frequency bins in order to build a square problem. However, the problem remains ill-posed which means that the inevitable measurement errors in $S(\omega)$ are magnified. Tikhonov regularisation is applied in order to achieve a positive and stable solution for $D(R_0)$. Assuming spherical bubbles, the flow rate is calculated as follows:

$$F_g = \frac{4\,\pi}{3}\int_{R_1}^{R_2} D(R_0){R_0}^3 dR_0 \tag{3}$$

This gives the final results that are compared to the independent measures from the mass flow meter (suitable corrections being made for the hydrostatic pressure imparted by the ~5 m of water). The comparison is made for nine flow rate regimes covering more than an order of magnitude in gas flow rate.

2.2 Results

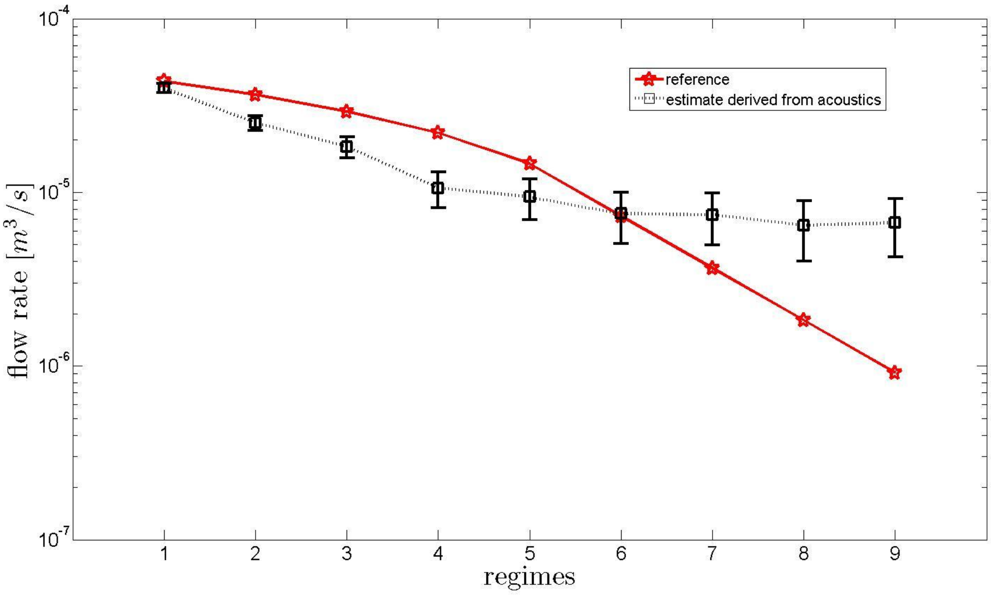


Figure 2: Comparison of different flow rates calculated at different regimes and plotted in a log scale. The values represented by the red curve with stars are the measurements from the mass flow meter. The black dotted line with squares is the flow rates inferred from the acoustic signal

generated by the needles system. The error bars represent the uncertainty resulting from the background noise of the recordings which represents $\mathbf{2.5 \times 10^{-6}\ m^3/s}$ when inverted.

The gas flow rates calculated using the inversion process described in the previous section is compared to measurements from the mass flow meter. The results for the nine regimes are shown in figure 2. Error bars show the uncertainty on the bubble count arising from the background noise. From this plot, it is noticeable that there is a good agreement at the highest flow rates. However, as the gas flux becomes smaller, the background noise contribution becomes increasingly significant compared to the bubble signal and so the difference with the mass flow meter measures becomes greater. The level calculated from the acoustic signals stabilizes when the flow rate becomes low (regimes 6-9) where the measurements are dominated by noise.

The model studied in this paper aim to quantify gas fluxes for large gas release events. However, for small events as observed by Leifer and Tang [8], presenting low flow rate, the model might not be appropriate because when individual bubble signatures can be identified, the time between these signatures contains just noise and as these intervals become longer, noise increasingly contributes to the spectrum. Identification of bubble generate rates in the natural world dates from the 1980s, and has been applied to waterfalls [9], ocean wave breaking [10], and rainfall over the ocean [11,12] and, more recently, explored to examine to bubble emissions from seeps [8, 13,14]. A combination of the two techniques possibly offers a good cover of flow rate ranges.

3 ACTIVE ACOUSTIC INVERSION

During JR253 cruise on August 2011 to the West Spitsbergen region, areas that exhibited strong methane venting during JR211 cruise [15] were investigated. In addition new gas plumes have been discovered in shallow depth regions (range of 80-100 m). The acoustic surveys were conducted using an EK60 single beam multifrequency echosounder scanning at three frequencies: 38 kHz, 120 kHz and 200 kHz. As the EK60 is a calibrated system, scattering cross-section per unit volume $\boldsymbol{S_v}$ could be calculated from the raw data and an example is show in figure 3. The echograms at three frequencies are presented and strong bubble plumes escaping from the seafloor can be observed at 5 minutes time. In this study, those echo levels are used to infer bubble abundances using an inversion technique based on the study by Vagle and Farmer [16], similar to methods used in fisheries acoustics for the calculation of fish densities [17].

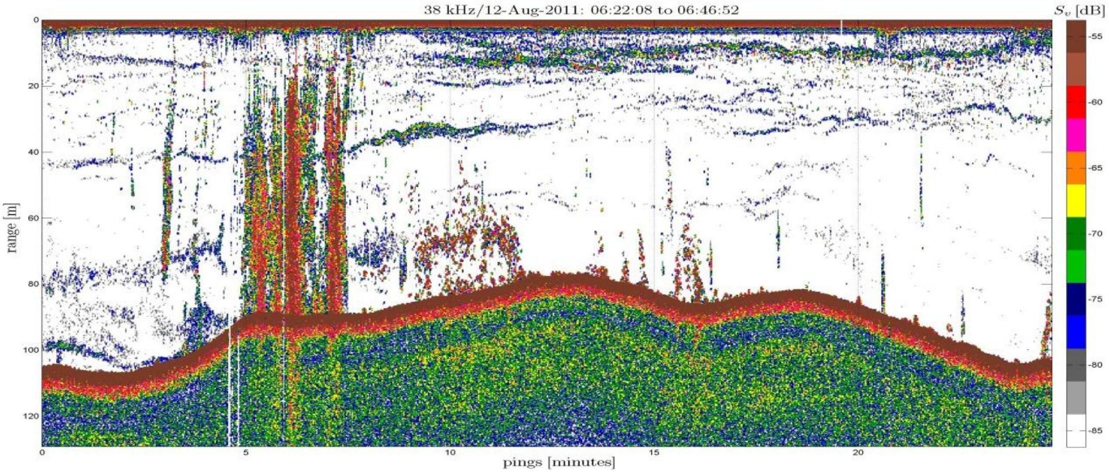
Depending on the frequency, a gas bubble is responding differently to an acoustic field. More specifically, the scattering behaviour of an object can be described by it scattering cross section σ_s. In the specific case of a spherical gas bubble, the theory was recently reviewed by Ainslie and Leighton [18] and is used for the calculation of σ_s in this study. The difference of echo level at different frequencies is directly related to the density of bubbles of different sizes and is used to calculate bubble abundances. At a frequency f_i, the backscattering volume expressed as inverse meter (m^{-1}) is related to the bubble distribution as followed:

$$S_v{}^{f_i} = \int_0^{+\infty} \sigma_s(f_i, R_0)\, n(R_0) dR_0 \qquad (4)$$

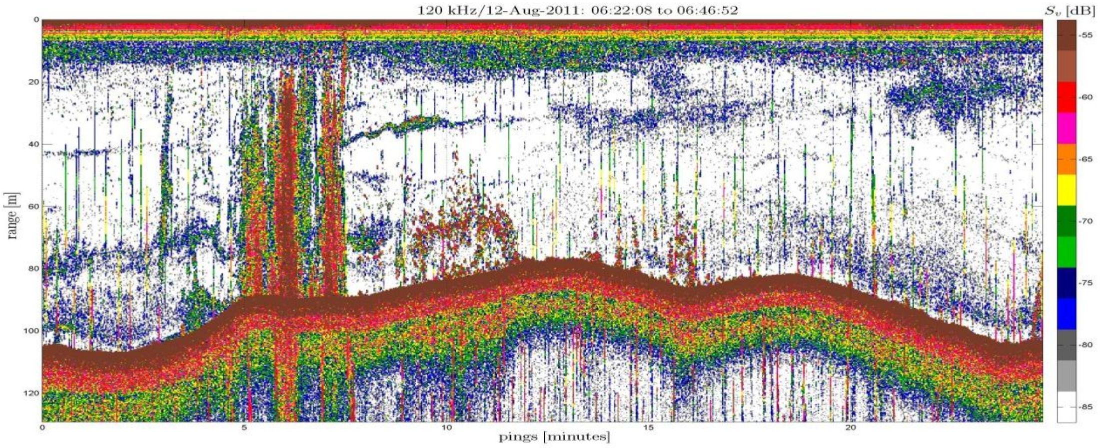
with $n(R_0)$ the bubble size distribution expressed in number of bubbles per cubic meters. This equation defines a Fredholm integral of the first kind that can be discretized. The determination of $n(R_0)$ consists on solving the following inverse problem expressed in matrix form:

$$\boldsymbol{n} = \boldsymbol{\sigma_s}^{-1}\, \boldsymbol{S_v} \qquad (5)$$

Using the data collected by the EK60, inversion is performed using backscattering volume levels from the bubble plumes at different frequencies from data set as presented in figure 3. The number of radius bins is chosen to be equal to the number of frequency bins in order to build a square problem. This problem also tends to be ill-posed because of inevitable errors in S_v and Tikhonov regularization is applied to control the growth of errors. The result of using such an approach will be a bubble size distribution based on the bubble in three frequency bins only, as the EK60 system gives echo levels at 38 kHz, 120 kHz and 200 kHz. Algorithms such as the one described by Lebourges-Dhaussy [19] that is used for zooplankton classification seem to be well suited for solving the problem stated in this study with increased number of radius bins while having a low number of frequency bins.



a)



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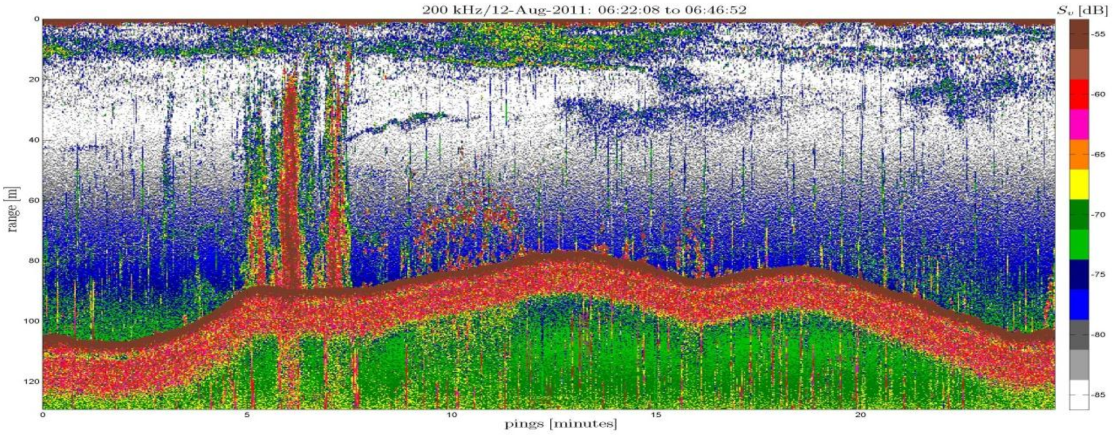

c)

Figure 3: this figure shows echograms from data collected during JCR253 scientific cruise using the EK60 single beam multifrequency echosounder. From the top to the bottom, the frequencies are a) 38 kHz, b) 120 kHz, c) 200 kHz. The scattering cross-sections per unit volume $\boldsymbol{S_v}$ are plotted versus time (minutes) and depth (meter). Strong bubble plumes can be observed, starting at 5 minutes time.

4 CONCLUSION

Active and passive acoustic measurements were performed and presented in this paper. First, the accuracy of a passive acoustic inversion model for the quantification of high flow rate gas leaks proposed by Leighton and White [5] was studied. Comparisons were made between measures from a calibrated hydrophone and a mass flow meter. Second, a three point inversion technique is presented with data it can be applied to.

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