NPL National Physical Laboratory

NPL REPORT AC 21

ACOUSTIC MONITORING TECHNIQUES FOR SUBSEA LEAK DETECTION

A REVIEW OF THE LITERATURE

FREYA MALCHER, PAUL WHITE

APRIL 2023

Acoustic monitoring techniques for subsea leak detection
A review of the literature

Freya Malcher
Ultrasound and Underwater Acoustics Group
Medical Marine and Nuclear Department

Paul White
Institute of Sound and Vibration Research
University of Southampton

ISSN 1754-2936

https://doi.org/10.47120/npl.AC21

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by
Dr Srinath Rajagopal, Science Area Leader.

CONTENTS

1 INTRODUCTION

The UK is required to meet net zero greenhouse gas emissions by 2050 [1]. One of the key strategies in the reduction of emissions from one of these gases, carbon dioxide (CO_2), is the use of carbon capture and storage (CCS) [2]. CCS has the potential to provide up to 13% [3], [4] of the global emission reduction required to meet the terms of the Paris agreement [3], [5].

Storage involves the use of geological reservoirs beneath the seabed to store CO_2 created from industrial processes. Depleted hydrocarbon fields, such as those in the North Sea, are ideal for CCS [6]. The storage of CO_2 needs to be reliable in order to ensure that CCS is an effective solution for the reduction of emissions. Therefore, any leakage from storage sites is of primary interest. The failure of a storage site can also be hazardous to human life and the natural environment [2], [3], so regulatory requirements [7]–[9] and guidelines [10] have been put in place to ensure that storage sites are safely managed and cause minimal damage to the marine environment [3], [5], [11], [12].

CO_2 leakage from a CCS site mostly occurs from two types of storage failure [6]. Firstly, from an injection site which could include faulty pipelines, wellheads or injection wells within the sea subsurface. This type of fault can be easily detected as it occurs at known locations close to the seabed. The second type is from seal failure including fractures in cap rocks and 'inadequately secured abandoned wells' [6], [13]. This type is less easily detected as it occurs at greater depth and it can take time to impact the seabed and for gas to escape into the water column [6], [13].

CCS leakage monitoring techniques are required to both localise and quantify a leak, but also need to be cost effective, easy to use and produce results quickly [3]. It is also important to ensure that a leak from a CCS site can be attributed to a single storage site and from other environmental anomalies [3], [14].

There are several methods which can be utilised in the detection, quantification & attribution of CO_2 leaks but this report will focus on acoustic methods, both active and passive. Passive methods involve listening to the sound made by bubbles formed from a leak, see Section 2. Active methods project sound at a leak and listen to the sound reflected back see Section 3. Acoustic methods can be used to detect and quantify leaks utilising the strong acoustic properties of bubbles, which will be discussed in the next section. It should be noted that research on acoustic subsea leak detection from pipelines and from different natural gas leaks (methane) is also of relevance for use in CCS monitoring.

1.1 ACOUSTICS OF BUBBLES

1.1.1 Bubble formation and sound generation

The process of bubble formation through a nozzle into a volume of water [15]–[17] can be used as a simple model to understand the principle of how bubbles are generated from gas pockets in the seabed.

As gas is injected into the water from the nozzle it forms a narrow neck, connecting a larger gas pocket to that leaking out into the water [15]–[17]. This neck stretches and thins, it will eventually break and release a small volume of gas into the water. As the neck breaks a small jet of water is propelled into the bubble, exciting a volume oscillation. It is this oscillation which creates an acoustic signal when the bubble is released. Figure 1 shows images of the bubble during the injection process at corresponding times in the acoustic signature [16].

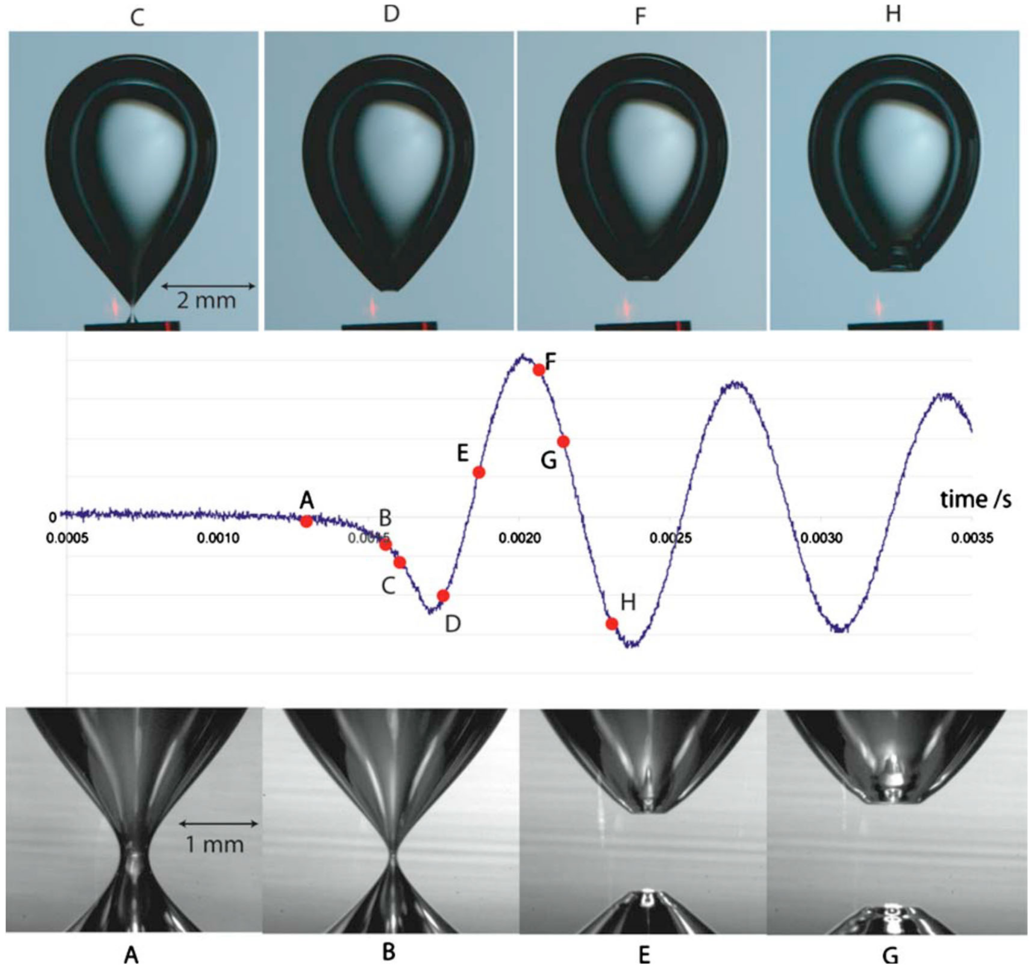


Figure 1 Images of the bubble during the injection process at different times during the acoustic signal [16]. **The jet of water inside the bubble can be seen in image E and F.**

1.1.2 Resonance frequency

Bubbles can pulsate in a variety of ways, but it is the lowest order of volumetric oscillation which changes the gas pressure in the bubble creating an acoustic field [15]. During this oscillation, the bubble acts like a simple harmonic oscillator where the stiffness comes from the internal gas and its inertia from the surrounding fluid which is much denser that the gas in the bubble [15].The bubble pulsations occur at the natural frequency of the bubble, which has been derived by Minnaert [15] using the analogy of a simple harmonic oscillator, to be

$$f_m = \frac{1}{2\pi R_0}\sqrt{\frac{3kp_0}{\rho}}$$

where R_0 is the radius of the bubble at rest, k is the polytropic coefficient, p_0 is the hydrostatic liquid pressure outside the bubble and ρ is the density of the water [15]. For air bubbles in water under atmospheric pressure, this equation reduces approximately to [15]

$$f_m R_0 \approx \ 3m/s.$$

Therefore, the frequency produced from individual bubble acoustic emissions can be used to estimate the size of the bubbles. This principle has been developed for use in passive leak detection [18]–[20] which will be discussed further in Section 2.

The acoustic properties of bubbles can also be exploited once they have been produced, by measuring the scattered acoustic signal from an insonfied bubble (though active acoustic methods).

1.1.3 Cross sections

The acoustic response of a bubble can be described by its acoustic 'cross-section' [15]. Three cross-sections of importance are: the extinction cross section which comes from the loss of energy of an incident wave on the bubble; the absorption cross section which accounts for the sum of the thermal and viscous losses; and lastly the scattering cross section which accounts for the loss of energy scattered by a bubble. The scattering cross section is given by [15], [21]

$$\Omega_b^{scat} = \frac{R_0^2}{\left(\left(\frac{f_0}{f}\right)^2 - 1\right)^2 + \delta^2}$$

where f is the frequency of insonfication and δ is a damping term. The scattering cross section can be converted into a target strength for a bubble with omnidirectional scattering using the equation [21]

$$TS = 10\log_{10}\left(\frac{\Omega_b^{scat}}{A_1}\right)$$

Where A_1 is the unit section (1 m^2). Figure 2 shows how the target strength of four different size bubbles with respect to frequency [21].

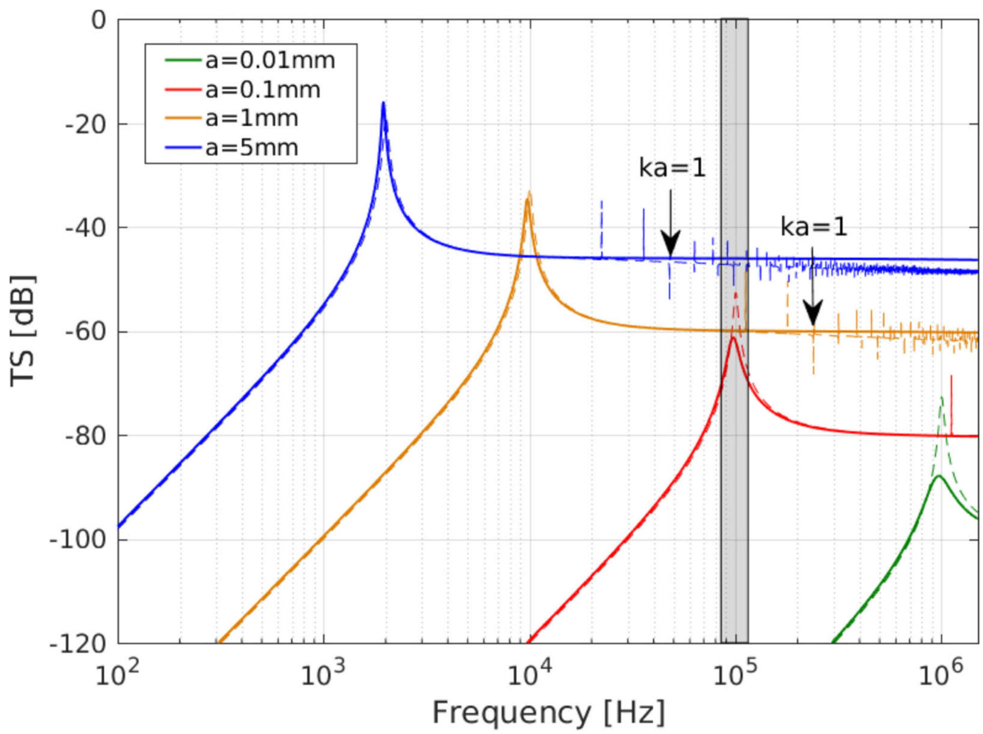


Figure 2 The target strength of single spherical air bubbles in water with respect to frequency [21]. **The solid lines show the target strength calculated using the equations in this section (1.1.3). The dashed lines show a modal series solution valid also for large values of ka. The grey shows the frequency range used by a HISAS sonar** [21].

It can be seen from Figure 2 that bubbles have a high target strength at their resonance frequency. This can be exploited in sonar systems if the operating frequency is within the range of the bubble resonance frequency as a strong reflected signal will be seen. It should be noted that large bubbles which are much greater than resonant size also have a high target strength so may contribute to reflected signal [21].

1.2 PROJECTS USING ACOUSTIC LEAK DETECTION

Various experiments have been undertaken in placing hydrophones to record the acoustic signatures coming from controlled CO_2 release experiments and natural seeps. This section will describe some of the large-scale projects that incorporate acoustic monitoring.

1.2.1 QICS – 2010 to 2014

During the QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage) project undertaken in Ardmucknish Bay Oban in 2012, 4200 kg of CO_2 was injected at an 11 m depth into the sediment over a period of 37 days [22]–[24]. A schematic of the experiment is seen in Figure 3.

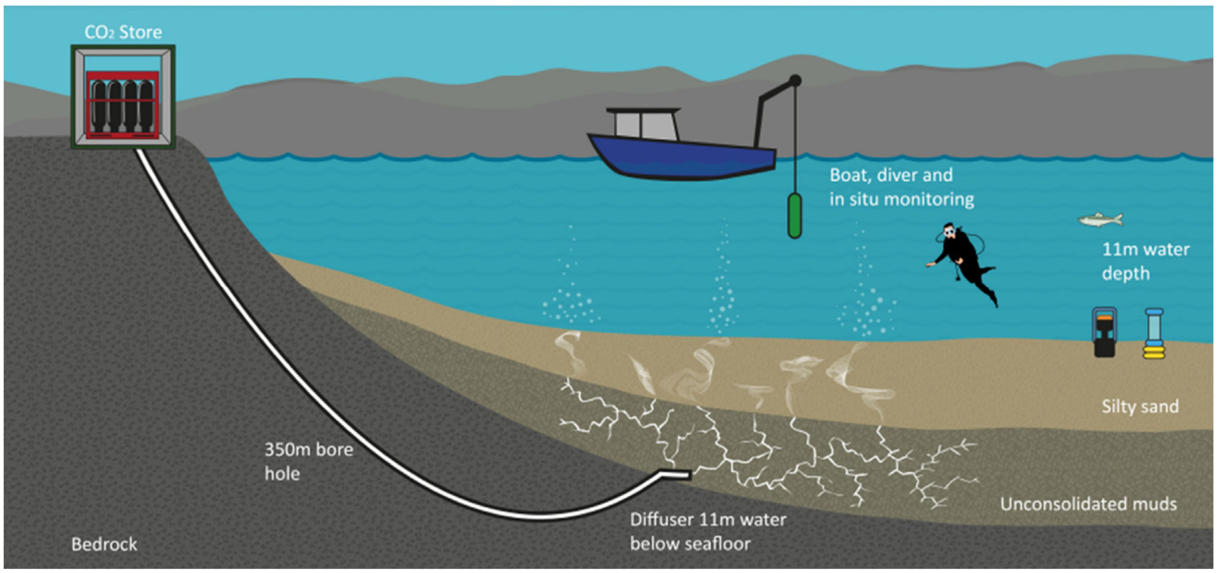


Figure 3 Schematic of the QICS experiment [22].

For passive acoustic monitoring purposes, a SM2M+ recorder was positioned 1 m from the sea floor within the region where the leak was occurring [23]. Data was recorded for 7 days during the gas injection period and for 7 days after to enable a comparison to be made [23]. The passive monitoring results were verified by divers collecting gas samples of visible bubble streams using an inverted funnel.

Active monitoring was undertaken in the form of high resolution 2D seismic reflection surveys using a Geoacoustics GeoChirp & Applied Acoustics Boomer, and multibeam bathymetry data acquired using a Kongsberg EM 2040-07 echosounder [25]. Surveys were taken both prior and during CO_2 release.

1.2.2 ECO_2 – 2011 to 2015

During the ECO_2 project [26], 6 CO_2 storage sites were investigated. Half were natural CO_2 seep and the rest were existing man made sites or potential future sites. The project set out to assess the risks associated with CO_2 storage, the likelihood of leakage and the impact leakage would have on marine ecosystems [26]. Active acoustic methods were assessed during this project (3D seismic surveys, high resolution bathymetry, Sub-bottom profiling multi-beam echo-sounder systems) [26] but encountered normal seedbed conditions [11].

1.2.3 ETI MMV – 2014 to 2018

The ETI MMV (Energy Technologies Institute Measurement, Monitoring and Verification of CO_2 Storage) project was undertaken between 2014-2020 with the aim of developing a marine monitoring system for underwater CCS sites [27]. Controlled release trials were undertaken in Portland Harbour, UK and the North Sea offshore Bridlington, UK [28]. During the trials, side scan sonar and chemical sensors were deployed on an Autonomous Underwater Vehicle (AUV) [28]. Side scan sonar was used to take high quality pictures of leaks. The active sonar lander system was able to detect a 10 l/min leak 110 m from the lander [28]. A passive acoustic array was also designed and tested. Since the project was primarily a commercial endeavour, only a small amount of the work and its results have been published [28].

1.2.4 STEMM-CCS – 2016 to 2020

During the STEMM-CCS (Strategies for Environmental Monitoring of Marine Carbon Capture and Storage) project [29] undertaken between 2016-2020, 675 kg of CO_2, with added tracers, was injected at 3 m depth into the sediment over a period of 12 days near the Goldeneye platform in the North Sea [30]. Bubble seeps were observed to enter the water column in 8 different locations around the injection site [31]. A schematic of the experiment is seen in Figure 4 [30].

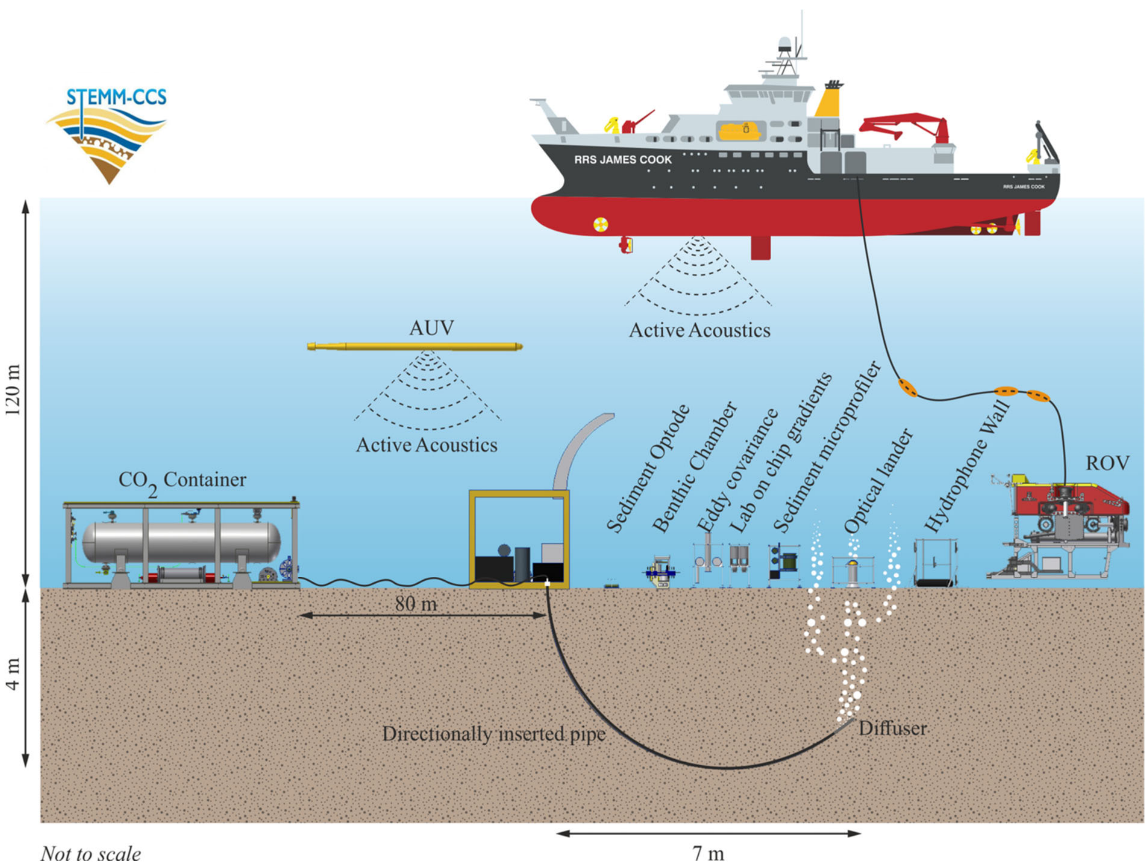


Figure 4 Schematic for the STEMM-CCS experiment [30].

For passive monitoring, an array of 5 calibrated hydrophones were deployed 3.3 m away from the injection site [4], [30]. The hydrophones were linked to an acoustic recorder (RS-ORCA) in order to archive the sound files [30]. Similar to the QICS experiment, gas was sampled using an inverted funnel to verify the passive acoustic results, but used a custom-built sampler operated by an ROV [30]. Additionally, cameras on a seabed lander were used to quantify the bubble flux from a single stream [32].

For active monitoring, gas in the sediment was imaged using high resolution seismic reflection data [4], [6]. Bubbles in the water column were imaged JC180 cruise using a ship-mounted multi-beam Kongsberg EM710 and the single-beam Simrad EK60. The EK60 was a calibrated system and was used to quantify the bubble size and flow rate [30]. A slightly different system was used during monitoring using the RV Poseidon. A Geoswath bathymetric side scan sonar mounted on the AUV was also used. The AUV surveys were taken before, during and after the CO_2 release [30].

2 PASSIVE ACOUSTIC MONITORING

Passive acoustic monitoring involves the use of hydrophones to record the acoustic signal which is generated by a bubble when it is formed. Where a leak is small, individual bubble signatures can be analysed to find the dominant frequency emitted and therefore their size, (see Section 1.1.1) thus determining the size of the leak [18], [20]. Work has also been undertaken to understand how the sediment impacts the acoustic signal emitted from a single bubble [33]. Where the gas flux is higher and the bubble signatures overlap, so that individual bubbles cannot be isolated, the gas flux can be quantified using the source level of the leak [34].

The principle of leak detection using these methods has verified using a number of small scale water tank experiments [18], [23], [33] before being applied to more realistic leaks from the seabed. The next sections will discuss this in more detail, particularly looking at quantification and localisation of the leak.

2.1 LEAK QUANTIFICATION

2.1.1 Using a single hydrophone

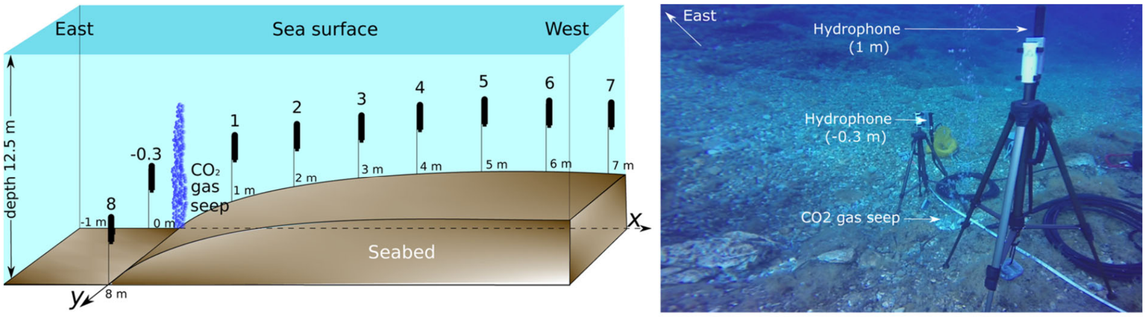
For the QICS project, the gas flux was estimated from the acoustic signature of the leak measured by a single hydrophone [23], but the results were limited by the presence of external noise sources (for example seal scarers and passing boats) [23]. For the portion of the measurements without external noise sources, the gas flux measurement was in agreement with the single measurement taken by divers with an inverted funnel. Additionally, changes in gas release rate were shown to correlate with tidal patterns [23]. As the tide height increases, the level of power spectral density of the leak, the gas flux and bubble size at the seabed changes in the opposite direction [35].

A natural methane seep was monitored for 12 hours as part of the E/V Nautilus expedition (NA072) in 2016 [36]. An estimate of the range of bubble sizes in the seep was calculated but no attempt was made to quantify the gas flux. A transponder was used to estimate the bubble sound levels, which will be discussed in Section 3 [36].

A leak at an abandoned well site in the North Sea (22/4b) was monitored from 2011 to 2012 [37]. A single hydrophone was deployed over a 7-month period near the leak site, 0.65 m above the sea floor. Because of the unknown distance to the leak, the method from [34] could not be used to quantify the leak flux, although comparisons have been drawn between the experimental data analysed using this method [34] to estimate some properties of the leak. This monitoring example highlights the need for the distance between the hydrophone and the leak to be known in order to enable leak quantification. Alternatively, if an array of hydrophones was used then the distance between the leak and the hydrophones could be found, allowing quantification of the gas flux.

2.1.2 Using an array of hydrophones

Leak quantification from a natural seep off the coast of the island of Panarea, Sicily [38] utilised multiple hydrophones. Recordings from two hydrophones were used to measure the acoustic signature, one was kept at 0.3 m (horizontally) away from the seep whilst the position of the other was moved at 1 m increments up to 8 m away from the centre of the seep site, see .Figure 5. This experiment not only enabled the leak to be quantified, but also investigated the range at which a leak could be detected.



(a) (b)

Figure 5 The passive acoustic monitoring set up off the coast of the island of Panarea, Sicily [38]**.**

The leak was successfully detected at ranges up to 8 m but could only be quantified (in terms of gas flux and bubbles size up to 4 m away from the leak. This was because the signal to noise ratio was low. The gas flux was measured directly by divers using the time it took to fill a container of a set size. The gas flux measured using passive acoustic methods was found to be within 10% of the direct measurement [38].

For the experiment conducted as part of STEMM-CCS, an array of 5 calibrated hydrophones was deployed 3.3 m away from the injection site [4], [30]. A large difference in the leak flux estimation between the acoustic and optical methods was found. This was considered to be because the optical method under measures smaller bubbles [31]. Therefore, further comparison would be required to determine the accuracy of measuring the bubbles using passive acoustic methods [31].

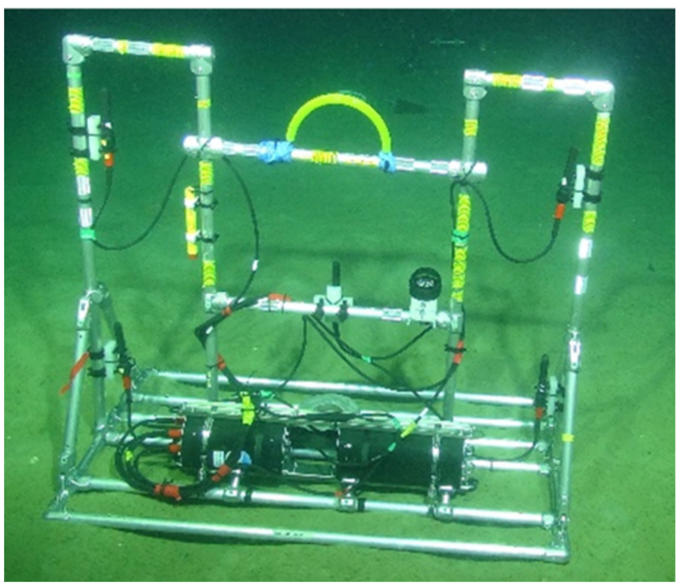


Figure 6 The hydrophone array used for passive acoustic monitoring in the STEMM-CCS experiment [30].

One of the main benefits of using multiple hydrophones in leak quantification is that beamforming techniques can be used to isolate the sound coming from the leak itself and/or subtracting an ambient noise measurement taken prior to the leak occurring [31].

The data from the STEMM-CCS was analysed using the beamforming techniques [32] to enhance the signal to noise ratio (SNR). A Minimum Variance Distortionless Response (MVDR) beamformer algorithm was used. An average SNR improvement of 3 dB was found across the frequencies used, with the best improvement found between 5 kHz to 8 kHz where the bubbles were resonant [32].

Beamforming works well for a single stream of bubbles but becomes difficult when there are multiple seeps close together. This is because the energy from nearby seeps may be detected and misallocated to the seep of interest [31]. This can be accounted for with the use of larger arrays of hydrophones.

2.2 LEAK LOCALISATION

The natural CO_2 seep off the coast of the island of Panarea, Sicily (discussed in the previous section) was used to investigate the effectiveness of passive acoustic localisation [39]. Signals from three hydrophones were used to measure the acoustic signature of the leak. Data processing from these recordings was used to localise the source of the leak with an error within ±0.3m for hydrophones up to 6.67 m away from the leak [39]. It was suggested that this method is most effective for localisation in deep water where the propagation time for the sound reflected from the sea surface is much longer than the direct path to the hydrophone. Other sources of error include the sound speed variation in the seabed and ambient noise level [39].

2.3 SUMMARY

Passive acoustic monitoring techniques can be used successfully to quantify and localise CO_2 leaks where at least two hydrophones are required where the distance between the hydrophone and the leak is unknown. One of the biggest problems in using passive techniques is the low SNR which limits the detection range. This can be improved with the use of multiple hydrophones and beamforming techniques. Subtracting the ambient noise from the signal can also be used if this data is available. Li et al. proposed a noise impact assessment model which can be used to determine if passive acoustics can be used to detect and monitor gas fluxes [40].This could be used to aid in determining whether passive acoustic monitoring could be used in specific monitoring scenarios. Work has also been recently published on the acoustic signature from bubbles released through synthetic sediment, giving greater understanding and improved quantification of gas flux from seeps [41].

3 ACTIVE ACOUSTIC MONITORING

Active monitoring involves projecting sound at a target and analysing the signal reflected back. Bubbles have a high target strength because of the difference in the acoustic impedance between water and gas [12]. This means that they can be picked up easily using active acoustic monitoring systems, both in the water column and the sediment [42]. The operating frequency of an active system can be tuned to the resonance frequency of the bubble to maximise the acoustic response (if the expected bubble resonant frequency is known) [12].

3.1 ACOUSTIC IMAGING OF BUBBLE CLOUDS (SONAR)

3.1.1 Single beam EchoSounder (SBES)

Single beam echosounders emit a single acoustic beam directed downwards onto the seabed. The intensity of the reflected beam from objects within the water column or on the seabed is recorded [43].

Berges *et al.* use data from a calibrated EK60 single beam multi frequency echosounder to calculate the scattering cross section per unit volume [44]. An inversion technique by Vagle and Farmer [45] was used (which is similar to the method for the calculation of fish densities [46]) to infer the bubble population, but no comparison was made to the validity of this method.

During the STEMM-CCS project, hull mounted sonar (EK60 system) was used to observe bubbles in the water column [4], [30]. In a water depth of 120 m and 15 m swath the system could detect bubbles within a spatial footprint of a few meters [4]. This detection may be limited by fast dissolution of bubbles and the tidally modulated reduction in bubble flow [4], [47] due to changing head pressure.

Single beam scanning sonar could be utilised in leak detection [12] where the transducer is moved mechanically to form a 360-degree image of the surroundings. The main benefit of scanning a single beam is two-way side lobe suppression which results in less noise in the image. However, because only one sensor is used, array signal processing is severely constrained and the snapshot is not instantaneous meaning that leakage detection is limited [12].

3.1.2 Split beam EchoSounder

A split beam echosounder (SBES) has multiple, typically 4, receive elements [12] which makes it possible to position a target more accurately [43].

An EK60 scientific SBES which uses split beam technology was used to detect methane seeps located west of Prins Karls Forland offshore NW Svalbard [48]. The data was processed manually to localise the seep. The acoustic backscatter from the seep was used to estimate the bubble flow rate [48] but validation of this method using a direct optical measurement was limited. It is also noted that large bubbles cannot be modelled as spherical, differing from the assumptions made in data processing [48]. A diagram of the measurement set up and corresponding echogram of the seep is shown in Figure 7.

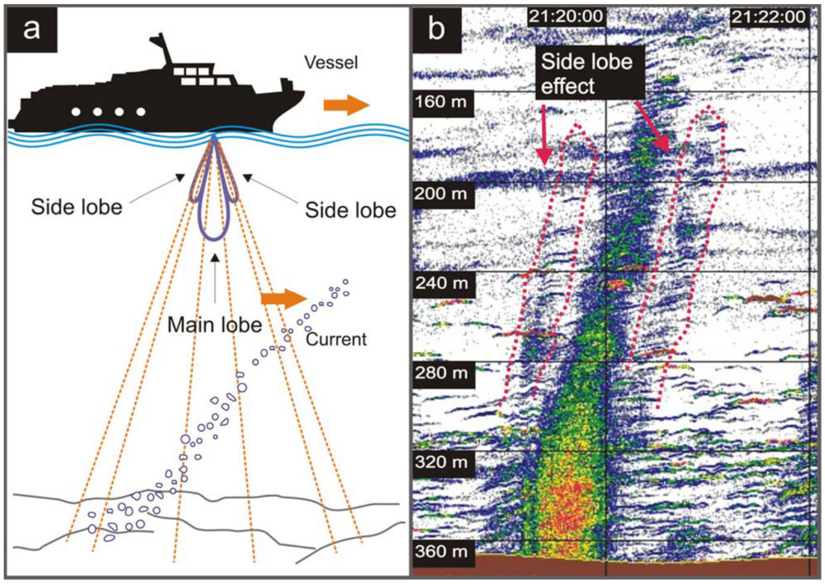


Figure 7 Diagram of the measurement set up and echogram from a split beam echosounder [48]. **Side lobe effects can be seen because of the strong backscattering of the bubbles.**

Leblond *et al.* [49] discuss the different methods of quantifying the gas flux from a leak using the backscattering strength, then makes comparisons to experimental data taken from an artificial leak created in a testing pool using Simrad EK-60 SBES. The devices were calibrated as described by Foote et al. [50]. The flow rate was controlled and the bubble size was measured using optical methods. Good agreement was found between the acoustic and optical data. The most sensitive parameter within the acoustic data processing was found to be the distance of the bubble stream, affecting the volume backscattering strength by up to 20 dB within the range of 0 m to 200 m [49]. This paper is complemented by a second paper extending the work to in situ validation [51].

A SBES operating at fixed frequencies (18 kHz and 38 kHz) was used to examine a methane seep in the northern Gulf of Mexico [52]. Since the data was calibrated using a standard calibration sphere, the gas flux could be estimated [53]. The gas flux was also directly measured by collecting gas samples using a funnel. A 35% increase was found between this and the acoustic data from the SBES [53]. This difference was attributed to the dissolution of methane bubbles in the direct capture measurement and the influence of nearby seeps in the data.

A Bubble OBservatory (BOB) was developed by the French Research Institute for Exploitation of the Sea (IFREMER) and consists of a Simrad ER 60 echosounder and a 120 kHz split-beam transducer [51]. It has a deployment depth range of up to 1500 m and an provide autonomous and continuous data acquisition for up to 3 weeks. A schematic of the system is shown in Figure 8 [51].

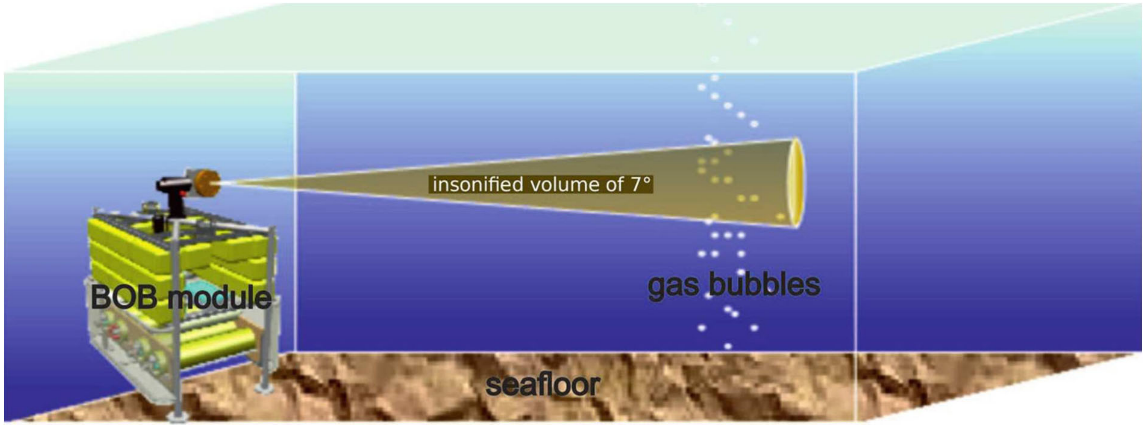


Figure 8 Bubble OBservatory developed by IFREMER. The tilt angle is set to 4 degrees to avoid sea floor reflections and the pan angle is set to 7 degrees [51]. **The beam could be scanned horizontally.**

It was concluded that a single SBES does not have any advantage compared with multibeam systems, although multiple split beam systems could be an efficient solution [51].

3.1.3 Side scan sonar

Side scan sonar systems are often mounted AUVs and used for seafloor imaging [12], [43]. They can cover a large area efficiently, so have potential to be an excellent tool for leak detection. However, because they are used side on, they doesn't necessarily give the typical 'flare' shape (from hull mounted sonar) for a seep, which may prove challenging for seep detection [12].

Interferometric side scan sonar (mounted on an AUV), when combined with array signal processing techniques and an understanding of spatial and acoustic properties of bubbles, has been shown to automatically detect a seep using a single ping [21]. This methodology can be applied to other interferometric side scan sonar systems including synthetic aperture sonar operated in side scan mode.

Interferometric side scan sonar has a single transmitter and two or more receive arrays separated by a vertical baseline see Figure 9 [21].

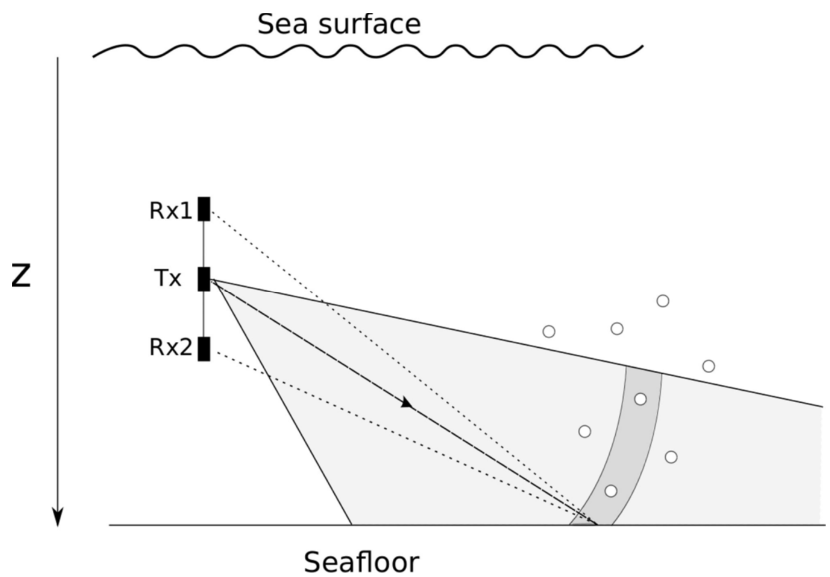


Figure 9 Diagram of the interferometric side scan sonar used by Blomberg *et al.* [21].

The intensity of a side scan image is high in the presence of a gas seep, although this information alone cannot be used definitively as stones, shells or other objects can also give a strong reflection [21]. The interferometric coherence between images formed by the receive arrays and further processing detailed in [21] can be used to verify presence of a leak. This method can improve the detection of a leak compared to conventional side scan sonar, allowing detection some leaks that would have been missed. Although it should be noted that without calibrated sensors the seep still cannot be characterised or quantified [21].

3.1.4 Synthetic Aperture Sonar (SAS)

Synthetic Aperture sonar systems are typically mounted on an AUV, taking advantage of the AUV movement to image the seabed on a centimetre scale [12]. The hardware used is similar to side scan sonar but the image quality is improved through coherently combining multiple pings to form a long receive array [12].

Nadimi *et al.* [54], [55] have proposed a method of computing the acoustic scattering of underwater targets called the ‘Texture Element Method’ (TEM) which can be used in SAS technology [54]. The method can be used to detect leak signals in a single pass and with greater accuracy than traditional sonar systems. Nadimi *et al.* [54] showed that the TEM improves leak detection using simulation but requires validation using experimental data. This method focuses on leak detection from pipes, not through the seabed [54].

3.1.5 Multibeam echo sounders (MBES)

Multibeam echo sounders create a larger overall transmit beam (using beamforming techniques) than single beam system with an imaging swathe of up to 120 degrees which is equivalent to several kilometres range in deep waters [12], [43]. The main limitation is the difficulty of calibration of these systems which makes quantification of gas flux difficult [12].

Acoustic backscatter data was taken both using SBES and MBES during survey operations in the northern Gulf of Mexico in 2011 [53]. The SBES data showed a wider looking seep then the MBES data, which is to be expected because the SBES has a wider beam width (11 degrees) compared to the MBES (1 degree), see Figure 11.

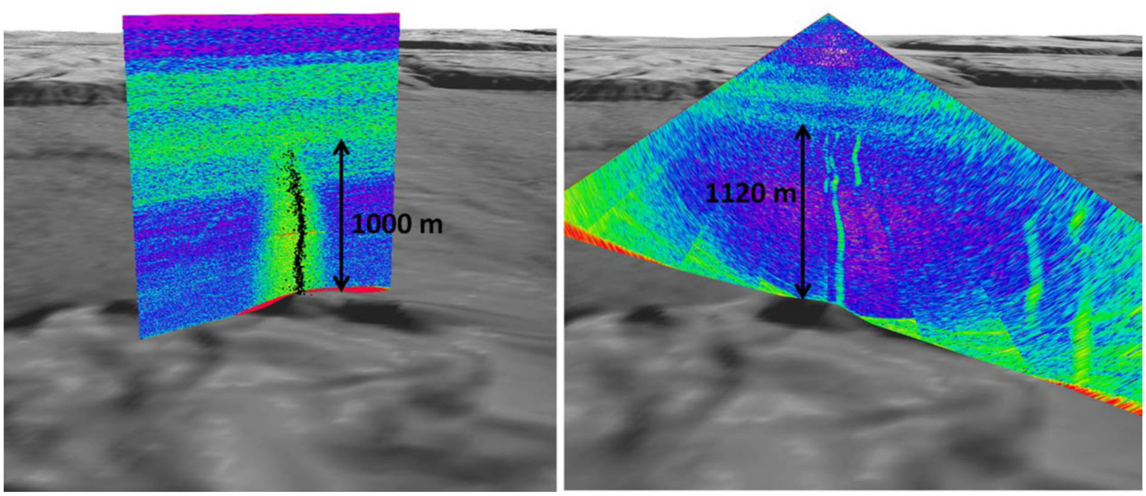


Figure 10 SBES (left) and MBES (right) images taken simultaneously for a methane seep in the Gulf of Mexico [53].

Using split beam technology on the SBES data, the targets were positioned to a similar accuracy to that of the narrow MBES beam [52].

During the QICS project, multibeam bathymetry data were acquired using a Kongsberg EM 2040-07 echosounder [25]. The location of gas seeps and pockmarks can be seen, the height of the steams potentially reflecting the relative gas flux [25], see Figure 11, although no quantitative measure is given.

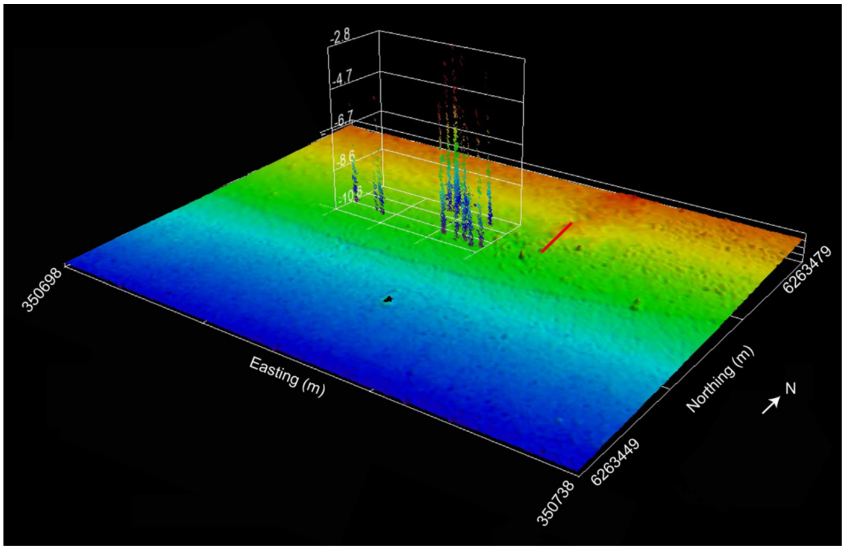


Figure 11 Multibeam bathymetry data taken during day 34 of the QICS project [25]**.**

Gas leaks can be detected in images either manually or using an automatic detection algorithm. An automatic detection method was proposed by Zhao *et al.* [56] to improve the reliability and efficiency of detection in images taken from multibeam echosounder systems. Their method improved detection compared to manual detection methods.

Multibeam data can also be used to identify gas hydrates in shallow sediments [57]. An area located southwest of the Kerch Strait at the Don-Kuban paleo-fan was surveyed using a SIMRAD EM 710 and EM 122 multibeam echosounder to obtain swath bathymetry [57] of the seabed. Higher resolution data was taken with a RESON 7125B multibeam sonar to find the location of areas of high backscatter which were likely to be because of shallow gas hydrates in shallow sediments, which was confirmed by gravity coring in the area.

3.2 SUB-BOTTOM PROFILING (SUBSEA IMAGING)

Seismic reflection data can be used to profile the seabed, showing the migration and development of the CO_2 plumes within the sea sub surface [12]. This type of imaging can be used to visualise the movement of gas though the seabed before it is released into the water column, allowing the evolution of gas migration pathways to be formed. A detailed description of this is given by Roche *et al.* [6].

During the QICS project [25], high resolution 2D seismic reflection surveys were undertaken, see an example in Figure 12. Because of the shallow depth of the water (typically less than 12 m) the frequency range of the system resulted in an improved resolution (tens of cm) compared to typical data taken (few meters) [25]. Two attributes of the seismic reflection data were used to infer variations in the spatial distribution and flux of the CO_2, the acoustic attenuation of near-surface sediments and reflection coefficient of the seabed/subsurface horizons.

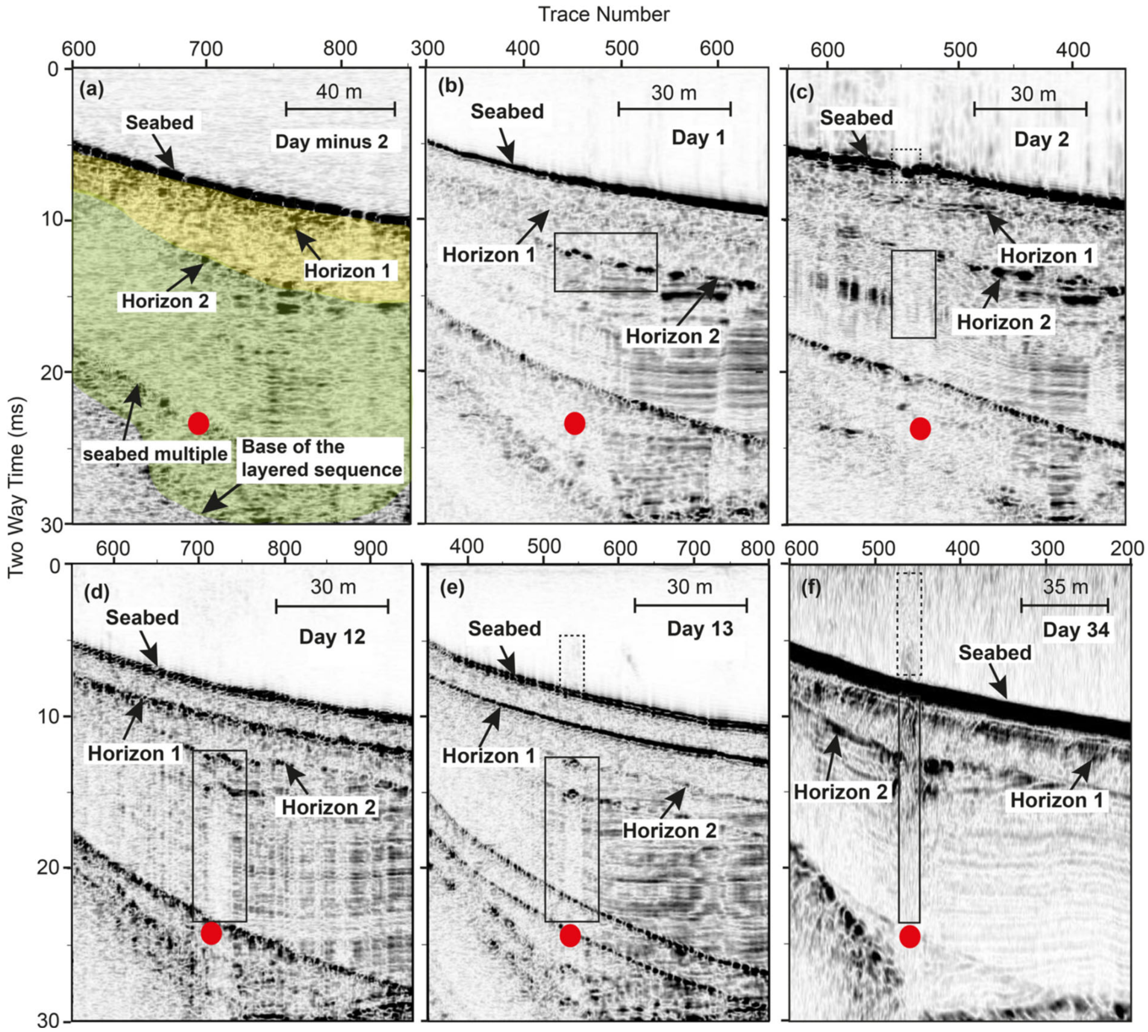


Figure 12 An example of seismic reflection data taken during the QICS project [25].

Data was used to build a picture of the propagation of CO_2 through the sediment and to better understand the impact of CO_2 on the sediment acoustic properties, but further work is required to improve estimates of gas content in the pore space [25].

Closely spaced 2D High resolution seismic reflection data [4], [6] was collected during the STEMM-CCS project using a GAVIA AUV. As well as imaging the seabed, the data could be used to estimate the amount of injected gas which remained in the sediment in gaseous form [6]. For the STEMM-CCS experiment it was estimated that 34 ± 12% of the injected gas remained within the sediment during the testing period [6].

3.3 OCEAN ACOUSTIC TOMOGRAPHY

A network of acoustic transponders could be used to detect gas leaks from the change in sound speed/sound travel time between transponders [58], [59]. However, no further research into the use of this for leak detection for CCUS has been undertaken since its use was proposed for this application by Shitashima *et al.* in 2013 [59]. This is most likely because of the practical challenges in setting up a network of sensors.

3.4 SUMMARY

Several active acoustic methods have been described here that have been shown to be successfully used in leak detection and localisation, both in terms of bubbles in the water column and in the migration of gas in the seabed.

The main limitation with methods to detect leaks in the water column is that it is difficult to quantify the leak. If calibrated, SBES and split beam technologies can overcome this problem, but further work is required to improve the accuracy.

4 NEXT STEPS & KNOWLEDGE GAP

4.1 PASSIVE ACOUSTIC TECHNIQUES

Future work on passive techniques could initially consider the existing uncertainties associated with quantification of leak size. Work needs to be undertaken to understand the acoustic energy associated with the emission of a bubble leaving the sediment to reduce these uncertainties.

Previous research has focused the sound emitted by near-surface bubbles, but the majority of marine CCS sites are at water depths where the assumptions of near-surface model are unlikely to be valid. Work is required to understand how the energy emitted varies with depth. Experiments could be undertaken using NPL's pressurised underwater acoustic chamber to better understand this. A model for the emitted energy from a bubble as a function of bubble radius and pressure could also be developed.

New understanding from this experimentation and modelling would allow datasets from the STEMM-CCS project to be re-evaluated to gain a better estimation of the leak size. Further work could include an investigation of the impact of vessel noise (background noise level) on the detection range of bubbles.

4.2 ACTIVE ACOUSTIC TECHNIQUES

The University of Southampton is developing an active monitoring system powered by a buoy generating energy from wave motion which is linked to the Danish funded Greensands Project. The aim is to gain a large set of baseline data which could be used to develop detection methods for gas leaks and to automatically distinguish them from other scatterers, e.g., schools of fish. NPL could assist with maximising the performance of these systems using data science/machine learning anomaly detection methods.

5 CONCLUSIONS

This report has highlighted the different passive and active acoustic methods that can be used for leak detection of CCS sites.

Passive methods (see Section 2) have been shown to be able to quantify and localise leaks, and can be used for monitoring over long periods of time [31]. Further work is required to minimise the uncertainties around leak quantification and the impact of background noise on detection, which is one of the main limitations.

Active methods are most effective for localisation with some limited capability for quantification of leaks. Further work is required to improve quantification of leaks. Active methods are particularly well suited for gases with low solubility (methane) but less so for high solubility (CO_2) because emerging gas plume is smaller [38].

It has previously been suggested that active acoustic methods would first be used to detect a leakage site which could then be monitored by passive methods [31]. Cross-validation has also been suggested to overcome the differing limitations between methods [23]. Acoustic methods cannot identify the gas species in the bubble so are not able to establish the source of a leak. Therefore, the use of combined systems including chemical sensors [12] and physical and biological monitoring [60] could be used to gain a complete understanding of leaks (localisation, quantification and attribution) [12].

6 ACKNOWLEDGEMENTS

The authors acknowledge the support of the UK Government's Department for Science, Innovation & Technology through the UK's National Measurement System programmes.

This work has also received funding from the European Partnership on Metrology programme project 21GRD06 MetCCUS, co-financed by the Participating States and from the European Union's Horizon Europe research and innovation programme.

7 REFERENCES

[1] HMG, *Climate Change Act 2008*. HMG, 2008. Accessed: Jan. 26, 2023. [Online]. Available: https://www.legislation.gov.uk/ukpga/2008/27

[2] Committee on Climate Change, "Net Zero The UK's contribution to stopping global warming," 2019. Accessed: Jan. 26, 2023. [Online]. Available: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf

[3] A. Lichtschlag *et al.*, "Suitability analysis and revised strategies for marine environmental carbon capture and storage (CCS) monitoring," *International Journal of Greenhouse Gas Control*, vol. 112, Dec. 2021, doi: 10.1016/j.ijggc.2021.103510.

[4] D. P. Connelly *et al.*, "Assuring the integrity of offshore carbon dioxide storage," *Renewable and Sustainable Energy Reviews*, vol. 166, Sep. 2022, doi: 10.1016/j.rser.2022.112670.

[5] J. Blackford *et al.*, "Efficient marine environmental characterisation to support monitoring of geological CO2 storage," *International Journal of Greenhouse Gas Control*, vol. 109, Jul. 2021, doi: 10.1016/j.ijggc.2021.103388.

[6] B. Roche *et al.*, "Time-lapse imaging of CO2 migration within near-surface sediments during a controlled sub-seabed release experiment," *International Journal of Greenhouse Gas Control*, vol. 109, Jul. 2021, doi: 10.1016/j.ijggc.2021.103363.

[7] OSPAR Commission, "OSPAR Decision 2007/02 on the Storage of Carbon Dioxide Streams in Geological Formations," 2007.

[8] IMO, "The London Protocol (2006 amendment to the 1996 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter)," 2006. https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx (accessed Jan. 30, 2023).

[9] European Union, "Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide," 2009. Accessed: Jan. 30, 2023. [Online]. Available: https://www.legislation.gov.uk/eudr/2009/31/contents

[10] IPCC, "IPCC Guidelines for National Greenhouse Gas Inventories," 2006.

[11] S. Hannis *et al.*, "Review of Offshore CO2 Storage Monitoring: Operational and Research Experiences of Meeting Regulatory and Technical Requirements," in *Energy Procedia*, Elsevier Ltd, 2017, pp. 5967–5980. doi: 10.1016/j.egypro.2017.03.1732.

[12] I. K. Waarum *et al.*, "CCS Leakage Detection Technology - Industry Needs, Government Regulations, and Sensor Performance," in *Energy Procedia*, Elsevier Ltd, 2017, pp. 3613–3627. doi: 10.1016/j.egypro.2017.03.1493.

[13] R. Gholami, A. Raza, and S. Iglauer, "Leakage risk assessment of a CO2 storage site: A review," *Earth-Science Reviews*, vol. 223. Elsevier B.V., Dec. 01, 2021. doi: 10.1016/j.earscirev.2021.103849.

[14] A. Flohr *et al.*, "Utility of natural and artificial geochemical tracers for leakage monitoring and quantification during an offshore controlled CO2 release experiment," *International Journal of Greenhouse Gas Control*, vol. 111, Oct. 2021, doi: 10.1016/j.ijggc.2021.103421.

[15] T. G. Leighton, *The Acoustic Bubble*. Academic Press, 1994.

[16] H. Czerski and G. B. Deane, "Contributions to the acoustic excitation of bubbles released from a nozzle," *J Acoust Soc Am*, vol. 128, no. 5, pp. 2625–2634, Nov. 2010, doi: 10.1121/1.3484087.

[17] M. S. Longuet-Higgins, "An analytic model of sound production by raindrops," *J Fluid Mech*, vol. 214, no. 1, p. 395, May 1990, doi: 10.1017/S0022112090000179.

[18] T. G. Leighton and A. J. Walton, "An experimental study of the sound emitted from gas bubbles in a liquid," *Eur. I. Phys*, vol. 8, pp. 98–104, 1987.

[19] A. O. Maksimov, B. A. Burov, A. S. Salomatin, and D. V. Chernykh, "Sounds of marine seeps: A study of bubble activity near a rigid boundary," *J Acoust Soc Am*, vol. 136, no. 3, pp. 1065–1076, Sep. 2014, doi: 10.1121/1.4892753.

[20] I. Leifer and D. Tang, "The acoustic signature of marine seep bubbles," *J Acoust Soc Am*, vol. 121, no. 1, pp. EL35–EL40, Jan. 2007, doi: 10.1121/1.2401227.

[21] A. E. A. Blomberg, T. O. Sæbø, R. E. Hansen, R. B. Pedersen, and A. Austeng, "Automatic Detection of Marine Gas Seeps Using an Interferometric Sidescan Sonar," *IEEE Journal of Oceanic Engineering*, vol. 42, no. 3, pp. 590–602, Jul. 2017, doi: 10.1109/JOE.2016.2592559.

[22] P. Taylor *et al.*, "A novel sub-seabed CO2 release experiment informing monitoring and impact assessment for geological carbon storage," *International Journal of Greenhouse Gas Control*, vol. 38, pp. 3–17, May 2014, doi: 10.1016/j.ijggc.2014.09.007.

[23] B. J. P. Bergès, T. G. Leighton, and P. R. White, "Passive acoustic quantification of gas fluxes during controlled gas release experiments," *International Journal of Greenhouse Gas Control*, vol. 38, pp. 64–79, 2015, doi: 10.1016/j.ijggc.2015.02.008.

[24] J. Blackford *et al.*, "Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage," *Nat Clim Chang*, vol. 4, no. 11, pp. 1011–1016, Nov. 2014, doi: 10.1038/nclimate2381.

[25] M. Cevatoglu, J. M. Bull, M. E. Vardy, T. M. Gernon, I. C. Wright, and D. Long, "Gas migration pathways, controlling mechanisms and changes in sediment acoustic properties observed in a controlled sub-seabed CO2 release experiment," *International Journal of Greenhouse Gas Control*, vol. 38, pp. 26–43, Jul. 2015, doi: 10.1016/j.ijggc.2015.03.005.

[26] ECO2, "ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems," 2019. http://www.eco2-project.eu/index.html (accessed Mar. 21, 2023).

[27] ETI, "Measurement, Monitoring and Verification of CO2 Storage (MMV) ," 2023. https://www.eti.co.uk/programmes/carbon-capture-storage/measurment-modelling-and-verrfication-of-co2-storage-mmv (accessed Apr. 21, 2023).

[28] M. Dean, J. Blackford, D. Connelly, and R. Hines, "Insights and guidance for offshore CO2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects," *International Journal of Greenhouse Gas Control*, vol. 100. Elsevier Ltd, Sep. 01, 2020. doi: 10.1016/j.ijggc.2020.103120.

[29] STEMM-CCS, "STEMM-CCS Project," 2023. https://www.stemm-ccs.eu/ (accessed Feb. 17, 2023).

[30] A. Flohr *et al.*, "Towards improved monitoring of offshore carbon storage: A real-world field experiment detecting a controlled sub-seafloor CO2 release," *International Journal of Greenhouse Gas Control*, vol. 106, Mar. 2021, doi: 10.1016/j.ijggc.2020.103237.

[31] J. Li *et al.*, "Acoustic and optical determination of bubble size distributions - quantification of seabed gas emissions," *International Journal of Greenhouse Gas Control*, vol. 108, no. 103313, 2021.

[32] J. Li *et al.*, "Passive acoustic monitoring of seabed gas seeps-application of beamforming techniques," *Proc. Mtgs. Acoust. 40, 070008* , 2020, [Online]. Available: http://acousticalsociety.org/

[33] A. Vazquez, R. Manasseh, and R. Chicharro, "Can acoustic emissions be used to size bubbles seeping from a sediment bed?," *Chem Eng Sci*, vol. 131, pp. 187–196, Jul. 2015, doi: 10.1016/j.ces.2015.03.058.

[34] T. G. Leighton and P. R. White, "Quantification of undersea gas leaks from carbon capture and storage facilities, from pipelines and from methane seeps, by their acoustic emissions," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 468, no. 2138, pp. 485–510, Feb. 2012, doi: 10.1098/rspa.2011.0221.

[35] J. Li *et al.*, "Natural seabed gas leakage-variability imposed by tidal cycles," in *OCEANS 2019 MTS/IEEE SEATTLE*, 2019.

[36] R. P. Dziak *et al.*, "Passive acoustic records of seafloor methane bubble streams on the Oregon continental margin," *Deep Sea Res 2 Top Stud Oceanogr*, vol. 150, pp. 210–217, Apr. 2018, doi: 10.1016/j.dsr2.2018.04.001.

[37] S. M. Wiggins, I. Leifer, P. Linke, and J. A. Hildebrand, "Long-term acoustic monitoring at North Sea well site 22/4b," *Mar Pet Geol*, vol. 68, pp. 776–788, Dec. 2015, doi: 10.1016/j.marpetgeo.2015.02.011.

[38] J. Li *et al.*, "Passive acoustic monitoring of a natural CO2 seep site – Implications for carbon capture and storage," *International Journal of Greenhouse Gas Control*, vol. 93, Feb. 2020, doi: 10.1016/j.ijggc.2019.102899.

[39] J. Li *et al.*, "Passive acoustic localization of a natural CO2 seep-implication for Carbon Capture and Storage," *International Journal of Greenhouse Gas Control*, vol. 93, no. 102899, 2021, [Online]. Available: https://www.researchgate.net/publication/352230224

[40] J. Li, P. R. White, J. M. Bull, and T. G. Leighton, "A noise impact assessment model for passive acoustic measurements of seabed gas fluxes," *Ocean Engineering*, vol. 183, pp. 294–304, Jul. 2019, doi: 10.1016/j.oceaneng.2019.03.046.

[41] B. Roche *et al.*, "Methods of acoustic gas flux inversion—Investigation into the initial amplitude of bubble excitation," *J Acoust Soc Am*, vol. 152, no. 2, pp. 799–806, Aug. 2022, doi: 10.1121/10.0013220.

[42] M. Ketzer *et al.*, "Gas hydrate dissociation linked to contemporary ocean warming in the southern hemisphere," *Nat Commun*, vol. 11, no. 1, Dec. 2020, doi: 10.1038/s41467-020-17289-z.

[43] A. E. A. Blomberg, I. K. Waarum, C. Totland, and E. Eek, "Marine monitoring for offshore geological carbon storage—a review of strategies, technologies and trends," *Geosciences (Switzerland)*, vol. 11, no. 9. MDPI, Sep. 01, 2021. doi: 10.3390/geosciences11090383.

[44] B. J. P. Bergès, P. R. White, M. Tomczyk, and I. C. Wright, "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," in *Proceedings of the 11th European Conference on Underwater Acoustics*, 2012.

[45] S. Vagle and D. M. Farmer, "The Measurement of Bubble-Size Distributions by Acoustical Backscatter," *Journal of Atmospheric and Ocean Technology*, vol. 9, 1992.

[46] J. Simmons and D. N. MacLennan, *Fisheries Acoustics: Theory and Practice*, 2nd Edition. Wiley-Blackwell, 2006.

[47] J. Blackford *et al.*, “Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage,” *Nat Clim Chang*, vol. 4, no. 11, pp. 1011–1016, Nov. 2014, doi: 10.1038/nclimate2381.

[48] M. Veloso, J. Greinert, J. Mienert, and M. de Batist, “A new methodology for quantifying bubble flow rates in deep water using splitbeam echosounders: Examples from the Arctic offshore NW-Svalbard,” *Limnol Oceanogr Methods*, vol. 13, no. 6, pp. 267–287, Jun. 2015, doi: 10.1002/lom3.10024.

[49] I. Leblond, C. Scalabrin, and L. Berger, “Acoustic monitoring of gas emissions from the seafloor. Part I: quantifying the volumetric flow of bubbles,” *Marine Geophysical Research*, vol. 35, no. 3, pp. 191–210, Sep. 2014, doi: 10.1007/s11001-014-9223-y.

[50] by K. G Foote, H. P. Knudsen, G. Vestnes, D. N. MacLennan, and E. J. Simmonds, “Calibration of acoustic instruments for fish density estimation: a practical guide,” 1987. doi: 10.17895/ices.pub.8265.

[51] G. Bayrakci *et al.*, “Acoustic monitoring of gas emissions from the seafloor. Part II: a case study from the Sea of Marmara,” *Marine Geophysical Research*, vol. 35, no. 3, pp. 211–229, Sep. 2014, doi: 10.1007/s11001-014-9227-7.

[52] T. C. Weber, K. Jerram, and L. Mayer, “Acoustic sensing of gas seeps in the deep ocean with split-beam echosounders,” in *Proceedings of Meetings on Acoustics*, 2012. doi: 10.1121/1.4772948.

[53] T. C. Weber, L. Mayer, K. Jerram, J. Beaudoin, Y. Rzhanov, and D. Lovalvo, “Acoustic estimates of methane gas flux from the seabed in a 6000 km 2 region in the Northern Gulf of Mexico,” *Geochemistry, Geophysics, Geosystems*, vol. 15, no. 5, pp. 1911–1925, 2014, doi: 10.1002/2014GC005271.

[54] N. Nadimi, R. Javidan, and K. Layeghi, “Efficient detection of underwater natural gas pipeline leak based on synthetic aperture sonar (Sas) systems,” *J Mar Sci Eng*, vol. 9, no. 11, Nov. 2021, doi: 10.3390/jmse9111273.

[55] N. Nadimi, R. Javidan, and K. Layeghi, “An Efficient Acoustic Scattering Model Based on Target Surface Statistical Descriptors for Synthetic Aperture Sonar Systems,” *Journal of Marine Science and Application*, 2020, doi: 10.1007/s11804-020-00163-1/Published.

[56] J. Zhao, J. Meng, H. Zhang, and S. Wang, “Comprehensive detection of gas plumes from multibeam water column images with minimisation of noise interferences,” *Sensors (Switzerland)*, vol. 17, no. 12, Dec. 2017, doi: 10.3390/s17122755.

[57] G. Meinecke, M. Römer, and G. Bohrmann, “Hydroacoustic mapping of gas bubble emissions at the Don-Kuban paleo-fan (Black Sea) using ship-mounted and AUV-based sonar systems Guineco-MeBo View project Invertebrate-microbial symbiosis at deep-sea natural gas and oil seeps View project,” 2012. [Online]. Available: https://www.researchgate.net/publication/259082385

[58] W. Munk and C. Wunsch, “Ocean acoustic tomography: a scheme for large scale monitoring,” *Deep-sea Research*, vol. 26, 1979.

[59] K. Shitashima, Y. Maeda, and T. Ohsumi, “Strategies for detection and monitoring of CO2 leakage in sub-seabed CCS,” in *Energy Procedia*, Elsevier Ltd, 2013, pp. 4283–4290. doi: 10.1016/j.egypro.2013.06.331.

[60] J. Blackford *et al.*, “Marine baseline and monitoring strategies for Carbon Dioxide Capture and Storage (CCS) 2 3,” 2015, [Online]. Available: http://www.iea.org/ccsdatabase/