REPORT

ACT4storage - Acoustic and Chemical Technologies for environmental GCS monitoring

RECOMMENDED GUIDELINES REPORT

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Executive Summary

Carbon capture and storage (CCS) is a promising tool for accelerating decarbonization and reaching international climate goals. The process involves capturing CO_2 from energy-intensive industries such as waste-to-energy plants, fertilizer production, and fossil fuel combustion, and injecting it into suitable geological formations for safe and permanent storage instead of releasing it into the atmosphere. A dedicated monitoring plan is required to verify that the CO_2 is safely stored over time and to detect and quantify leakage if it should occur. For offshore carbon storage, the primary monitoring is based on seismic methods and in-well monitoring, complemented by marine monitoring targeting the seabed and the water column above the storage reservoir. This report is intended to provide support for parties involved in the design of a marine monitoring program for offshore CCS sites.

Detailed monitoring of the marine environment above the entire geological reservoir is generally not recommended. Instead, a marine monitoring plan should be site specific and related to a local site assessment including identification of potential risk structures. Further, the monitoring plan should address the different phases of an offshore CCS project, from site characterization prior to injection, through the CO_2 injection phase, to assurance monitoring after the injection has stopped. Pre-injection monitoring (baseline monitoring) is aimed at characterizing the site in order to differentiate between natural variability and potential indications of leakage at a later stage. The risk level is higher during the injection phase when the system is pressurized, typically demanding more intensive monitoring of identified risk structures such as the injection well. Post-injection marine monitoring is intended to verify long term conformity, i.e., that there are no indications of CO_2 escaping the reservoir and migrating to the seabed over time. Regulatory requirements (although vague) are in place to ensure satisfactory marine monitoring efforts throughout the CCS project.

The range of monitoring needs in terms of area coverage, required level of detail, monitoring time frame and temporal resolution, suggest that different monitoring approaches may be necessary to meet the different needs of a CCS project. A range of technologies are available on the market, and it is technologically feasible to monitor the marine environment in great detail. A significant challenge lies in selecting appropriate sensor technologies as well as sensor carriers to achieve adequate information without introducing unnecessary or prohibitive costs. Features that are of particular interest during CCS marine monitoring include emission of gas bubbles at the seabed, anomalous water geochemistry indicating a non-biotic CO_2 source, shallow sedimentary features such as shallow gas accumulation or sub-seabed pockmarks, and features on the seabed related to fluid flow.

In this report we start by offering an overview of marine monitoring technologies, focusing on acoustic sensors (able to detect CO_2 bubbles in the water column or sediments, as well as provide seabed imagery and bathymetry) and chemical sensors (able to detect variations in pCO_2, pO_2 or pH in the water column). We also discuss different platforms, or sensor carriers, on which these sensors may be mounted. These include research- or survey vessels, autonomous underwater vehicles (AUVs), gliders, remotely operated vehicles (ROVs), and stationary seabed templates (landers). The interested reader can find a more complete description of relevant sensors and sensor platforms including their comparative performance in Appendix A and in (Blomberg, et al., 2020).

Further, we provide recommendations related to how to use and combine these sensor technologies to meet different CCS marine monitoring needs. We have chosen to group the recommendations according to different monitoring tasks, each of which may be relevant during one or more phases of a CCS project. The tasks we have identified are baseline monitoring (site characterization), screening surveys, monitoring of a spatially limited area of interest such as a CO_2 injection well, and monitoring of a spatially extended area such as a potentially non-sealing fault. Because a marine monitoring plan needs to be site specific and the monitoring needs may vary between different sites, we do not recommend a specific solution but rather point to which technologies are suited for the different monitoring tasks. We discuss in detail what the different sensor technologies can measure, as well as the achievable spatial and temporal resolution. We also discuss the implications of mounting these sensors on different platforms and estimate the resulting area converage rates. Finally, we offer recommendations for sensor packages, i.e., meaningful combination of sensors on different platforms in order to meet different monitoring needs.

We define the "baseline monitoring" as monitoring activities aimed at understanding and documenting the state of the marine environment above and near the storage location prior to, or in the absence of, CCS activity. As with the rest of the environmental monitoring scope, the baseline monitoring activities should be related to an initial site-specific risk analysis and consider relevant information including geophysical data from the area. Depending on the risk assessment, baseline monitoring may require information on different scales and at varying levels of detail, i.e., ranging from sparse screening surveys domumenting large-scale indications of natural fluid flow to detailed documentaiton of focus areas or risk structures.

The aim of a screening survey is to provide an overview of a large geographical area and identify medium-to-large scale features at the seabed or in the water column. Screening surveys may be relevant during several phases of a CCS project, such as during site characterization and during post-injection assurance surveys. The significant area coverage requirements during a screening survey suggest the use of moving platforms such as survey vessels, AUVs and gliders. These platforms operate in different ways, and offer different and often complementary information about the marine environment.

A survey vessel equipped with a multibeam echo sounder and a sub-bottom profiler provides significant area coverage rates and can reveal medium-to large scale pockmarks on the seabed, occurrences of gas seeps, seabed bathymetry, and (through the sub-bottom profiler) shallow sub-seabed structures and occurrence of shallow gas. If more detailed information is required, an AUV traveling near the seabed can map the seabed and upper sedimentary layer on a finer scale, and (depending on the sensor payload) simultaneously acquire chemical data including pCO_2, O_2 and pH measurements. High-resolution seabed imagery can be acquired using a side-scan sonar or sunthetic aperture sonar (SAS). An interferometric SAS system has the additional capability of offering high-resolution bathymetry co-located with the seabed imagery, making it possible to detect small-scall features indicating fluid flow, such as bacterial mats and small-scale pockmarks. An AUV can be equipped with a sub-bottom profiler to probe the upper sedimentary layers (up to a few tens of metres depending on sediment type), and a downward-looking multibeam echo sounder can be used to "fill in the gaps" in the sidescan/SAS imagery directly below the AUV. A high-definition optical camera can also be used to document small regions of particular interest such as a wellhead. For chemical mapping using an AUV, high sample rates are required to capture spatially limited geochemical anomalies such as a dissolved CO_2 plume. The significant natural variability in the vertical direction in the water column suggests that event with state-of-the-art sensors and high sampling rates it can be challenging to detect chemical anomalies with an AUV which typically stays at a fixed depth. Natural vertical variability may be orders of magnitude higher than local anomalies related to small-to-medium size leaks, implying that a more complete spatial mapping may be required to discriminate between natural variability and leak-induced anomalies. There are different AUVs available on the market with varying capability in terms of sensor payload and endurance, but a reasonable operating time for an AUV is in the order 12 – 48 hours, with some exceptions.

The glider platform is in rapid development, and is recommended when oceanographic and chemical mapping of an extended area is an objective. Conventional gliders do not provide seabed mapping, but have the advantage of long endurance and 3D coverage of the water column. "Traditional" gliders do not use a propellor but control their movement through a combination of buoyancy control and "wings". This allows them to follow a zig-zag pattern covering either the entire water column or focusing on a pre-defined depth layer of interest. While some gliders are equipped with echo sounders and can identify bubble seepage, their main advantage is chemical and oceanographic mapping of the water column over time. Because traditional gliders do not rely on a propellor, they have longer endurance than AUVs and can typically be in the water for several monghts at a time. "Hybrid" gliders are apparing on the market, for instance with the ability to use a propellor to stay at a fixed depth for a period of time before resuming its traditional travel path. For moving platforms such as gliders and AUVs, we recommend a pH sensor complementing the pCO_2 sensor, since pCO_2 sensors normally suffer from extended response times limiting the ability to detect small CO_2 plumes.

In addition to screening surveys, monitoring of focus areas may be required either as part of the primary monitoring plan or for anomaly investigation. Depending on the size of the focus area and the monitoring needs both survey vessels, AUVs and gliders may be relevant also for this purpuse. As for the screening surveys, an AUV is recommended if detailed mapping of the seabed is required, and a glider can be used to obtain long-term mapping of geochemical and oceanographic conditions in the water column. When the focus area is small (< 60 m), we recommend deploying one or several stationary seabed templates (landers) equipped with a sesnor-package tailored to the monitoring

needs. This template can take many forms, including a temporarily deployed lander, an ROV hovering near a point of interest such as a CO_2 injection well, or even a glider with "landing" capabilities. We stress the importance of combining pCO_2 and O_2 measurements for robust detection of non-biotic CO_2, as well as the need for high sample rates (0.1-1 Hz) to ensure reliable identification of anomalies with a minimum of false alarms. We propose a low-cost alternative for chemical monitoring of a focus area based on correlations between CO_2 and O_2 over time. We demonstrate this approach using data acquired in the Oslo Fjord over a continuous period of 27 days with a set of controlled CO_2 release experiments and intermediate periods of background measurements.
This report provides discussions, examples and recommendations related to monitoring scope. Where possible we provide specific recommendations related to AUV travel path, sensor settings, data acquisition schemes and meaningful sensor "packages".

List of Abbreviations

CCS	Carbon capture and storage
GCS	Geological carbon storage
MBES	Multibeam echo sounder
SBES	Single beam echo sounder
SBF	Sub-bottom profiler
SAS	Synthetic aperture sonar
CO_2	Carbon dioxide
O_2	Oxygen
N_2	Nitrogen

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Appendix

Appendix A Technology overview

Review and reference page

1 Introduction

This report is intended as support material for the design and development of a marine monitoring program for offshore geological carbon storage (GCS) sites. It is based on experiences from the ACT4storage project, along with available material from relevant research projects and input from the industry.

GCS can contribute to significantly reducing CO_2 emissions and reaching international climate goals. While the risk of harmful leakage is considered low, monitoring is required to verify long-term storage, and to detect and quantify leakage if it should occur. While geophysical monitoring methods (e.g time lapse seismics) target the storage reservoir and overburden, marine environmental monitoring focuses on the seabed and the water column above a storage reservoir. The marine environmental monitoring should be linked to the deeper sections, allowing marine focus areas and monitoring scope to be adjusted according to the most recent information available about the subsurface and the development of the injected CO_2 plume.

Further, a marine environmental monitoring plan needs to be developed specifically for the site in question, based on an initial site-specific risk assessment. Factors that may affect the risk analysis and therefore also the scope of the marine monitoring plan include geological conditions and potential risk structures identified in geophysical data, the presence and condition of legacy wells in the area, and long-term evidence of reservoir integrity. The required level of detail in the monitoring plan may vary between the project stages (from pre-injection to post-injection) and the different monitoring regions (e.g. near the injection well as opposed to a large area above the reservoir), which guides the choice of monitoring technologies.

This report offers recommendations for a wide range of monitoring activities – from screening surveys mapping the marine environment on a large spatial scale, via detailed mapping of structures of interest on the seabed, to continuous monitoring of a specific focus area such as an injection well. Our intention is that this report should provide support when implementing the different stages of a marine monitoring plan from pre-injection to project closure and be applicable to different storage locations.

Section 1 includes an introduction to marine environmental monitoring of GCS, focusing on a risk-based framework, as well as a summary of relevant technologies for successful marine monitoring. In Section 3 we present our recommendations for marine GCS monitoring. This section is structured into four main monitoring scopes (screening survey, spatially extended focus area, spatially limited focus area, and baseline monitoring), for which we present relevant technologies and discuss their monitoring capabilities. In Section 4 we describe a low-cost alternative for chemical monitoring and anomaly detection, suitable for stationary seabed templates including temporarily installed landers near a point of interest. Finally, we summarize and suggest topics for future research Section 5.

2 Marine environmental monitoring of geological carbon storage

Storing CO_2 in offshore geological formations is a relatively new activity, and existing recommendations for monitoring are under continuous development. A number of research projects, including ECO_2, ETI-MMV, and STEMM-CCS, propose strategies for environmental monitoring of GCS storage sites. While the proposed strategies vary to some extent, there is agreement about the fundamental aspects; the monitoring plan should be based on a site-specific risk analysis ensuring that monitoring resources are allocated to where they are needed, and the monitoring plan should be flexible and able to adapt to changes in the assessed risk level. The likelihood of significant amounts of CO_2 escaping the reservoir and harming the marine environment is considered low (Alcalde, et al., 2018). Therefore, much of the motivation for marine GCS monitoring lies in providing assurance and verifying the storage integrity.

Figure 2-1 illustrates a risk-based monitoring framework. An initial risk assessment is made based on available information such as seismic data revealing potential risk structures in the subsurface (faults or other potential CO_2 migration pathways), location and state of any legacy wells potentially penetrating the injected CO_2 plume, and the geological characteristics of the reservoir and overburden. Observed features related to past or on-going fluid flow such as pockmarks, observations of gas seepage, or bacterial mats on the seabed should also be included in the initial risk assessment.

An initial marine monitoring scope is set, based on the initial risk assessment. The risk assessment is continuously updated and may be influenced by many factors including indications of unintended vertical CO_2 migration observed in seismic imagery, signs of potential leakage to the marine environment, and anomalous pressure measurements (high or low) obtained from downhole instrumentation in wells. The monitoring plan should be flexible enough to adapt to this change in risk level. On the other hand, if the storage site is adequately monitored, confidence in the storage integrity is built over time, potentially reducing the current risk level along with the required monitoring scope.

Figure 2-1 In a risk-based GCS monitoring strategy, an initial monitoring scope is based on available information, and adjusted continuously as new information becomes available. Adjustment of the monitoring scope may be in terms of frequency of surveys, focus on target areas, and choice of sensor technologies. As confidence in the storage site is built, the monitoring scope may be down-scaled.

Keeping in mind that the probability of leakage from a well-planned CO_2 storage site is considered very low (Alcalde, et al., 2018), and that the area to be monitored is potentially very large (in the order of 10-100km^2), detailed monitoring of the entire site over an extended time period is neither necessary nor economically feasible. Previous studies also indicate that the predicted environmental impact related to different leak scenarios is spatially confined and that normal conditions are restored within days or weeks after the leak has stopped (Blackford, et al., 2020).

While the risk of harmful CO_2 leakage into the marine environment can be considered low, there can be significant risk related to public perception of the on-going project. It can be worthwhile investing in a baseline study which provides a strong understanding of the marine environment as well as the system (including the overburden and reservoir). This can significantly improve the ability to detect changes to the marine environment related to the storage project, and to handle false alarms related to natural processes. After the baseline study, marine monitoring efforts can be triggered either by anomalous measurements or observations, or through a monitoring plan including periodic assurance surveys or monitoring of a focus area such as the injection well during CO_2 injection. Figure 2-2 illustrates an offshore storage project time line and examples of relevant monitoring activities, from pre-injection to project closure.

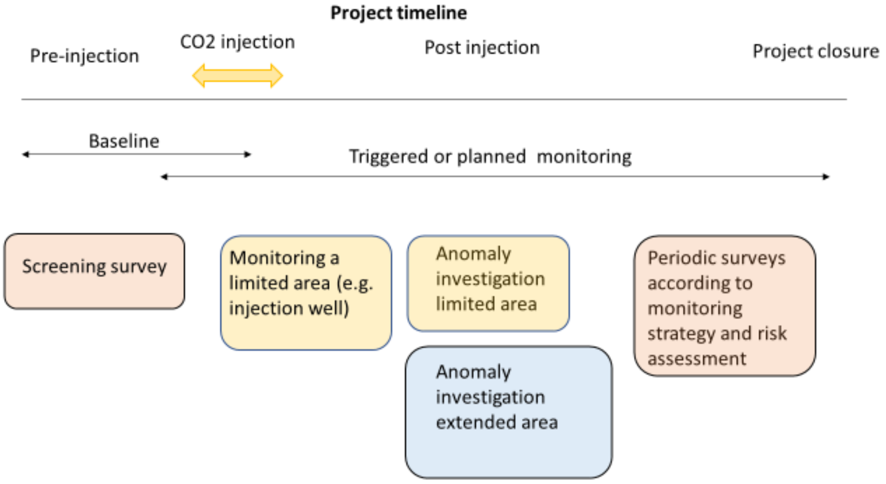

Figure 2-2: A marine monitoring plan for a CO_2 storage project covers several phases including a pre-injection phase, a CO_2 injection phase, and post-injection phase. A marine baseline is established prior to CO_2 injection in order document its state. After an initial baseline study, the marine monitoring may be trigger-based, meaning that monitoring efforts are triggered by unexpected observations, or by scheduled periodic assurance surveys. A range of monitoring tools are available to address different monitoring tasks (examples in coloured boxes).

2.1 Technologies for marine environnemental monitoring

Relevant technologies for marine carbon storage monitoring include sensors with the ability to detect and monitor changes in the marine environment which may be related to a storage project. This includes chemical sensors, because they can detect changes in the water chemistry including levels of CO_2, pH, O_2, and salinity. Acoustic sensors are relevant because they can detect gas bubbles in water, as well as features on the seabed including pockmarks and bacterial mats. Low-frequency acoustic systems (sub-bottom profilers) can also reveal sub-sediment structures such as hidden channels or shallow gas accumulations. Additional sensors potentially relevant for environmental include optical sensors, fibre optics, and recent sensor developments such as lab-on-a-chip for in situ automated chemical analysis of nutrients and other chemical species. Optical sensors (cameras) are useful in some cases and are standard equipment on ROVs. Their main limitation is the need for good light conditions and limited range. In practice, a camera must be placed within a few meters of the point of interest, and the image quality suffers when there are particles in the water. This report focuses on selection, use and combination of acoustic and chemical sensors.

In addition to a wide range of sensor technologies, there are several options related to what kind of platform, or sensor carrier, to mount the different sensors on. Depending on the monitoring requirements, relevant platforms include a survey vessel observing the marine environment from above and acquiring water samples, an autonomous underwater vehicle (AUV) to acquire high-resolution imagery of the seafloor and reveal shallow sub-seabed structures or shallow gas, a glider used to measure the water chemistry, and a stationary template placed at the seabed to monitor an area of interest such as an injection well. Note that a stationary template can take many forms, including a temporarily deployed lander collecting data for a certain time period, or an ROV hovering near an area of interest such as a CO_2 injection well.

An overview of relevant GCS marine monitoring objectives along with suitable technologies and platforms is shown in Table 2-1. In the next section we discuss these in more detail and make recommendations for meaningful and cost-effective selection and use of these technologies. The interested reader can find a more detailed overview of relevant sensor technologies and platforms in Appendix A, where we also discuss the implications of placing sensors on different platforms and offer sensor-specific recommendations based on the ACT4storage controlled release experiments. For a more detailed description of the different sensors used in the ACT4storage project as well as the controlled release experiment and results, please see (D3 - 2019 Nearshore evaluation report, 2019).

Table 2-1 Overview of relevant marine GCS monitoring objectives, and sensor technologies and platforms with corresponding capabilities

Monitoring objective	**Sensors**	**Platform**
Detect bubbles in the water column (seeps)	MBES, SBES, sonar	Survey vessel, AUV, stationary template
Identify seabed features related to fluid flow	MBES, SAS, sidescan sonar	Vessel, AUV
Identify sub-seabed features including shallow gas accumulation	SBF	Survey vessel, AUV
Quantify gas-phase CO_2 emission from seabed	SBES	Survey vessel, stationary template, (AUV)
Identify anomalous chemical signature in water masses	pCO_2, pO_2, S, T, other chemical	Stationary template, glider, AUV, survey vessel
Quantify amount of excess CO_2 in the water masses	pCO_2, pO_2, S, T, other chemical	Stationary template, glider, AUV, survey vessel

3 Recommendations related to monitoring scope

There is no one size fits all solution for a site-specific marine monitoring plan, and many factors may influence the choice of monitoring methods and technologies. In this section we give an overview of technological monitoring options addressing different monitoring tasks. We start by considering the different scales of monitoring (from screening a large area to monitoring a single focusing point), and which platforms (sensor carriers) that are relevant depending on the scale and the required spatial and temporal resolution. Further, we discuss which sensors to place on the different platforms, depending on the monitoring scope. Figure 3-1 shows a simplified overview of what we consider the most relevant platforms (sensor carriers) related to the size of the area to be monitored.

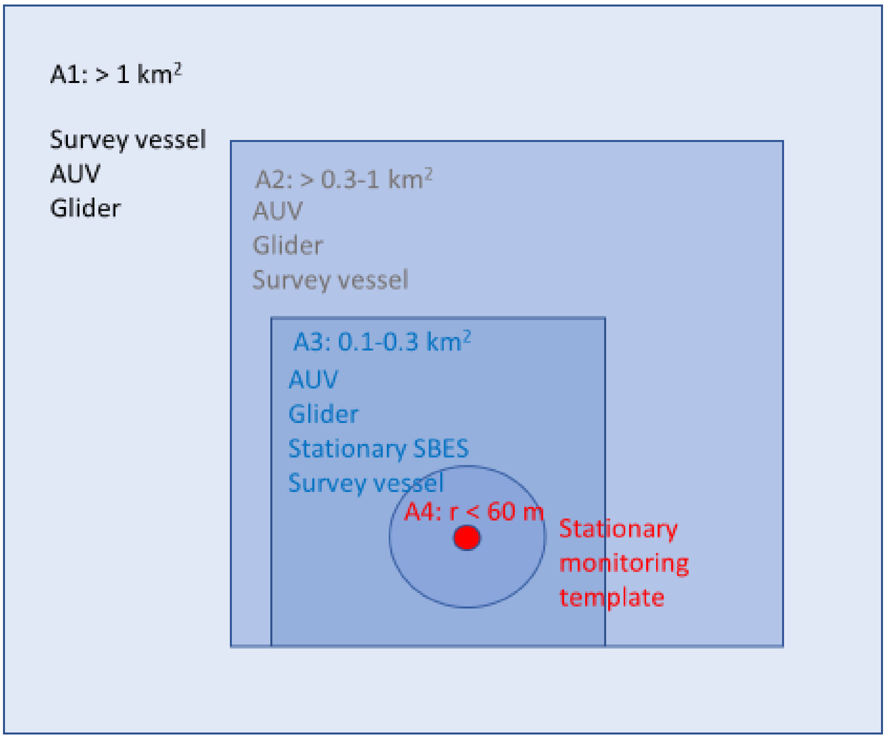

Figure 3-1 Relevant platforms for marine GCS monitoring include survey vessels, AUVs, gliders and stationary seabed templates. The size of the area as well as the required information and level of detail should be considered when selecting the appropriate platform for different monitoring tasks.

During a screening survey (A1), a survey vessel or autonomous underwater vehicle (AUV) is recommended to efficiently map the water column and the seabed. The choice between a vessel or an AUV depends largely on the level of detail required. If oceanographic and chemical mapping of the water column is required for assurance or as part of a baseline study, a glider equipped with suitable sensors is the preferred platform.

If sub-sections of A1 (such as A2 and A3) are identified as potential risk zones, more detailed mapping of the water column and seabed may be required. In this case an AUV traveling near the seabed can reveal small-scale features on the seabed such as bacterial mats and pockmarks, as well as identify bubble seeps. For limited regions of up to ~0.3 km^2 (A3), a stationary seabed template equipped with a split beam echo sounder (e.g. the Kongsberg EK80) can detect bubble seeps even at low leak rates. A survey vessel may also be used to map the seabed and water column and to acquire water samples in a smaller area (A3 and A4), especially if the vessel is available in the area.

Finally, for continuous or periodic monitoring of a spatially limited focus area such as an injection well (A4), a stationary seabed template equipped with acoustic and chemical sensors can reliably detect signs of leakage or verify the opposite. The size of the area in A4 is based on recent publications such as (Blackford, et al., 2020), where the authors conclude that a CO_2 leak of 1 tons/day can be chemically detected at 60 m horizontal distance. This is in agreement with observations from the ACT4storage experiments, although we see potential for increasing the chemical anomaly detection distance by combining high resolution CO_2 and O_2 measurements at fixed locations (see Section 4).

In general, the level of detail obtained in this approach increases from a single mission with data acquisition documenting the general state of the marine environment (screening survey), to continuous acoustic and chemical monitoring of a region of interest.

Another perspective is shown in Figure 3-2, where we present relevant technology configurations based on the monitoring scope. Here, the monitoring scope is categorized as either a screening survey, chemical/oceanographic water column mapping, monitoring or anomaly investigation of an extended area, and monitoring or anomaly investigation in a limited area such as an injection well. For each monitoring scope, different monitoring objectives are listed, such as mapping natural gas seepage in the water column or obtaining detailed seabed imagery.

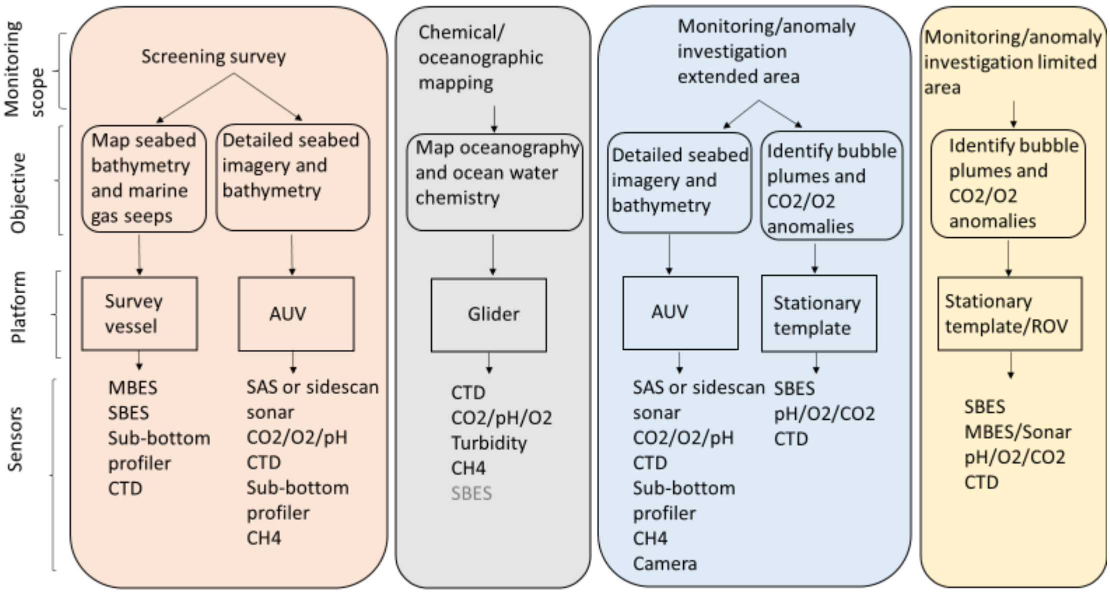

Figure 3-2 Recommended technologies related to monitoring scope. For a screening survey, either a survey vessel or an AUV is recommended, depending on the level of detail required by the risk assessment and monitoring plan. Oceanographic and chemical mapping of an extended area may be required as part of the baseline study or during subsequent assurance surveys. For this purpose, a glider equipped with suitable sensors is recommended. For anomaly investigation, either an AUV or a stationary platform can be suitable, depending on the monitoring requirements.

In the remainder of this section, we describe the capabilities and limitations of different monitoring technologies in more detail. We provide specific recommendations related to different monitoring scopes, structured into four categories:

1) Screening surveys (A1-A2)
2) Monitoring a spatially extended region of interest such as the seabed above a fault zone identified as a potential CO_2 migration pathway (A2-A3).
3) Monitoring a spatially limited region of interest such as a CO_2 injection well (A4).
4) Baseline – documenting the state of the marine environment prior to CO_2 storage (A1-A4).

3.1 Screening survey

A screening survey is recommended to document the state of the marine environment prior to CO_2 injection, and if necessary to confirm that the environment stays unaffected by the storage project. This is a natural part of a baseline study and may also be relevant for periodic assurance surveys. The required spatial coverage and level of detail in this survey depends on the monitoring strategy and the site-specific risk assessment, but a general characteristic of the screening survey as defined here is that it maps a relatively large area (A1 and A2 in Figure 3-1).

3.1.1 Ship-based survey

Using a ship (research/survey vessel or seismic vessel) is an efficient way to survey a large area. The vessel should be equipped with a multibeam echo sounder (MBES) to map the seabed and water column, and preferably also a sub-bottom profiler (sometimes referred to as shallow seismic sensor) to identify potential risk structures or shallow gas occurrences. Water samples can be collected at strategic locations to provide a "snapshot" of the current water chemistry. The vessel speed and line spacing will vary depending on the water depth and the sensors used. A conservative estimate of the area coverage rate in 100 m water depth and when using a MBES and a sub-bottom profiler is 4-6 km^2/hour.

A MBES has the ability to map the water column and document the presence of gas phase CO_2 (without distinguishing between e.g. CH4 and CO_2), and can also detect medium-to-large scale pockmarks on the seabed related to past or on-going fluid flow (Figure 3-5). For a more complete mapping, a sub-bottom profiler can be used to map the upper few meters of the sediments (~5-100 m depending on sediment composition and hardness), and to document accumulations of shallow gas and geological risk structures such as "chimneys" (Figure 3-6). Mapping the upper sedimentary layer can be helpful in data interpretation, potentially indicating weather a seabed feature is non-problematic for the storage project, or whether it can be related to a deeper risk structure. MBES and sub-bottom profilers operate at distinctly different frequencies and can normally be operated simultaneously without acoustic interference affecting the data quality. The presence of acoustic interference is instrument-dependent and should be verified prior to or in the beginning of the survey to avoid loss of data.

Bubble rise heights and the applicability of vessel-mounted MBES:
During the ACT4storage project we used multiple MBES to document the release of CO_2 bubbles from a nozzle on a seabed template at 65 m water depth (Figure 3-3). The bubbles had an estimated radius of 2-6 mm, similar to what was observed during the STEMM-CCS controlled release experiment. Leak rates varied from 0.1 l/min to 1.3 l/min, at the release point. We used six different echo sounders and sonars and acquired data for two eight-hour days. We consistently observed CO_2 bubbles rising more than 25 m above the seabed for leak rates of 0.3 l/min, and more than 35 m above the seabed for leak rates of 1.3 l/min, indicating that ship-based MBES surveys are highly useful for marine GCS monitoring. The rise heights are consistent with initial modelled results (Figure 3-4), based on the TAMOC model (Socolofsky, et al., 2015) indicating that while most of the CO_2 is dissolved below 17 m above the seabed, a bubble plume consisting mostly of other gases including O_2 and N2 persists (Loranger, Pedersen, & Blomberg, 2020). It is worth noting that the CO_2 dissolution rate increases with water depth. At water depths of more than ~500 m, the CO_2 enters the water as droplets instead of bubbles and is less visible using echo sounders and sonars.

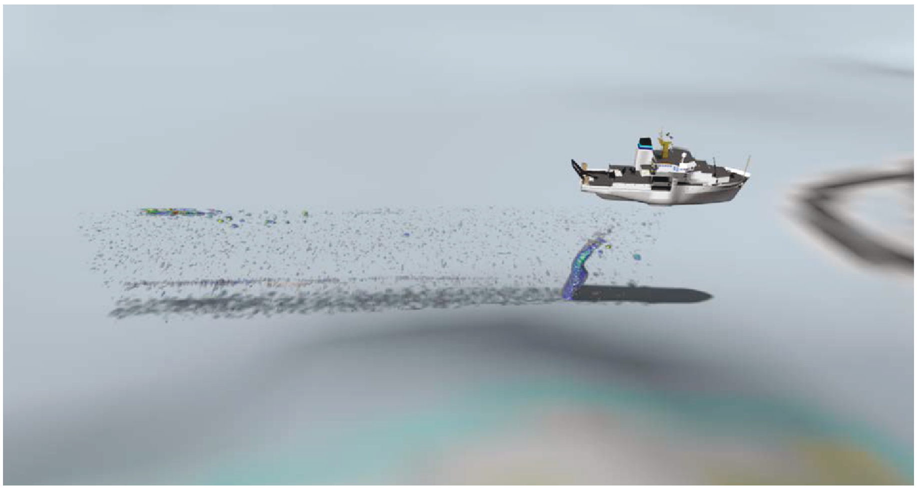

Figure 3-3 EM712 MBES image acquired during the ACT4storage project. CO_2 bubbles were released at a rate of 1.3 l/min at the seabed and can be recognized as a "flare" shaped structure rising ~40 m above the release point at the seabed.

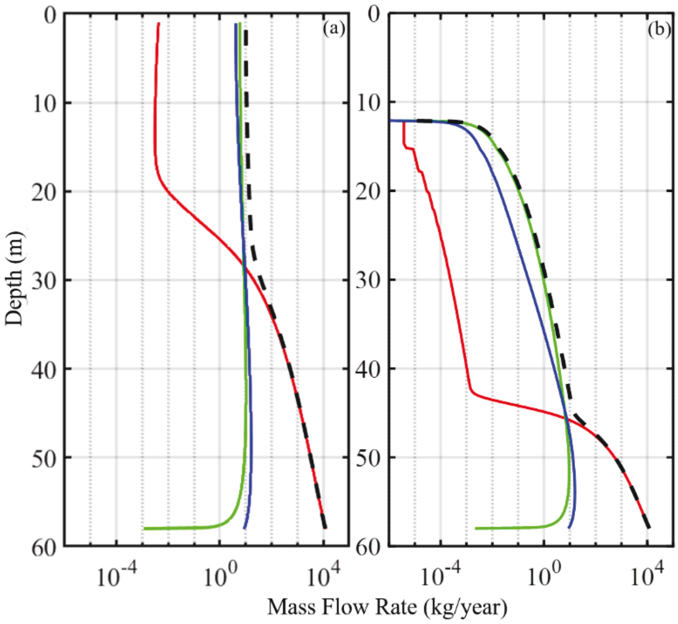

Figure 3-4 Modelled mass flow rate during the ACT4storage controlled release experiment indicating the amount of CO_2 (red), O_2 (blue), N_2 (green) in the plume as a function of water depth. The release rate is 1.3 l/min. Left: Results for a maximum initial bubble radius of 5 mm. Right: Results for a maximum initial bubble radius of 3 mm. This shows that while most of the CO_2 has dissolved at ~17 m above the seabed (right-hand example), the bubble plume persists higher in the water column but with O_2 and N2 being the prevailing gases.

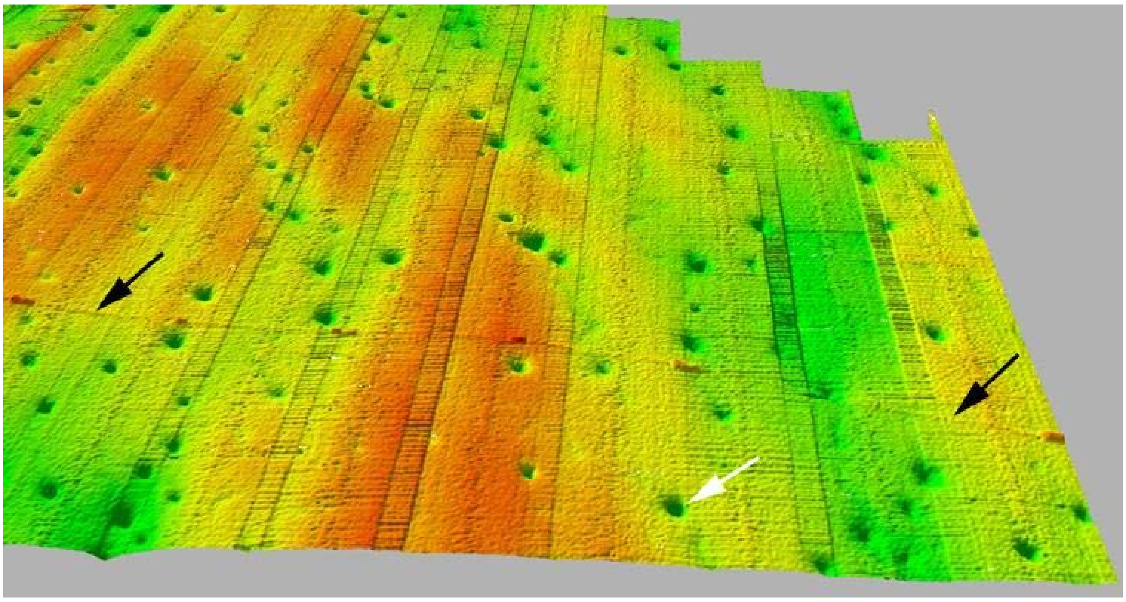

Figure 3-5 MBES imagery showing pockmarks related to gas emission. Reference: Hovland, Martin. (2012). Marine Life Associated with Offshore Drilling, Pipelines, and Platforms. 10.1007/978-1-4419-0851-3_478. The diameter of the pockmark indicated by the white arrow is ~70 m, and the water depth here is ~300 m.

MBES image resolution and area coverage rate:
The image resolution of the seabed obtained using vessel-mounted MBES systems depends on the angular beam separation, which varies between 1-2 degrees. This sets a limit to the scale of features on the seabed which are detectable. In addition, features such as bacterial mats are more easily detected when insonified from the side using a high resolution sidescan or SAS sonar, than when using a ship-mounted MBES.

The resolution at the seabed for a 1-degree system at 100 m water depth is 1.7 m, and 5.2 m at 300 m water depth. Thus, small scale pockmarks (< 5.2 m in the 300 m water depth case) will not be detected. In comparison, at 300 m water depth a synthetic aperture sonar (SAS) offers an image resolution of 3x3 cm and can therefor detect features as small as 3-5 cm.

The large swath width of these MBES systems makes them efficient for mapping extended areas. As an example, at 100 m water depth the EM2040 MBES maps 750 m of the seafloor perpendicular to the ship for each transmission, or "ping". The line spacing should allow ~20 % overlap between acquisition lines since gas seeps may be poorly visible in the outer beams. The allowable line spacing and thus the area coverage rate increases linearly with water depth. For instance, at 300 m the line spacing may be increased by a factor of 3 compared to at 100 m water depth.

Sub-bottom profiling:
Sub-bottom profilers (SBFs) complement MBES by mapping the upper part of the sediment layer. In the event that CO_2 migrates from the reservoir, models as well as experimental results indicate that most of the CO_2 will dissolve in the sediment layer and not enter the water column. Thus, early indications of leakage within the sediments can be highly relevant.

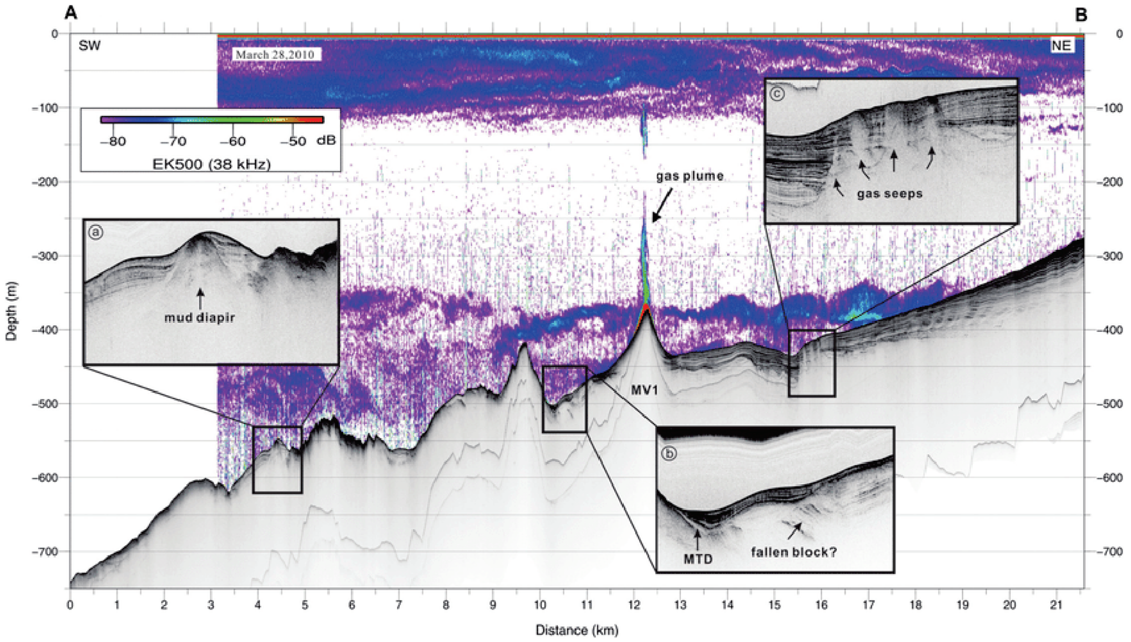

Figure 3-6 Sub-bottom profiler image (grey) combined with Simrad EK500 echo sounder data showing the water column. This example is from (Hsu, et al., 2018), and shows shallow methane gas escaping the sediments. A distinct gas plume is visible in the echogram, and multiple features are visible in the sub-bottom data indicating gas within the sediments. These sediments are usually recognized as areas of "acoustic shadowing" visible as brighter regions (less acoustic energy reflected).

During the ACT4storage field trials we did not use a sub-bottom profiler since the CO_2 release point was on the seabed (as opposed to below the seabed). Other trials, e.g. the STEMM CCS offshore trial, have documented these sensors' ability to map the occurrence of gas and related features in the sediments (reference not yet available).

3.1.2 Mapping using an AUV

While ship-based surveys are highly efficient for mapping large areas, an AUV has the additional advantage of traveling near the seabed and can therefore document the seabed on a finer scale (2-10 cm resolution compared to several meters resolution). The sensor payload on an AUV can be tailored to monitoring needs, for example detailed mapping of the seabed using sidescan or synthetic aperture sonar (SAS) to document pockmarks, bacterial mats and bubble seeps, while simultaneously measuring the level of dissolved

CO_2, pH, O_2, salinity, temperature and turbidity. Depending on the choice of AUV (size and sensor payload capacity), the AUV may also carry a MBES and a sub-bottom profiler. A high-definition subsea camera can be used to document special areas of interest such as a wellhead. While it may be costly to deploy an AUV to map an extended area, the data acquired can convey detailed information about the seabed and the deep sections of the water column. Note that AUVs normally follow a pre-programmed path for each survey, often a lawn mower pattern at a fixed depth covering the area of interest. The consequence is that chemical mapping is done in one dimension only. If chemical mapping is one of the objectives of a survey, it may be wise to allow the AUV to repeat its lawnmower pattern at several distinct depths for a more complete mapping of the different vertical layers in the water column.

Figure 3-7 The HISAS mounted on the HUGIN AUV, with capabilities for mapping the seabed and detecting gas seeps in the water column. This image was taken in Horten during the ACT4storage nearshore experiment.

Acoustic sensors on an AUV:
The seabed can be acoustically imaged using either a sidescan sonar or a synthetic aperture sonar (SAS) mounted on the AUV. In both cases, one transmit-receive pair is placed on each side of the AUV, providing simultaneous imagery to both sides (Figure 3-8). The swath width varies between about 100 and 300 m to each side, depending on the system, the seafloor bathymetry and AUV travel height above the seabed. The "blind zone" directly beneath the AUV can be covered using a downward-looking MBES. In addition, a sub-bottom profiler may be included to map the upper sediments and detect gas occurrences or other interesting features, as well as characterize the sediment type locally based on its hardness. A hydrophone may be included to listen for bubbles in the water column.

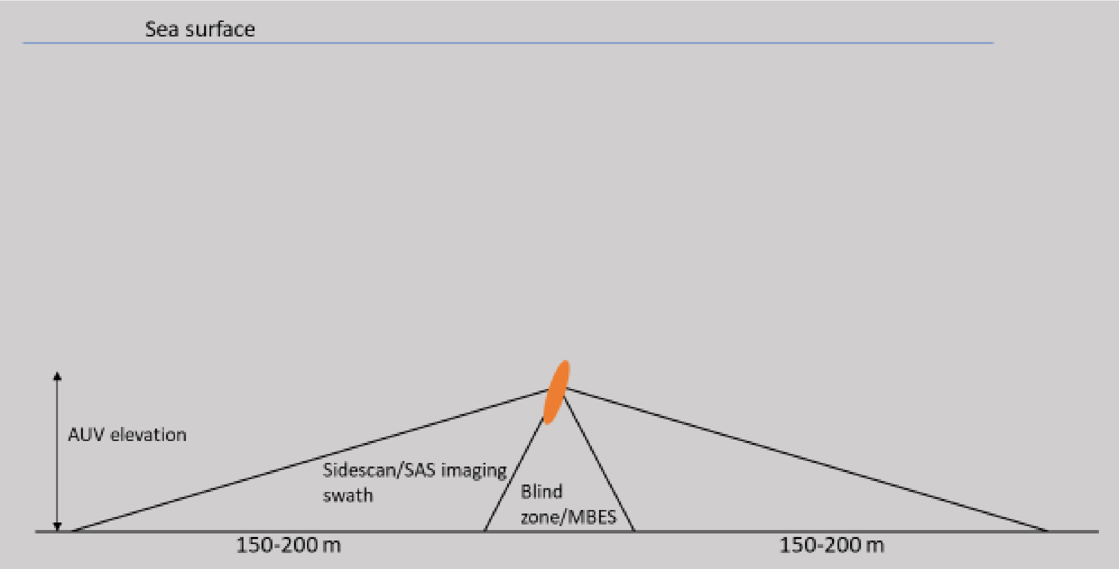

Figure 3-8 Imaging geometry for an AUV equipped with a sidescan sonar or SAS. A swath of ~150 to 200 meters to either side of the AUV is obtained. The blind zone directly below the AUV can be covered by limiting the spacing between consecutive lines, or by using a downward-looking MBES.

Table 3-1 lists the recommended minimum sensor payload on a HUGIN type AUV for marine environmental monitoring:

Table 3-1 Recommended sensors for marine environmental monitoring using a HUGIN type AUV

SAS or sidescan sonar	For detailed seabed mapping and bubble detection
Sub-bottom profiler	Mapping of upper sedimentary layers
MBES	Blind zone coverage without compromising line spacing
CO_2/O_2/pH sensor package	To document water chemistry and identify anomalies
CH4 sensor	To differentiate between CO_2 and CH4 in the water column
CTD	Supplementary data including salinity and temperature

Area coverage rate and travel path:

The area coverage rate for an AUV survey depends on the travel path, which again depends on the monitoring needs. For seabed imaging, i.e. identifying pockmarks, bacterial mats, bubble seeps, or other features related to fluid flow, the sensor of interest is the sidescan sonar or SAS. We will focus on the HUGIN AUV and the SAS because of its superior mapping capability. For normal seabed mapping, a typical sonar altitude is 30 m above the seabed, and with a speed of 2 m/s the area coverage rate is about **2 square kilometres per hour.** The operating time for current HUGIN AUVs with this sensor payload is up to 48 hours. For the time being, the AUV normally requires an accompanying ship for reliable navigation. Note that this is an area in continuous development. For instance, the new HUGIN Superior is now on the market and offers a dual-receiver SAS, significantly increasing the area coverage rate. The HUGIN superior also uses SAS Displaced Phase Centre Analysis (DPCA) aided navigation, i.e., it uses the SAS data in real time for improved navigational accuracy.

When searching for bubble seeps, the travel path should be considered carefully. We recommend a higher AUV altitude than usual, for instance 50 m above the seabed. This is due to the imaging geometry, and the fact that bubbles appear in the water column and not on the seabed (see (D3 - 2019 Nearshore evaluation report, 2019)for details). We recommend planning a survey which takes this into account and disregards data where less than 5 m of the water column is captured. In practice this means reducing the effective swath width and implementing a smaller line spacing. Combining the effects of a higher sonar altitude (thus imaging a larger part of the seabed for each ping and increasing the imaging swath) and disregarding the outer edges of the imaging swath where bubble seeps are less likely to be detected (thus reducing the imaging swath), the expected area coverage rate is expected to remain approximately 2 square kilometres per hour.

If, on the other hand, the main monitoring objective is to document the water chemistry and to detect potential anomalies caused by CO_2 entering the water column, the AUV should travel close to the seabed because of the high dissolution rate and limited spatial footprint of a dissolved CO_2 plume. In this case, an AUV altitude of 10 m above the seabed (less if possible) is recommended. The lower altitude implies that a chemical plume is more focused in space because it has had little time to disperse, which again necessitates a smaller line spacing in the AUV travel path to avoid missing the plume. It is also recommended to reduce the vehicle speed as much as possible so that the chemical sensors have more time to respond to an anomaly. For the HUGIN AUV, the lowest possible speed without compromising vehicle stability is ~3 knots (1.4 m/s). The area coverage rate is then drastically reduced, to **~0.35 square kilometres per hour.**

A meaningful approach when using an AUV with both an imaging sonar and chemical sensors would be to design the survey for seabed mapping for optimal area coverage, and to allow the AUV to travel closer to the seabed and inspect areas of special interest in more detail. For the chemical sensors, it is also important to consider sensor response times. We found that a pH sensor can act as an efficient proxy for a CO_2 sensor, because of the slower response time of membrane-based CO_2 sensors.

Figure 3-9 shows examples of seabed imagery and chemical measurements obtained using sensors mounted on the HUGIN AUV. More details on the use of the HUGIN AUV for marine GCS monitoring and the results from the ACT4storage nearshore controlled release experiment can be found in Appendix A, and in D3 – 2019 Nearshore evaluation report, 2019.

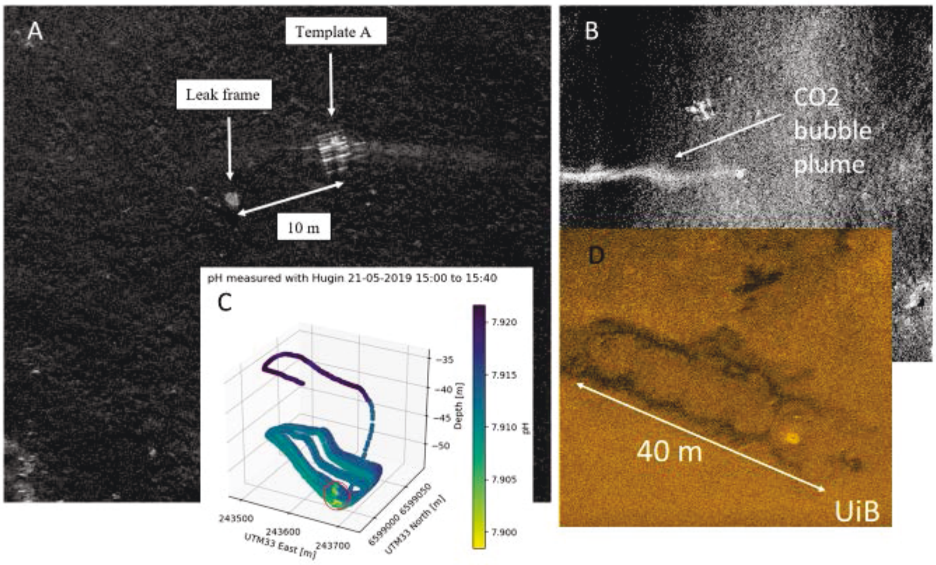

Figure 3-9 Example images obtained using sensors mounted on the HUGIN AUV. A and B show seabed imagery obtained using the the HISAS sonar during the ACT4storage controlled release experiment, with and without a CO_2 release. In C, a chemical anomaly (reduced pH) can be seen directly above the leak frame during a continuous release. C was obtained during the ECO_2 project (Pedersen, et al., 2013), and shows sonar imagery of features related to natural fluid flow in the North Sea.

3.1.3 Mapping using a glider

A glider is also an AUV, but developed specifically for long endurance with a typical operational capacity of several months at a time depending on sensor payload. Traditional gliders follow a zig-zag (up-down) pattern in the water column covering an area of interest in three dimensions. Gliders are often equipped with oceanographic and potentially also chemical sensors and are cost-efficient platforms for monitoring water volumes over time. For chemical and/or oceanographic water column mapping and profiling, especially in large water volumes and over time, gliders are well suited because of their long endurance compared to propellor-driven AUVs such as the HUGIN.

Because of the specific conditions at the controlled release site used during the ACT4storage project (closeness to shore and a strong density gradient in the water column which complicated glider navigation), we do not have the same in-depth experience with the glider platform as with the other platforms. However, although we did not observe any obvious anomalies related to the CO_2 release, the oceanographic and chemical data provided by the glider was useful during modelling and data interpretation. For example, the modelled plume height shown in Figure 3-4 was based on salinity, temperature, O_2, N_2, and CO_2 profiles obtained from the sensors on the

SeaExplorer glider. An important advantage provided by the glider technology was the mapping of the oceans in 3D (spatial xy-coordinates and water depth).

As with the AUV, sensor response times are important when mounted on a glider. Because the glider is only inside the plume for a given period (typically in the order of a few seconds), the sensors must have a fast response time in order to detect an anomaly. We recommend a sensor payload including CTD, O_2, pH, CO_2, and CH_4 sensors. Our experience from laboratory tests and from the HUGIN AUV was that a pH sensor can act as an effective proxy for the slower CO_2 sensor which has more difficulty detecting small plumes. O_2 and CTD sensors already have response times compatible with glider movement velocity. As with an AUV, the vehicle should move as close to the seabed as possible and at low speed. The sensor sampling rate should be as high as possible to avoid moving through a CO_2 plume without registering it.

Recent advancements in glider technology are making it possible to mount acoustic SBES on the glider, but this was not tested during the ACT4storage project (it requires a different and larger glider such as the Kongsberg Seaglider). For more power-hungry sensors such as seabed imaging sonars, an AUV is currently required.

3.1.4 Temporarily installed landers

While stationary templates are of limited use for screening an extended area, it can be relevant to deploy temporary autonomous platforms (landers) at the seabed as part of a screening survey using a vessel. Continuous measurements using chemical and oceanographic sensors (CTD, pCO2, pO2, and temperature) over a period of days to months can provide important information about the natural variability in these parameters. This may increase the ability to detect a chemical anomaly at a later stage, and to reliably differentiate between an anomaly and natural variability.

3.2 Spatially extended focus area

A spatially extended focus area may be related to the footprint above a risk structure identified in the seismic imagery such as a non-sealing fault or other potential fluid migration pathway. It may also be an area with abandoned wells identified as potential CO_2 escape routes, or anomalies such as bacterial mats or pockmarks detected during a baseline or screening survey.

The recommended technologies for a spatially extended focus area overlap with those for a screening survey (Figure 3-1). However, if a higher level of detail is required, an AUV operating close to the seabed and equipped with acoustic and chemical sensors may be preferred in comparison to a survey vessel. If the area is relatively small (< 0.3 $km^{2)}$, it can be covered using a stationary seabed template with a SBES detecting bubble seepage. The area coverage in this case is related to the operating range of a SBES such as the EK80 with the capability to detect bubbles at distances of 3-500 m. In this case the seabed template could also be equipped with chemical and oceanographic sensors (CO_2, O_2, pH, CTD, ocean currents) although this would require a proximity to the source of about 10-100 depending on the leak rate, because of the limited spatial footprint of a dissolved CO_2 plume. In (Blackford, et al., 2020), the authors use a collection of models to conclude that a leak of 1 tonne/day is chemically detectable at 60 m distance.

Table 3-2 shows relevant platform-sensor configurations as part of a screening survey or when surveying a spatially extended area. The configuration should be tailored to meet the specific needs of the project. In many cases the same configuration can be used to monitor a smaller area of interest but may not be a cost-effective alternative for that purpose.

Table 3-2 Examples of relevant platform-sensor configurations for moving platforms (vessels, AUVs and gliders) and their monitoring capabilities. For each configuration in the left column, we summarize what kind of information is obtained and estimate the area coverage rate. These configurations are relevant for screening surveys, as well as surveys of spatially extended focus areas, e.g. related to potential migration pathways identified in seismic imagery.

Platform and payload	**Information provided**	**Area coverage rate**	**Comments**
Research- or survey vessel w/ MBES	Occurrences of gas seeps in the water column and seabed bathymetry including medium-to-large scale pockmarks	In the order of 4-6 km^2/hour depending on water depth and vessel speed	Standard on most survey vessels
Research- or survey vessel w/ MBES and sub-bottom profiler	Indications of shallow gas and risk structures in the upper sediments, in addition to seeps in the water column and seabed bathymetry	In the order of 4-6 km^2/hour depending on water depth and vessel speed	
HUGIN AUV with HISAS, Sub-bottom profiler, CTD and CO_2/pH/O_2 sensors. Optionally MBES to fill in the blind zone below the AUV	Detailed seabed imagery revealing bacterial mats, pockmarks, seafloor bathymetry, and gas seeps. Shallow seismics revealing risk structures and shallow gas. Oceanographic and chemical mapping at discrete water depths according to AUV altitude	In the order of 2 km^2/hour depending on vehicle altitude	The HISAS can be replaced with a sidescan sonar at the expense of reduced image quality and coverage rate
Glider with pH/O_2/CO_2 and oceanographic sensors.	3D mapping of the water column documenting oceanography and water geochemistry. Long-term monitoring of a large (or small) area of interest.	In the order of 25 km^2/day depending on water depth, and expected vertical extent of the plume	A pH sensor may act as a proxy for the CO_2 sensor if response time, space and/or weight is an issue.

3.3 Spatially limited focus area

Examples of a spatially limited focus area include a CO_2 injection well, an abandoned well, and a structure such as a pipeline. If a single region of a limited size (< 0.1 $km^{2,}$ or a circle with r < 60 m as in Figure 3-1) needs to be monitored over time, the current state of the art is to use a stationary seabed template equipped with acoustic, chemical and oceanographic sensors. Note that a stationary seabed template can take different forms, it can for example be an ROV hovering near the seabed for an extended period, or a retrievable seabed lander. It is also worth noting that some gliders can land on the seabed for an extended period. The following sensors are recommended, depending on monitoring objectives:

- A high-resolution sonar such as the Kongsberg M3 to map the seabed and structures, and to detect and monitor gas seepage with intermediate flow rates (> 3 l/min in our experience. Lower leak rates may be detectable by optimizing sensor position and data processing).
- The Simrad EK80 SBES to detect small amounts of gas seepage (< 0.15 l/min @ 65 m distance), and to acoustically quantify the amount of escaping gas.
- A hydrophone to provide acoustic measurements including the sounds produced by bubbles. Our experiences and early results from the STEMM-CCS project indicate a detection distance of ~20-40 m for moderate leak rates (1-5 l/min) under limited background noise conditions.
- Chemical sensors (CO2, O2, pH) to detect anomalies or verify normal conditions. See Section 4 for a proposed method for anomaly detection.
- Oceanographic sensors (Ocean currents, CTD, turbidity)

Table 3-3 summarizes key sensor technologies recommended for a stationary seabed template monitoring a limited area of interest. For each technology, we estimate the distance at which a CO_2 leak can be detected. There are many factors influencing the detection distance including ocean currents and the size of a potential CO_2 leak, so these numbers should be considered estimates. We also include the estimated detection threshold, based on our experience and available literature from related projects. For the SBES, the detection distance is based on literature as well as extrapolation of the data from ACT4storage. In the ACT4storage experiment the SBES was placed at 65 m distance from the leak, but numerical extrapolation suggests detection distances of > 300 m even for small leak rates (1-5 l/min) when the CO_2 is in gas phase.

*Table 3-3 Recommended sensors for monitoring a limited area of interest, and estimated detection distance and detection capability. *) Chemical sensors are point sensors that need to be in contact with the affected water mass of interest. The detection distance for the chemical sensors is affected by the size of the leak, its duration, and ocean currents. A reasonable estimate for detecting a* CO_2 *anomaly related to a 1 tonne/day leak is 60 m (Blackford, et al., 2020).*

Sensor	**Detection distance to gas leak**	**Power/ battery require ments**	**Can detect**	**Comment**
pH	0-60 m*	Low	Dissolved CO_2 anomaly	Affected by CO_2
pO_2	0-60 m*	Low	Dissolved CO_2 anomaly	Affected by CO_2
pCO_2	0-60 m*	Low	Dissolved CO_2 anomaly	Limited by response time
CTD	0-60 m*	Low	Oceanography, depth	
CH4	0-60 m*	Low	CH4	Attribute observed bubbles to CH4 seepage
SBES	1 – 300 m	High	Gas phase CO_2 > 0.1 l/min	Depending on distance and sensor
MBES (M3)	1-80 m	High	Gas phase CO_2 > 3-5 l/min	Depends on leak rate and viewing angle
Camera	1-5 m	Medium	Gas phase CO_2 > 1 l/min	Limited by turbidity, light and marine growth
Hydrophone	1-40 m	Low	Gas phase CO_2 > 1 l/min @ 12 m distance verified in ACT4storage	Detection range depends on background noise levels and sensor sensitivity

In Table 3-4 we show examples of relevant sensor configurations, or technology packages, for a stationary sensor platform monitoring a limited focus area, and the information provided for each configuration. During the ACT4storage project (Figure 3-10) we combined all three sensor packages for robust monitoring and the ability to detect small amounts of CO_2 bubbles (EK80 SBES), detect chemical anomalies related to pCO_2/pO_2, and get an overview of the seabed and the different instrument frames (M3 MBES).

Table 3-4 Examples of relevant sensor configurations for stationary seabed templates, and their monitoring capabilities. These are relevant for monitoring of a spatially limited area of interest, such as a CO_2 injection well or a legacy well.

Platform and payload	**Information provided**	**Area coverage rate**	**Comments**
Stationary seabed template equipped with pCO_2, pO_2, pH, and CTD	Documents geochemistry in a small region and can detect if a non-biotic CO_2 source affects the water masses passing the sensors.	~up to 0.01 km^2 (r=60 m) depending on ocean currents and emission rates	The template can be in the form of a lander, an ROV, or a glider with "landing" capabilities. High sampling rate preferred (> 0.1 Hz).
Stationary seabed template with a scientific echo sounder (such as the EK80)	Detects bubbles in the water column. The EK80 also has capabilities for release quantification based on acoustic data	Up to 0.3 km^2 (r=300 m) in open water	Control of the echo sounder position and viewing angle is important. Accurate emission quantification is possible but non-trivial.
Stationary seabed template with an imaging sonar (e.g. the Kongsberg M3) and a passive hydrophone	Detailed monitoring of the seabed including the ability to detect multiple gas seeps using the sonar. A hydrophone can detect and quantify CO_2 bubble emissions.	60-80 m for the M3 sonar for moderate gas release (20-50 l/min). < 10 m for passive release quantification, a few tens of meters for passive bubble detection, depending on leak rate.	

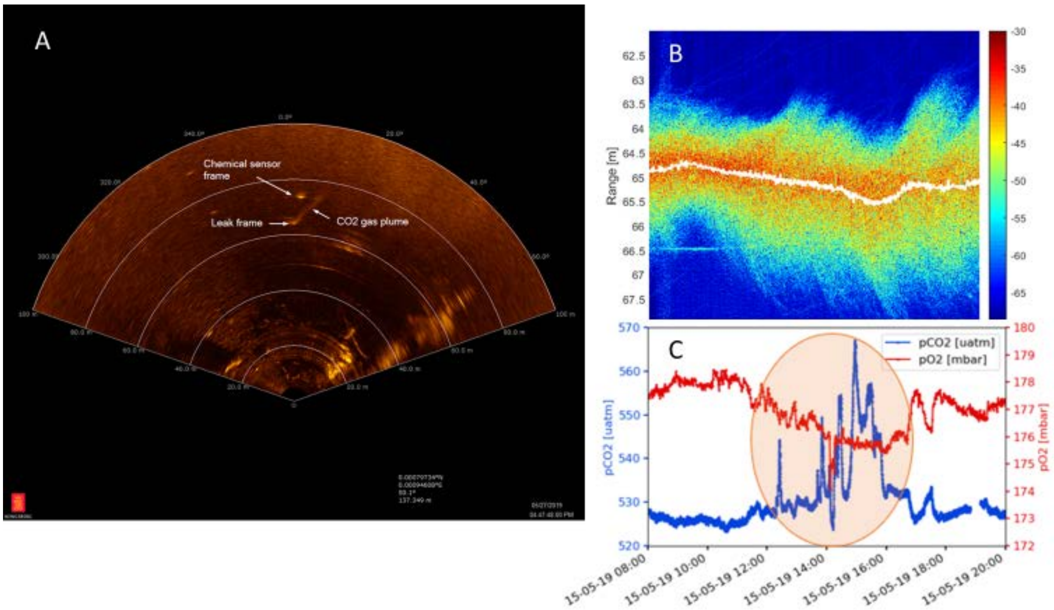

Figure 3-10: Examples from a stationary seabed template used during the ACT4storage controlled release experiment. The seabed structures as well as a CO_2 bubble release of 25 l/min (A) at 65 m distance is visible in (A), while (B) shows an EK80 echogram with a clear response from a 1.3 CO_2 release at the same distance. A chemical anomaly is measured using Template A, 25 m from the release point, is shown in (D).

3.4 Baseline

We define the baseline survey as the monitoring activities aimed at understanding and documenting the state of the marine environment above and near the storage location prior to, or in the absence of, GCS activity. An important motivation for carrying out a baseline survey is to verify long-term storage integrity, to have tools to confidently detect and characterize leakage if it should occur, and to avoid that natural events or observations are incorrectly attributed to the on-going GCS activity. A strong understanding of baseline conditions adds confidence and may contribute positively to public acceptance for CCS.

A range of spatial scales and varying levels of detail may be relevant during a baseline study. A screening survey of the entire footprint above the storage reservoir at a sparse spatial scale may be sufficient in some cases, while known risk-structures from the seismic imagery or indications of past or on-going fluid flow at the seabed may warrant more detailed documentation of the state of the seabed in certain areas. Thus a baseline may involve A1-A4 in Figure 3-1, and the technology recommendations follow those in Sections 3.1 to 3.3. To minimize the costs during a baseline survey, it is important investigate the availability of data and site-specific knowledge from sources such as government agencies, fishing and the hydrocarbon industry.

In recent years the need for a baseline study has been debated. Modelled results based on simulated leak scenarios suggests that potential leakage along geological pathways will be slow, leakage rates limited, and the environmental impact limited and spatially limited to a few tens of meters (Blackford, et al., 2020). These results are supported by experience from operational storage sites, showing no indications of leakage. In addition, the complexity and significant natural variability of the marine environment above a storage formation makes the task of documenting its state prior to CO_2 storage and identifying anomalies challenging and potentially costly.

While currently available information suggests that the risk of CO_2 leakage to the marine environment is small, our long-term experience with geological CO_2 storage is limited, and there are uncertainties in the accuracy of numerical simulations and models. The need for a baseline study has been highlighted by several research projects including STEMM-CCS, ECO_2, and QICS. The complexity and area coverage requirements of a baseline study warrants careful selection of monitoring technology and smart use of different platforms and sensors to obtain adequate information without unnecessary costs.

Monitoring efforts that may be relevant (depending on the risk assessment and monitoring strategy) during a baseline study include

1. MBES survey of the seabed above and near the storage site documenting naturally occurring gas release, seabed bathymetry and sediment type, and pockmarks indicating past or on-going fluid flow. Simultaneous data acquisition using a SBP adds valuable information about the upper sediments below the seabed.
2. Measurement of the geochemical conditions (pH, pCO_2, O_2, DIC, salinity) and the natural variability in these parameters, either at selected locations over time using seabed templates or covering a large area one or more times using a glider or an AUV.
3. Detailed mapping of the seabed using an AUV to document naturally occurring gas release, image the seabed and upper sedimentary layers in detail, and measure the baseline geochemical conditions.
4. Documentation of the state of identified risk areas such as legacy wells prior to CO_2 injection.

As with the rest of the environmental monitoring scope, the baseline monitoring activities and scope should be related to an initial site-specific risk analysis and consider relevant information including geophysical data from the area. A relevant possibility is to complement baseline surveys using the "ship of opportunity" concept, where vessels traveling in the area for other purposes are asked to acquire data relevant for the baseline study. The data acquired from instruments on research vessels, fishery vessels, seismic vessels, and others can be combined into a database and integrated into the baseline study. The marine monitoring at the Sleipner site was performed partially through research programs including ECO_2. This is also a good alternative – to encourage and facilitate research programs which collect relevant data in the area.

4 Monitoring geochemical conditions in the sea – a low cost alternative

One of several potential indications of CO_2 leakage into the marine environment is a change in the geochemistry in the water. This includes increased levels of dissolved CO_2, reduced pH levels, and potentially changes in other parameters such as salinity and temperature. These parameters can be measured by direct water sampling, by chemical sensors mounted either on a moving platform such as an AUV or a glider, or on a seabed template.

Identifying spatially limited chemical anomalies using moving platforms can be challenging since it requires de-coupling of variations related to natural spatial and temporal variability and vessel movement, and chemical variations related to an anomaly. On the other hand, the lack of spatial coverage is a challenge when using direct water sampling or multiple stationary templates spread out in an area of interest.

The affected water mass moves with currents and tidal changes while mixing with other water masses, thereby gradually losing its signature. A stationary platform with chemical sensors can be able to pick up signals form such a body of water as it passes the sensors with less difficulty than mobile platforms because other changes in chemical and oceanographic parameters are smaller when measuring at a constant depth (and at a fixed point).

Geochemical measurements coupled with models and spatial interpolation can be used to document the "normal" conditions in the marine environment above a CO_2 storage site, such that deviations related to leakage can be detected. This approach is based on determining a large-scale baseline and identifying statistically significant deviations from this. Significant efforts have been and continue to be directed towards optimizing the spatial locations of such measuring stations, and improved modelling aimed at identifying deviations from normal conditions (Abdirahman, Maribel, & Alendal, 2019). This approach can be challenging because of the significant variations in seawater geochemistry both on a short-term scale as different water masses are moving and mixing, on a seasonal scale, and more long-term. In addition, one can expect significant and to a large extent undocumented spatial variation.

In this section we propose a low-cost alternative to performing a comprehensive chemical baseline study. This approach is based on identifying a non-biotic CO_2 source through the CO_2/O_2 correlation at a point of interest, thus removing the need for a chemical baseline and the use of absolute or relative thresholds. Previously, the Tomakomai CO_2 storage project off the coast of Japan was temporarily stopped because of incorrectly determined CO_2 thresholds causing false alarms of leakage. While the CO_2/O_2 correlation has been suggested previously as an indicator for CO_2 leakage, we have verified this method using realistic field data. We conclude that high sample rates are crucial for detecting CO_2 anomalies, and propose a preliminary algorithm for automatic leak detection.

Findings from the ACT4storage controlled CO_2 release experiment suggest that anomalies related to a non-biotic CO_2 source can be reliably detected based on the correlation between CO_2 and O_2 at a single measuring point. A direct result of this is that it is not necessary to know or estimate the geochemical conditions over a large area, since the method does not rely background CO_2 or pH levels. Instead, anomalies are detected by identifying time spans where the expected biotic CO_2-O_2 correlation is lacking. Chemical marine monitoring is then limited to specific sites of interest such as the CO_2 injection well, and legacy wells or geological features identified as risk structures.

The motivation for this approach is that it is less costly and time consuming than performing a large-scale chemical baseline, and the amount of measuring stations can be reduced from many to a single station or a handful of stations depending on the monitoring scope. This approach also has the benefit of being robust against natural variations, since natural correlation between CO_2 and O_2 persists independent of seasonal or regional variations. While the results with this approach are consistent and promising, it should be verified by placing 1-4 measuring stations in the North Sea (or other relevant sites) for a period of several weeks or months. This would provide information about the natural biotic pCO_2 vs pO_2 correlation and its spatial and temporal variability, as well as identify sources of false alarms and ensure that these are properly handled by an alarm algorithm.

Figure 4-1 shows example time series of pCO_2 (blue curves) and pO_2 (red curves) measurements from the ACT4storage nearshore controlled release experiment in 2019. Each of the six plots shows a 12-hour period, during which there was no CO_2 release (baseline conditions). The expected inverse CO_2-O_2 biotic correlation can be observed and is confirmed by the scatter plots in Figure 4-2. Figure 4-3 shows the time series and corresponding CO_2-O_2 scatter plots on three different days with a controlled CO_2 release. Anomalies are indicated by coloured ellipses and identified by a deviation from the natural biotic correlation which can be seen in the time series (left) as well as in the spread of the scatter plots (right).

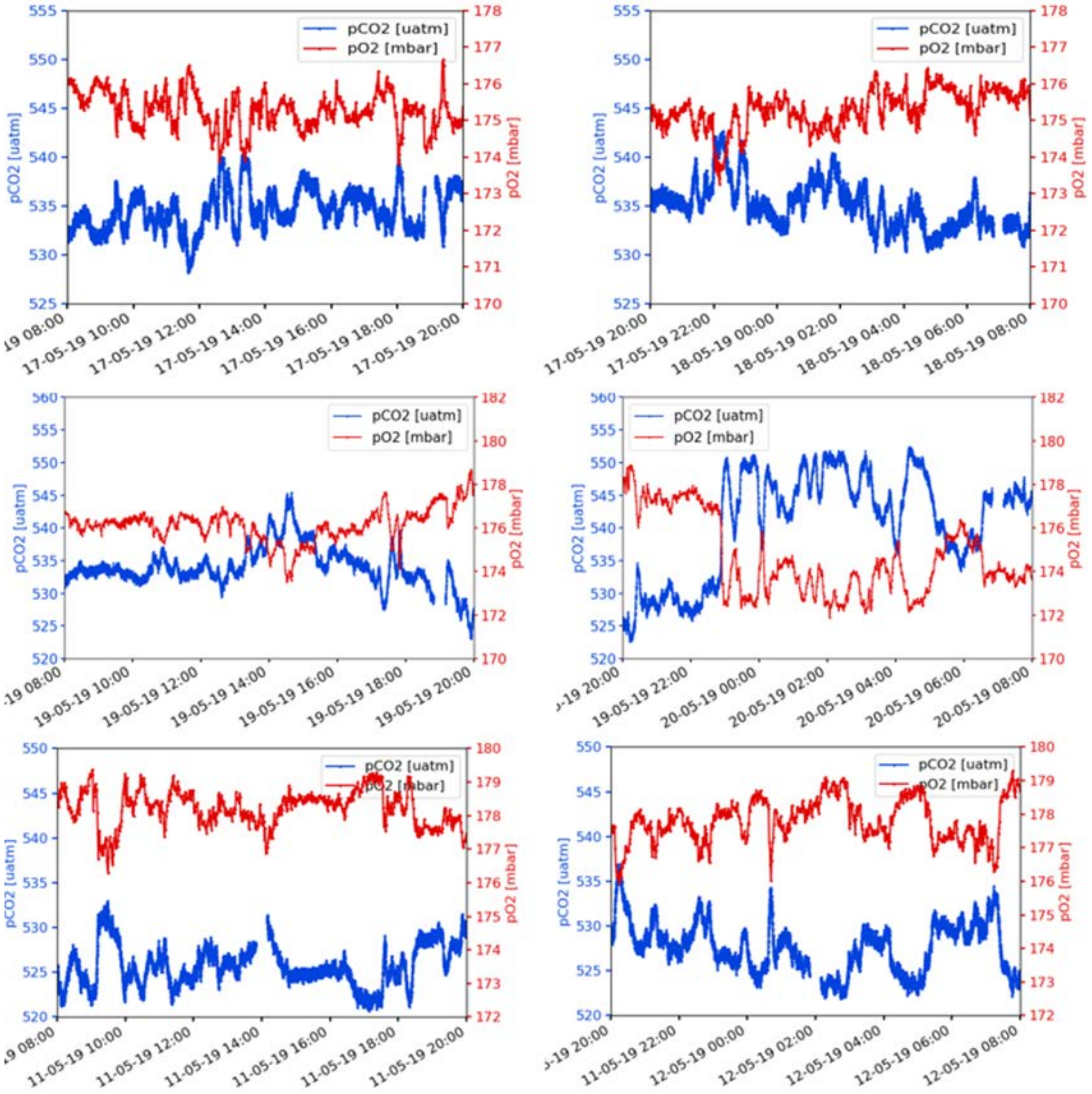

Figure 4-1 Baseline conditions: observed inverse correlation between CO_2 and O_2 for three days and three nights without controlled CO_2 release

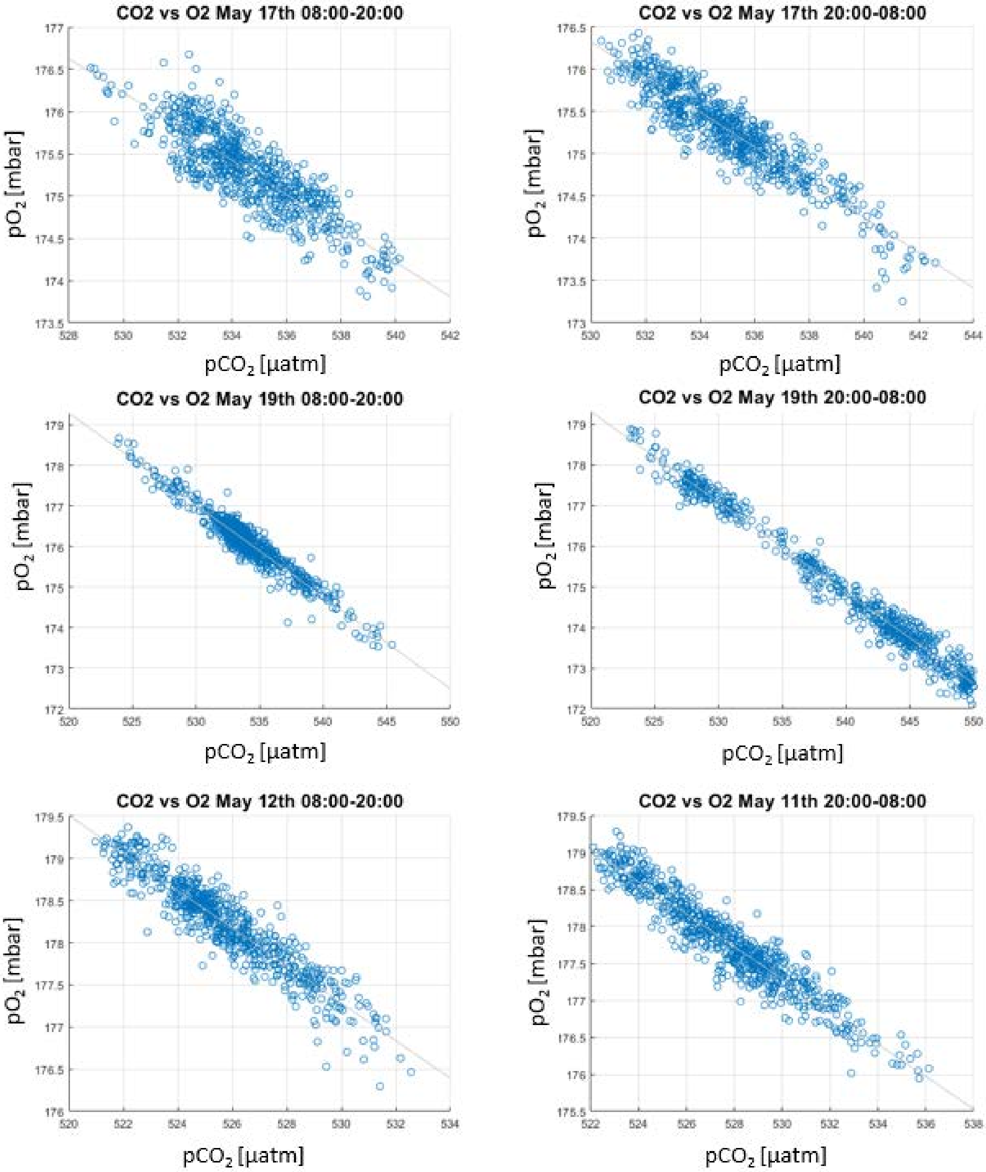

Figure 4-2 Baseline conditions: scatter plots of pCO_2 and pO_2 for the same time periods as in Figure 4-1 indicating the linear relationship during baseline conditions

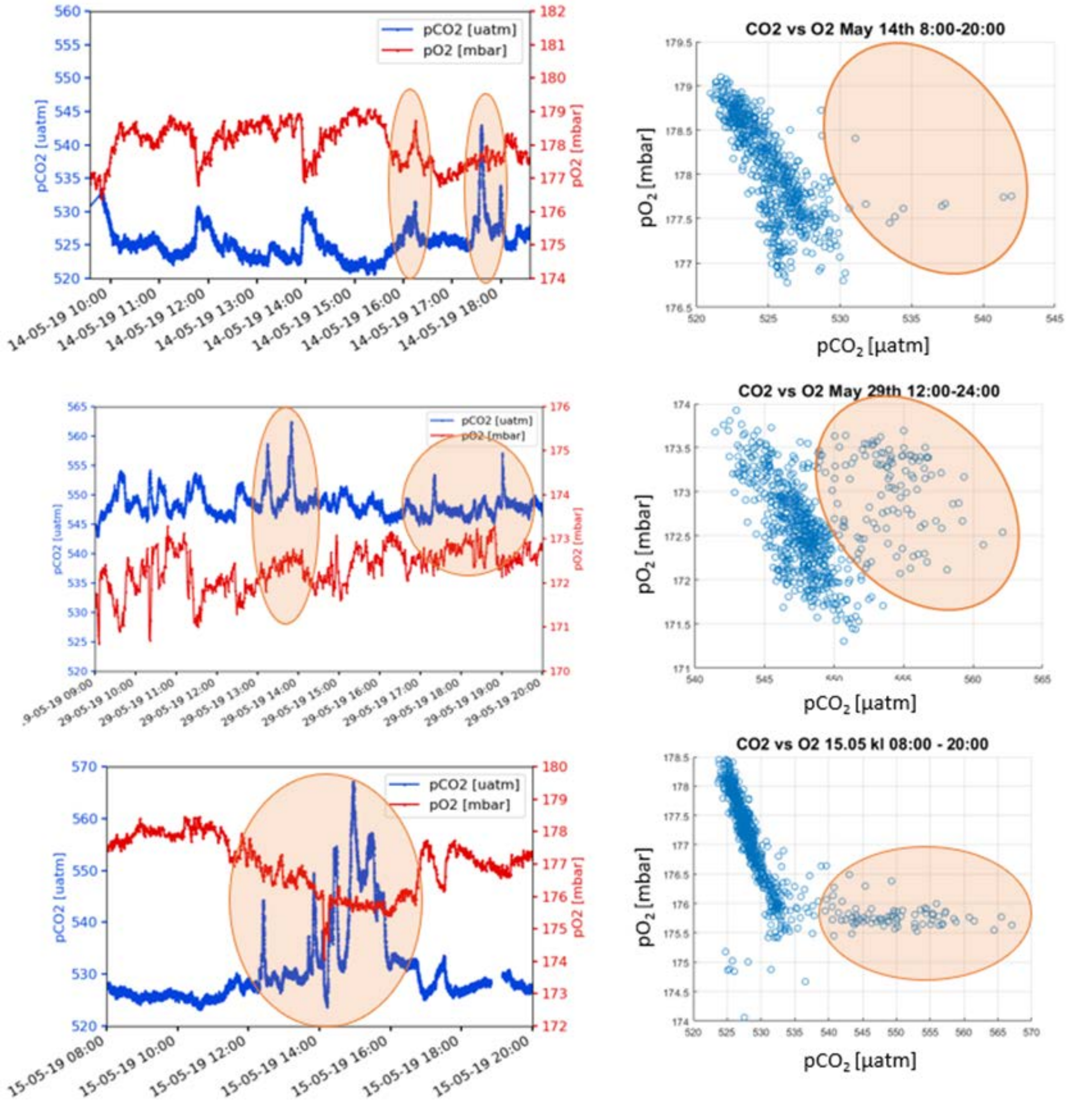

Figure 4-3 Measured CO_2 and O_2 during periods with a controlled CO_2 release (left), and the corresponding scatter plots with deviations from a linear correlation (right)

The amount of data produced during continuous acquisition at high sample rates is substantial, and automatic methods are required to reduce this data set to information which is relevant for an operator. While this is a topic for further research, we describe a preliminary algorithm for automatic anomaly detection below. This method shows consistent results when applied to data from the ACT4storage release experiment.

Proposed algorithm:

1- Measure pCO_2 and pO_2 using co-located sensors placed close to a point of interest (preferably < 60 m for detection of 1 tonne CO_2/day). Ensure a high sampling rate (0.1 – 1 Hz), and sufficient deployment time (days to months).
2- Align sensor measurements in time.
3- Filter measurements to remove obvious spikes or invalid measurements.

4- Detect anomalies by identifying time spans where the CO_2-O_2 relationship deviates substantially from the expected correlation. (Figure 4-4). In this preliminary algorithm, CO_2 samples deviating by more than two standard deviations from a predicted linear correlation are identified as anomalous. More refined algorithms should be developed and is left for future work.

Figure 4-4 shows the results of this algorithm applied to a section of the ACT4storage data. The CO_2 curve is in blue, while the red region indicates anomalous samples. The yellow and green rectangular lines indicate release of CO_2 in gas- and dissolved phase, respectively. While the time between a release and a measured anomaly varies (mainly due to ocean currents), we consistently observe anomalies related to significant CO_2 release events, without the presence of false alarms.

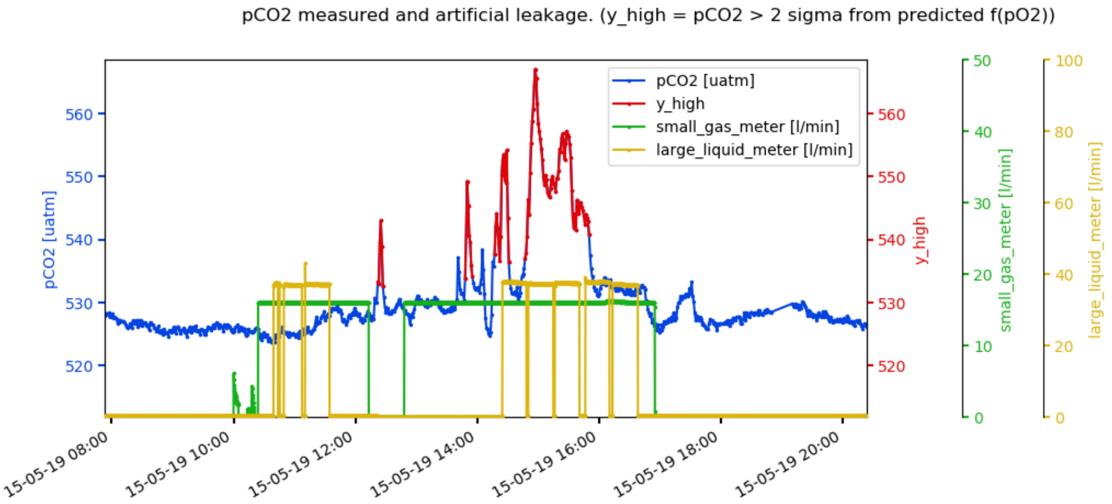

Figure 4-4 Chemical anomaly detected during the ACT4storage controlled release experiment. Blue line: Measured pCO_2 where the concentration is within 2 standard deviations from what is predicted from concurrent O_2 measurements (blue). Red line: Measured pCO_2 where the concentration deviates with >2 standard deviations from what is predicted from concurrent O_2 measurements. Green and yellow lines indicate artificial release of CO_2 in gas and liquid phase respectively.

Finally, it should be noted that this approach is aimed at detecting anomalies near a defined focus area such as a well and does not necessarily capture large-scale oceanographic changes such as increased seawater acidity. The latter is better described using a chemical baseline approach (Abdirahman, Maribel, & Alendal, 2019).

Placement of chemical sensors:

Chemical anomalies related to CO_2 escaping into the water column are predicted to be localized to within a few tens or hundreds of meters of the leak, depending on the leak scenario (Alendal, et al., 2014) (Blackford, et al., 2020). We also expect the chemical footprint of a CO_2 leak to be found close to the seabed. While CO_2 bubbles may rise several tens of meters above the seabed, most of the CO_2 is dissolved within the first few meters above the seabed. As CO_2 from the bubbles is dissolved into the surrounding water it produces a water mass with higher density, causing it to gradually sink toward the seabed. In the absence of bubbles, a dissolved CO_2 leak will also be expected to stay near the seabed, unless the accompanying pore fluids have a lower density than the surrounding water (i.e., low saline pore water). Therefore, the placement of a stationary template should be near the seabed, with the chemical sensors as close as possible to the seabed without risking excessive exposure to sediments and marine vegetation.

Recommended sampling rate and measuring interval – stationary template:
Based on the experience from the act4storage controlled release experiments, we conclude that is important to have an adequately high sampling rate to capture short-term anomalies. This is because the CO_2 enriched water after stabilising horizontally based on its density, is likely to move and mix with ambient water horizontally in a randomly manner. This process is often referred to as eddy diffusion. This means that the water mass with enhanced CO_2-concentration can move out and over the sensors in an unpredictable manner and that the high sampling rate is necessary to collect as much data as possible when the leak-plume reaches the sensors, enabling a reliable detection of the anomaly. We recommend a sampling rate of 0.1-1 Hz.

One of our findings from the ACT4tsorage experiment was that even with a continuous CO_2 release with high flow rate (estimate from report), the anomaly measured by the chemical sensors a few metres away is of variable and often of short duration. We expect that this is a result of plume dynamics, and the effect that a plume of CO_2-enriched water reaches the sensors and passes by them before it sinks below the sensors and the CO_2 accumulates near the seabed. This could also be related to eddy diffusion. In the leftmost plots in Figure 4-3, five anomalies are highlighted by coloured ellipses. The CO_2 release is continuous and similar for all cases (except for varying salinity and minor variations in release rate), and we observe that the anomaly persists between ten minutes and about two hours. For the ten-minute events, a sampling rate of 1 Hz results in 600 samples which makes it possible to statistically identify this anomaly from the background. With a lower sample rate of e.g. 1 sample/minute, this event would be difficult to detect.

Temporal variations both in event duration and the time it takes a plume to reach the sensor sets some demands to the measurement duration. We recommend continuous data recording when possible. In situations where battery capacity is a limitation, an option would be to define a measuring pattern where the sensors record data at a high sample rate for pre-defined time periods (for example 4 hours of continuous data acquisition, followed by 8 hours "sleep mode"). This can be particularly relevant for remote locations and when using CO_2 sensors requiring a pump since these draw more power than e.g. pH and O_2 sensors. The data acquisition pattern should take ocean currents into account, ensuring that the sensors record data while downstream of a potential leak point.

5 Summary and discussion

In this report we propose sensor technologies and platforms suitable for a marine monitoring study for geological carbon storage, ranging from relatively low-cost solutions to highly detailed studies. We avoid generic recommendations since a successful GCS monitoring plan should be site specific and related to local risk assessments and monitoring strategies. Our intention is to present the full spectrum of options, such that a meaningful selection can be made according to the site-specific risk assessment and cost considerations. We propose monitoring solutions suitable for monitoring at different scales, from a continuous monitoring of a single point of interest to screening surveys covering several tens of km^2. We also summarize which technologies are capable of detecting relevant features including pockmarks, bacterial mats, gas bubbles in the sediments or rising through the water column, shallow buried channels and accumulations of shallow gas, and chemical anomalies related to a non-biotic source of CO_2. Detection ranges and expected sensitivity for the different technologies are estimated.

This report is based on the findings and experiences from the ACT4storage project, as well as available information from related research projects and literature. While we have evaluated a wide range of sensor technologies available on the market, this is a field in rapid development and there may be recent advancements which are not captured by this study. For example, the eddy covariance method has previously been used to monitor gas exchange between sediments and the atmosphere or the sea and was tested and validated for marine GCS monitoring within the scope of the STEMM-CCS project (Burba, Madsen, & Feese, 2013). The method seems promising for detection of CO_2 anomalies, and requires that sensors are placed very close to the source. It could thus be implemented by installing sensors on a seabed template close to the point of interest (e.g. CO_2 injection well).

5.1 Future work

Technologies for successful marine GCS monitoring are available on the market. On-going developments include more durable AUVs and gliders, and solutions for increasing the sensor payload on these. Thus the building blocks for reliable monitoring solutions are in place, and specific systems including solutions for power supply and data communication, embedded processing and automatic warning systems can be designed and implemented in cooperation with industry and GCS operators.

To further pave the road for implementing large scale GCS, an important goal related to environmental monitoring is cost reduction without compromising the assurance quality. An important step in that direction, is to reduce the required human effort while increasing the reliability of automated processes. Specific relevant topics include:

Data acquisition - Autonomous sensor platforms; we expect this technology to mature drastically over the lifetime of a storage project in terms of deployment, range, sensing capabilities and autonomy.

Automated data analysis - Build a framework for automated analysis and develop targeted algorithms to handle the large amounts of data, and to provide automatic warning systems minimizing the need for human involvement.
Integrated monitoring / data based operations - A framework for decision support, i.e. determining which mechanisms/situations should trigger changes in the monitoring scope, and what these changes should be. This framework should include not only the marine environment, but also integrate data from reservoir and overburden.
Leak quantification – While several approaches to leak quantification have been tested and show promising results, further studies and experimental verification is needed to reliably quantify CO_2 emissions.

Another important research task is to optimize the chemical monitoring by modelling the eddy diffusive mixing of CO_2-enriched water from a leakage in order to improve estimates of the probability of detection at different distances from the source.

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Appendix A

TECHNOLOGY OVERVIEW

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A1 Sensor technologies

Acoustic sensors (sonars, echo sounders and hydrophones) and chemical sensors are considered the most relevant sensors for marine environmental GCS monitoring. Chemical sensors are point sensors and need to be in contact with the affected water to identify anomalies such as increased levels of CO_2. Maintenance is typically required every 3-6 months to achieve acceptable accuracy and to remove marine growth. Active and passive acoustic sensors are remote sensors and can detect bubbles or seabed features at a distance. Maintenance requirements are typically lower than for chemical sensors.

Sensor	Can detect	Range	Response time	Maintenance/ calibration interval
Chemical	Dissolved CO2 and related chemical changes	0m (~10-100 m detection distance)*	Seconds to minutes**	6 months
Active acoustic	Bubbles in water	10 – 5000 m	Near instant	1 year
Passive acoustic	Bubbles in water	~10-50 m	Near instant	1 year

Figure A1.1 We consider chemical and acoustic sensors the most relevant sensors for marine GCS monitoring. A range of sensors are available on the market with diverse applications, capabilities and limitations. In general, chemical sensors are point sensors while acoustic sensors are remote sensors. Chemical sensors require frequent maintenance to ensure stable and accurate measurements, while acoustic sensors generally can operate over a longer period without maintenance.

** Depending on leak rate and leak duration, as well as ocean currents.*

*** This is sensor-dependent, with membrane-based sensors including most available CO2 sensors have a longer response time than for instance pH sensors which do not rely on the water diffusing through a membrane.*

A1.1.1 Chemical sensors

Several chemical sensors on the market are designed to measure the aqueous concentrations of specific chemical components that can be directly or indirectly associated with leakage of CO_2. Since seawater naturally contains many different chemical components, including CO_2 at variable concentrations, these sensors must give reproducible measurements that are solely an effect of the concentration of the analyte and not influenced by (or this can be corrected for) concentration changes of other components.

pCO_2: Several pCO_2-sensors are commercially available. In most cases, pCO_2 sensors are equipped with a membrane between the water column and an internal chamber where

CO_2 in gas phase is quantified. It is assumed that the concentration in the gas phase is in equilibrium with the concentration in the water column. The transfer of CO_2 through the membrane means that there is a time lag between the concentration in the water phase and the concentration in the gas phase. The time lag has a consequence for survey strategies; if the sensor is mounted on a vessel, the vessel should preferably remain stationary until equilibrium is reached whenever the concentration is measured. For an AUV or a glider passing through a CO_2 plume, the sensor response time sets a lower limit to the size of a plume which can be detected. Physical obstacles such as marine growth may further reduce the rate of diffusion through the membrane; this is a potential challenge for long-term installations and biofouling technology must be considered.

During the ACT4storage controlled CO_2 release experiment we used the Franatech pCO_2 sensor and the CONTROS HydroC pCO_2 sensor. Both types of sensors were mounted on a seabed template placed at varying distance from the leak frame, and also integrated on the HUGIN AUV. Detailed results are documented in D3 – 2019 Nearshore evaluation report, 2019. In general, the CONTROS HydroC performed well when mounted on a stationary seabed template and consistently identified anomalies related to a simulated CO_2 leak. Due to hardware issues the Franatech sensors did not provide valid data. When mounted on the HUGIN AUV the Franatech and CONTROS HydroC sensors performed similarly, but neither was able to detect the simulated leak because of the sensor time lag (response time). The leak was only identified after applying Response Time Correction (RTC) in the post processing of the data.

pH: The concentration of H^+-ions (acidity) can be measured in the seawater by a pH electrode where the H^+-ions is adsorbed to a glass membrane creating a potential difference between the inside and the outside (sample side) of the glass of the membrane. pH sensors are widely used in marine research, and performance has been evaluated on several occasions. For application to GCS sensor accuracy is a challenge since modelling estimates smaller changes in pH, typically less than 0.03 pH-units at a few hundred meters distance from moderate leakages (Alendal, et al., 2014). New developments are ongoing in several EU-projects for a higher precision (<0.001) sensors also using the marine standard for pH bases on the total scale. (Reggiani et al). The highest accuracy is needed when it is important to compare pH-values measured for instance at the same location at different times and when the measurements are done during different sampling campaigns and typically with different pH-sensors. However, measurements of relative changes in pH, as an indication of changes in pCO_2, can also have great value in the monitoring and then the precision of the sensor is much more important than the accuracy.

During the ACT4storage controlled release experiment we used an Idronaut pH sensor with a reported accuracy of 0.01 pH units. This sensor performed well both on the stationary seabed template and when mounted on the HUGIN AUV. The faster response time made it possible to identify the simulated CO_2 leak as the AUV passed through the plume (see D3 – 2019 Nearshore evaluation report for details).

A1.1.2 Acoustic sensors

Active acoustic technologies applicable to GCS monitoring include multibeam echo sounders and sonars, scientific echo sounders, single beam scanning sonars, side-scan sonars and synthetic aperture sonar (SAS). With the exception of SAS systems which require a moving platform, all of these technologies have the flexibility to be mounted either on the hull of a surveying vessel, on an AUV, or on a stationary platform for long-term monitoring. Hull-mounted multibeam echo sounders as well as scientific single- and split beam echo sounders are currently state-of-the-art for marine gas seep detection.

The range and diversity of active acoustic sensors makes it possible to tackle different monitoring tasks including efficiently mapping gas seeps using vessel-mounted multibeam echo sounders with large area coverage, imaging the seabed in a centimeter resolution in order to identify features related to fluid flow using an AUV-mounted synthetic aperture sonar (SAS), or passively "listening" for bubbles using a hydrophone with low power and maintenance requirements. These technologies are briefly described below, and their applicability to marine GCS monitoring discussed. Where possible we include examples and lessons learned from the ACT4storage controlled release experiment.

Multibeam echosounders and sonars: Multibeams can be divided into two main categories; *multibeam echosounders* used for seafloor mapping purposes (normally mounted on the hull of a survey vessel or AUV), *and multibeam sonars* (normally mounted on an ROV or stationary platform) designed for monitoring a region of interest.

Multibeam echosounders designed for surveying purposes transmit a wide swath of up to 120 degrees in the cross-track direction of the vessel, resulting in a high area coverage rate (up to 10 times the water depth). Typical operating frequencies are in the range 100 kHz to 700 kHz. These systems are excellent tools for surveying large areas, offering an efficient way of creating overview maps including bathymetry and seafloor backscatter. Marine gas seeps are visible as characteristic "flares" rising from the seafloor and into the water column, provided that the acoustic response from the seep is significantly higher than the background. Figure A1.2 illustrates the wide swath obtained by a hull mounted multibeam echosounder. The water column imagery (blue and green) shows the water column data from a single ping. Identified seeps are shown as point clouds, and the seabed bathymetry is in grey. This image is from the University of New Hampshire and has been produced using the QPS Fledermaus software package. Figure A1.3 and Figure A1.4 show data from the ACT4storage controlled release experiment, obtained using the EM2040 and EM70 multibeam echo sounders, respectively. The CO_2 release rate is 1.3 l/min, and with no post-processing applied.

There are several MBES systems available, with Kongsberg Maritime being the main technology provider in Norway (Table A1.1). The main difference between the different available systems is the frequency of the transmitted acoustic pulse. High frequencies offer higher image resolution and can therefor image smaller-scale features on the seabed. However, in deep waters lower frequencies are used due to the strong attenuation of sound at high frequencies.

Table A1.1 Overview of selected Kongsberg Maritime MBES. The SN90 is a relatively new technology showing promising results for seep detection and mapping. All of these sensors were used during the ACT4storage controlled release experiment and they all performed well, detecting CO_2 gas releases as low as 0.1 l/min (not all sensors were tested at this flow rate).

Instrument	Frequency (kHz)	Max range (m)	Beam/Fan width (°)	Swath width factor	Depth rating (m)
EM2040	200-400	900	200	7.5	6000
ME70	70-120	500	2-140	5.5	20
EM710	40-100	3600	140	5.5	20
SN90	70-120	2000	5-160	N/A	20

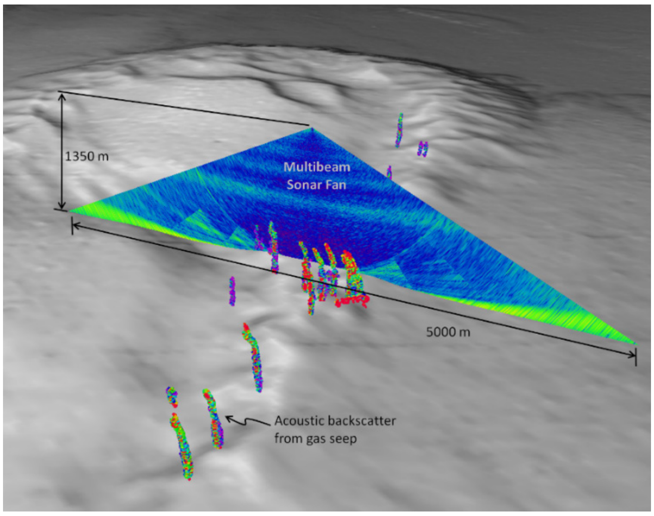


Figure A1.2 An example illustrating the wide area coverage of a hull-mounted multibeam echosounder used for marine seep detection. The seeps have been extracted from the multibeam data. Credit: Image produced by the University of New Hampshire Center for Coastal and Ocean Mapping / Joint Hydrographic Center using IVS Fledermaus software.

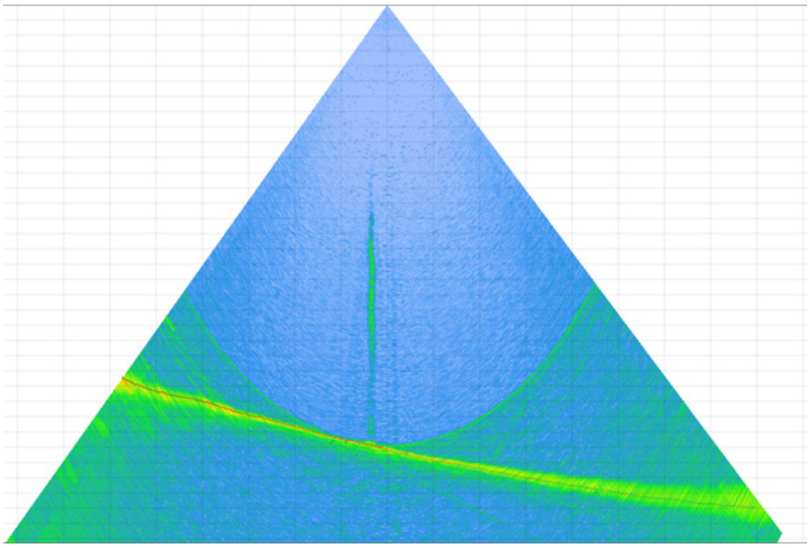
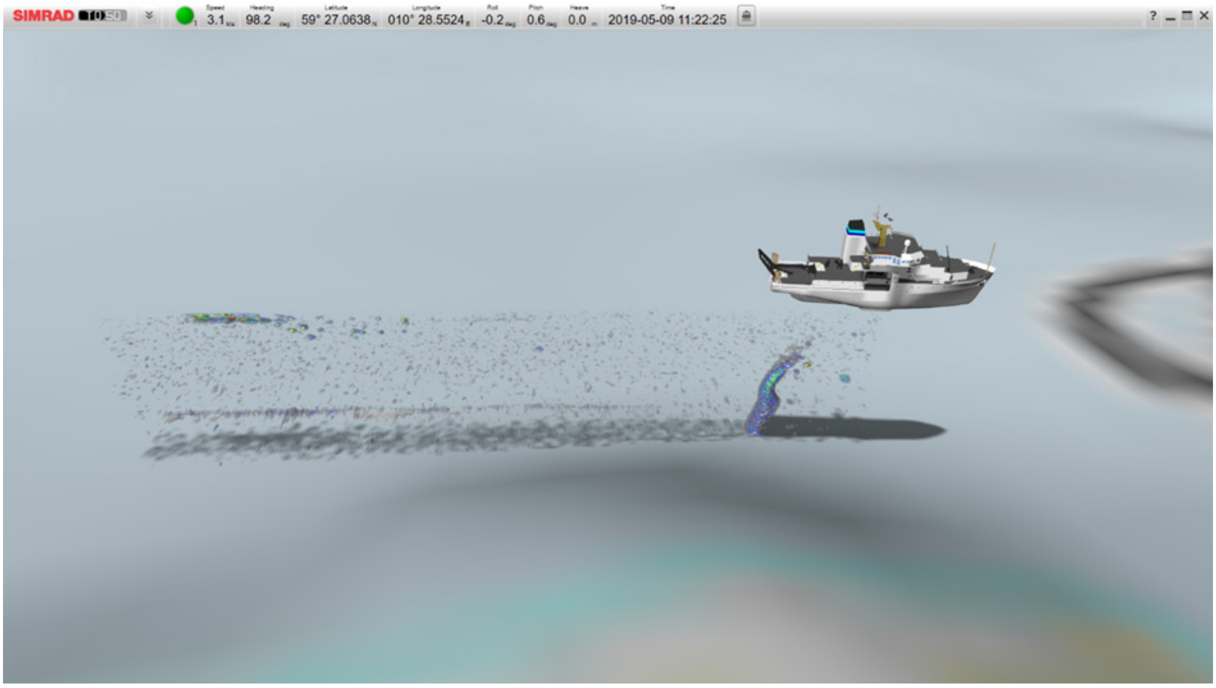


Figure A1.3 *Example image from the ACT4storage controlled release experiment obtained using the EM2040 multibeam echo sounder. The vertical range is 70 m and the seep is visible in the middle of the swath with an observed bubble rise height of approximately 30 m. The release rate is 1.3 l/min CO_2.*



Speed 3.1 kts
Heading 98.2 deg
Latitude 59° 27.0638 N
Longitude 010° 28.5524 E
Roll -0.2 deg
Pitch 0.6 deg
Heave 0.0 m
Time 2019-05-09 11:22:25

Figure A1.4 *Example image from the ACT4storage controlled release experiment, obtained using the ME70 and presented in real time in the 3D visualisation software Simrad TD50. This is from the same simulated CO_2 release as in Figure A1.3., with a 1.3 l/min release rate.*

Multibeam sonars are typically used for inspection purposes or monitoring of a region of interest such as an underwater structure. Figure A1.5 shows an image obtained using the Kongsberg Mesotech M3 multibeam sonar during the ACT4storage controlled release experiment. In this case the sonar was mounted on a stationary template on the seabed, 65 m from the leak frame. A 25 l/min simulated CO_2 leak is visible in the image, as is the leak frame itself and another seabed template placed nearby.

Our experience is that the M3 sonar is less sensitive to small CO_2 releases than the EK80 scientific echo sounder, but still very useful for gaining an overview of an area of interest on the seabed. The operating range is ~100 m, and the angular coverage rate is 120-140 degrees depending on user settings. For optimal plume detection, the user should consider sonar settings including the vertical beamwidth. We used a 30-degree vertical beamwidth since this captures a large part of the water column and thus the reflections from many rising bubbles accumulate making the plume more easily detectable than using the other options (3- or 7-degree vertical opening angle). Further, the vertical tilt of the sonar can be optimized to capture the water column while minimizing the response from the seabed. This increases the sensitivity and ability to detect small seeps. Finally, a background removal filter is available in the accompanying software, which we found useful for increasing the visibility of the CO_2 plume (not applied in Figure A1.6).

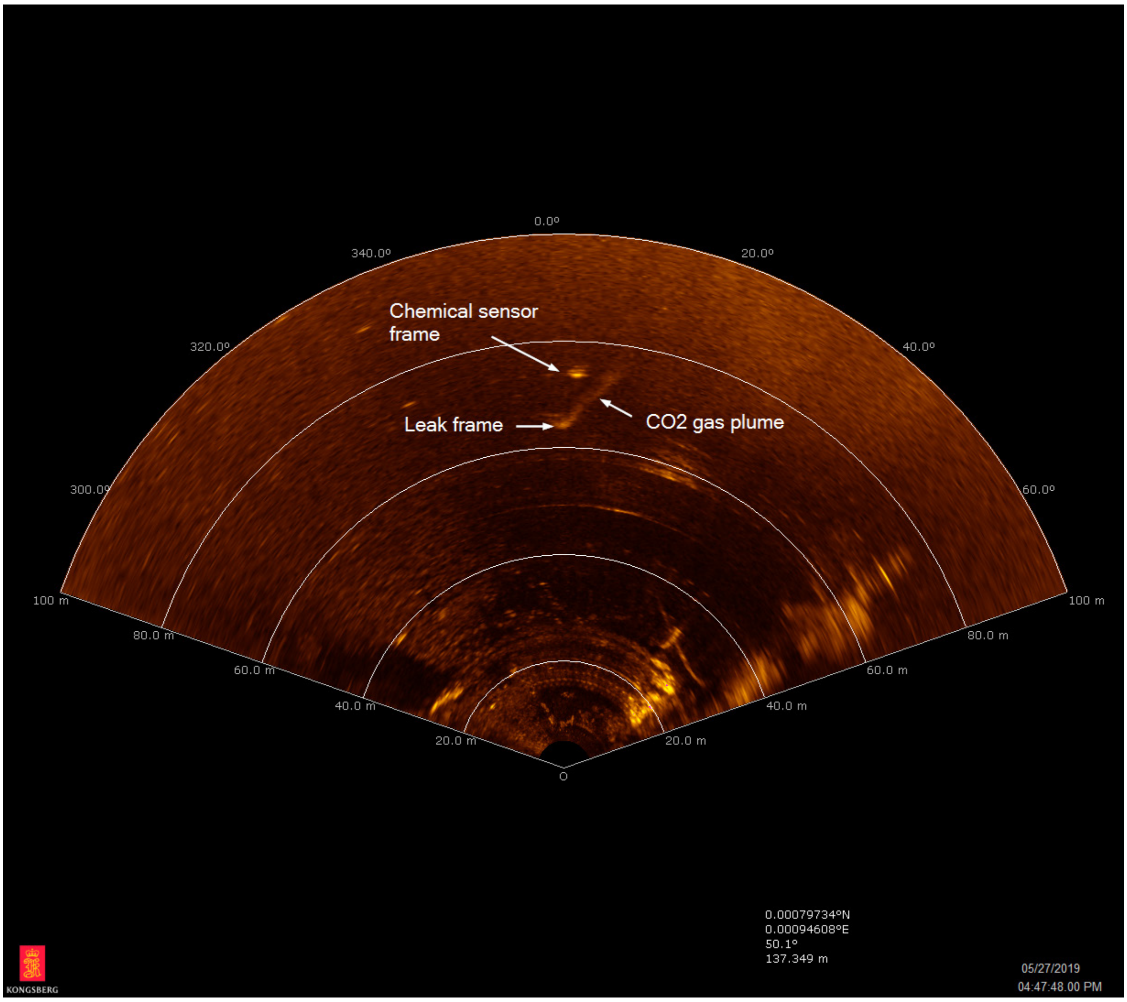


Figure A1.5 M3 multibeam sonar image from a controlled CO_2 gas release of ~25 l/min (CO_2). The CO_2 plume is visible as an extended region of high intensity (bright colour). This sonar image was acquired during the ACT4storage project, with the sonar horizontally mounted on a seabed template at ~60 m water depth (see Figure A1.6).

Scientific fish finding echo sounder: The Simrad EK80 single- and split beam scientific echo sounder has a much smaller area coverage rate than multibeam echosounders (11-degree beam as opposed to 120-degree swath) but has other properties that are useful for leakage characterization. This includes multiple operating frequencies, broadband capabilities, high sensitivity and split-beam capabilities. Multiple operating frequencies or broadband capabilities are useful for seep detection and characterization, since the acoustic bubble response is highly frequency dependent. The EK80 scientific fish finding echo sounder can be calibrated, which makes it possible to relate the target strength to bubble flux, given an estimate of the bubble size distribution.

During the ACT4storage controlled release experiment we used the EK80 mounted on a seabed template observing the simulated CO_2 leak from a horizontal angle (Figure

A1.6), as well as on the Simrad Echo R/V observing the release from above (Figure A1.7). The CO_2 release rate is 1.3 l/min in both Figures.

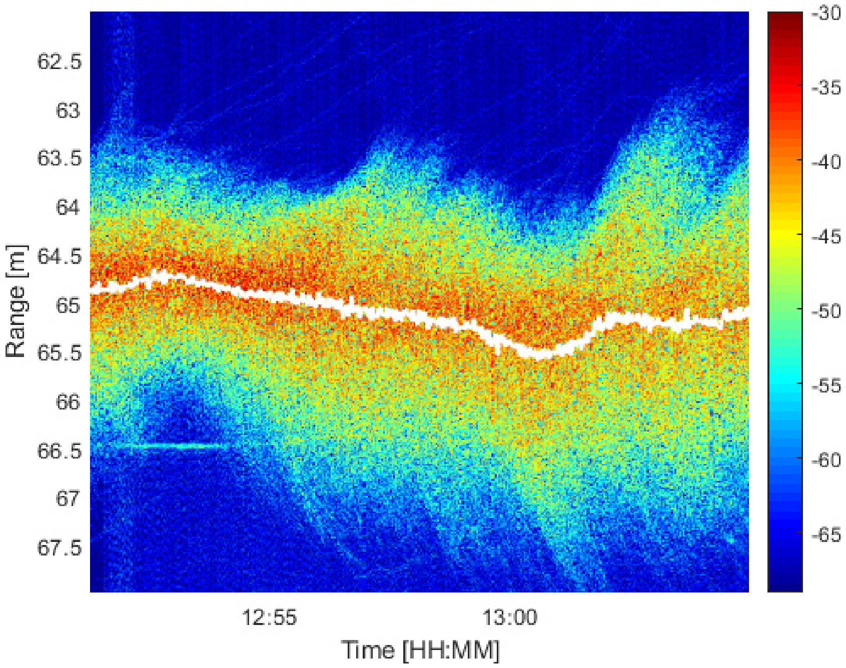


Figure A1.6 *EK80 single beam echo sounder data showing the response to a 1.3 l/min leak at 65 m water depth. The distance between the echosounder and the gas release is 65 m.*

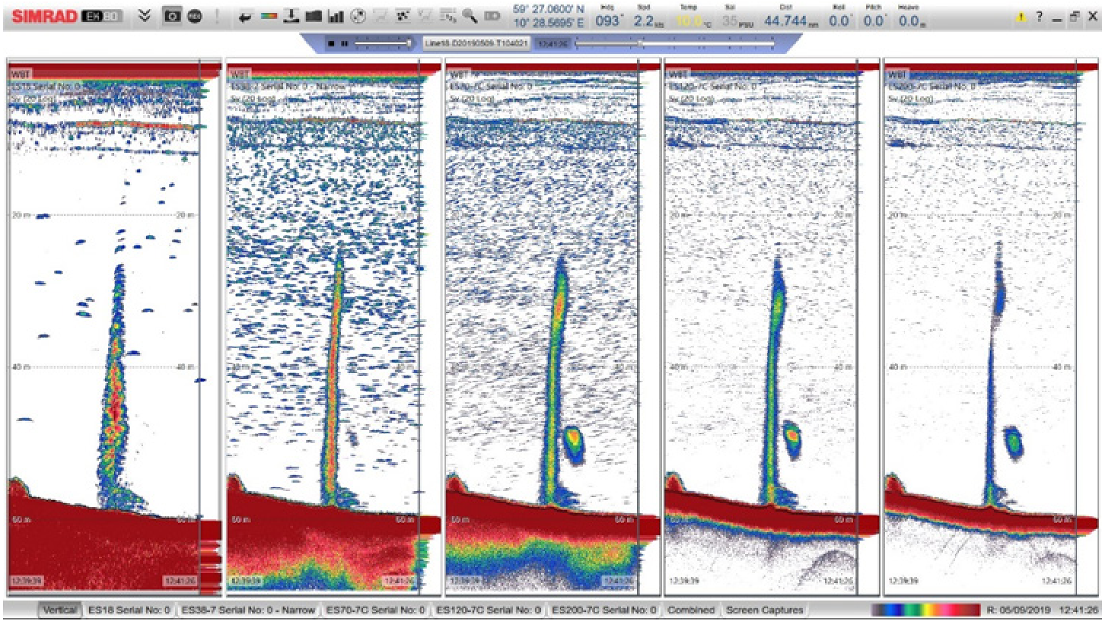


Figure A1.7 *The EK80 shows the acoustic response of the CO_2 plume at different frequencies, ranging from 18 kHz in the leftmost panel to 200 kHz in the rightmost panel. The plume is observed nearly 40 m above the release point (60 m) at the seabed, with a leak rate of 1.3 l/min.*

Single beam scanning sonar: This technology has seen long-term usage as part of an alarm system aimed early detection of gas leaks beneath a subsea construction (Strout, Sparrevik, Hayes, Kvistedal, & Tollefsrud, 2014). The narrow beam width and low side lobe levels of a mechanically rotating single beam sonar was chosen to avoid acoustic interference from metal and concrete structures. This technology has a potential for monitoring near wellheads or other infrastructure. Typical operating frequency range is 300 kHz to 600 kHz.

A high-resolution scanning sonar of the same type as the ones installed in (Strout, Sparrevik, Hayes, Kvistedal, & Tollefsrud, 2014) was used during the ACT4storage controlled release experiment. It was installed on the same seabed template as the EK80 and the M3, 65 meters from the leak frame. We found that at this distance the simulated leak was difficult to detect. This could be related to the limited range of this sonar, but it could also be a result of suboptimal sonar positioning. While the M3 and EK80 were both placed on a pan-tilt unit making it possible to optimize the sonar viewing angle, the scanning sonar was not.

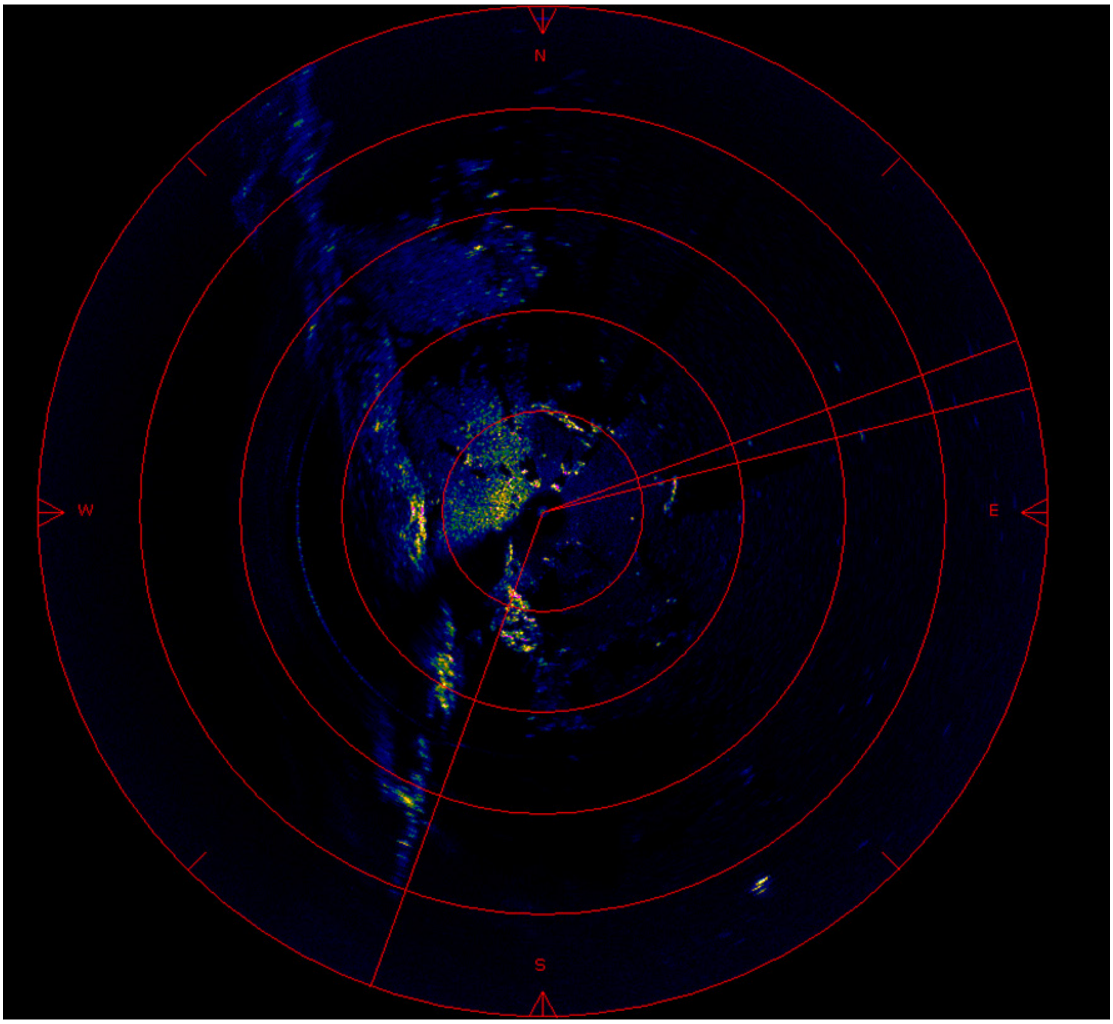


Figure A1.8 *High resolution scanning sonar image showing a complete 360-degree scan of the area. Rocks and boulders are shown on the seabed. We were not able to detect a* CO_2 *leak using this instrument. It should be noted that the position and viewing angle of this sonar was not optimized since it was not placed on the pan/tilt unit. The limited sensitivity and dynamic range of this sonar makes it better suited for leak detection at closer range (< 20m).*

Side scan sonar: Side scan sonars are normally mounted on an AUV or a towed vessel, operating near the seafloor and using the vessel movement to form an image of the seafloor by concatenating many consecutive pings. Side scan systems operate either at high frequencies for high resolution seafloor mapping, or at intermediate or low frequencies for range coverage at the expense of a lower image resolution. The cross-track resolution is limited by the operating frequency and the receiver length (D), roughly calculated as wavelength/D. While sidescan sonars have been used to map bubble seeps at the seafloor, the imaging geometry makes seep detection challenging. An AUV normally travels near the seafloor and views the seeps at an angle such that acoustics returns from the seep are combined with the acoustic response from the seafloor. Sidescan sonars may still be applicable to GCS monitoring, by changing the imaging geometry (i.e, mounting the sonar at an angle that avoids mixing the acoustic returns from the seafloor and bubbles present in the water column). Again, multiple receive elements can be used to enhance seeps and improve detection capability. Figure 5 shows an example sidescan image acquired using the HISAS 1030 system operated in sidescan mode. In this case, the small methane seep near the middle of the image is difficult to detect by visual inspection but can be automatically detected by making use of the system's interferometric capabilities (two vertically separated receiver arrays) (Blomberg, Sæbø, Hansen, & Austeng, 2016). We did not use a sidescan sonar during the ACT4storage project, but used a similar but more advanced synthetic aperture sonar (SAS) instead.

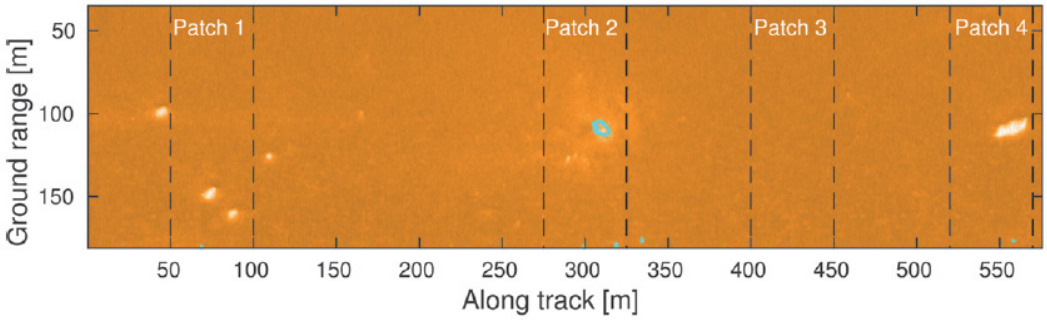


Figure A1.9 A sidescan image acquired using the HISAS system operated in sidescan mode. A small methane seep from a leaking well is present near the middle, and the blue line indicates where it has been automatically detected using an algorithm which combines sidescan image intensity with interferometric coherence (Blomberg, Sæbø, Hansen, & Austeng, 2016). Notice that when looking only at the sidescan (or SAS) image, it is difficult to differentiate between bubble seeps and other highly scattering objects on the seafloor.

Synthetic aperture sonar (SAS): SAS has become a mature seafloor imaging and mapping technology in recent years. SAS systems are based on the same hardware as a sidescan systembut achieve significantly higher cross-track resolution by using the vessel movement to synthesize a long receiver array. SAS systems are typically AUV-mounted and can achieve seafloor imagery and bathymetry on a centimeter scale. High-resolution seafloor imagery makes it possible to detect the presence of seep-related features on the seafloor, such as pockmarks and bacterial mats. Recent research shows that an interferometric SAS sensor may also be used to automatically detect the presence of bubbles in the water column (Blomberg, Sæbø, Hansen, & Austeng, 2016). During the ACT4storage controlled release experiment we used the HISAS 1030 mounted on the HUGIN AUV to document the CO_2 release at the seabed (Figure A1.10 and Figure A1.11). The leak frame as well as Template A is visible in the image. No CO_2 is released in Figure A1.10, while Figure A1.11, shows the CO_2 plume with a release rate of 25 l/min. These images were formed using standard "out of the box" processing in the FOCUS software package. Further image enhancement and dedicated post processing may be performed to enhance objects of interest including gas plumes.

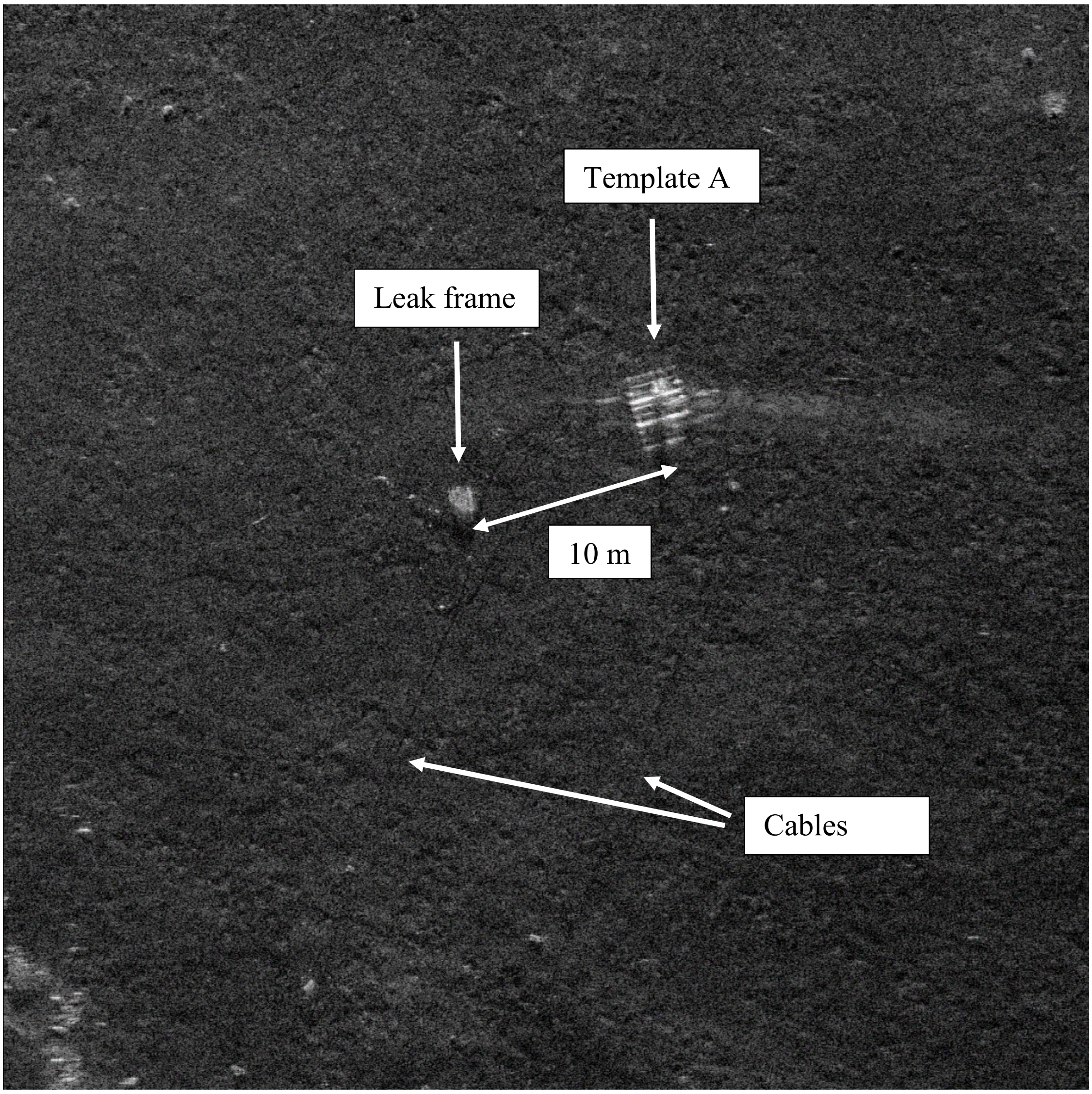


Figure A1.10 HISAS image of the seabed including the leak frame and Template A. This image has a 4 X 4 cm resolution. Notice that cables and hoses on the seabed are visible in the image.

We observe that gaseous CO_2 is nicely documented using the HISAS sonar. The ability to image the bubbles, however, depends on the imaging geometry. Taking the sonar field of view into account, we observe that the CO_2 plume is best imaged when the AUV is traveling at a height of 30-50 m above the seabed. When the AUV s traveling near the seabed (10 m), the plume is completely missed when the distance to the plume is larger than 50 m. Based on these observations we conclude that the HISAS is useful for detecting and imaging CO_2 gas plumes, and that the imaging geometry should be considered when planning the AUV travel path.

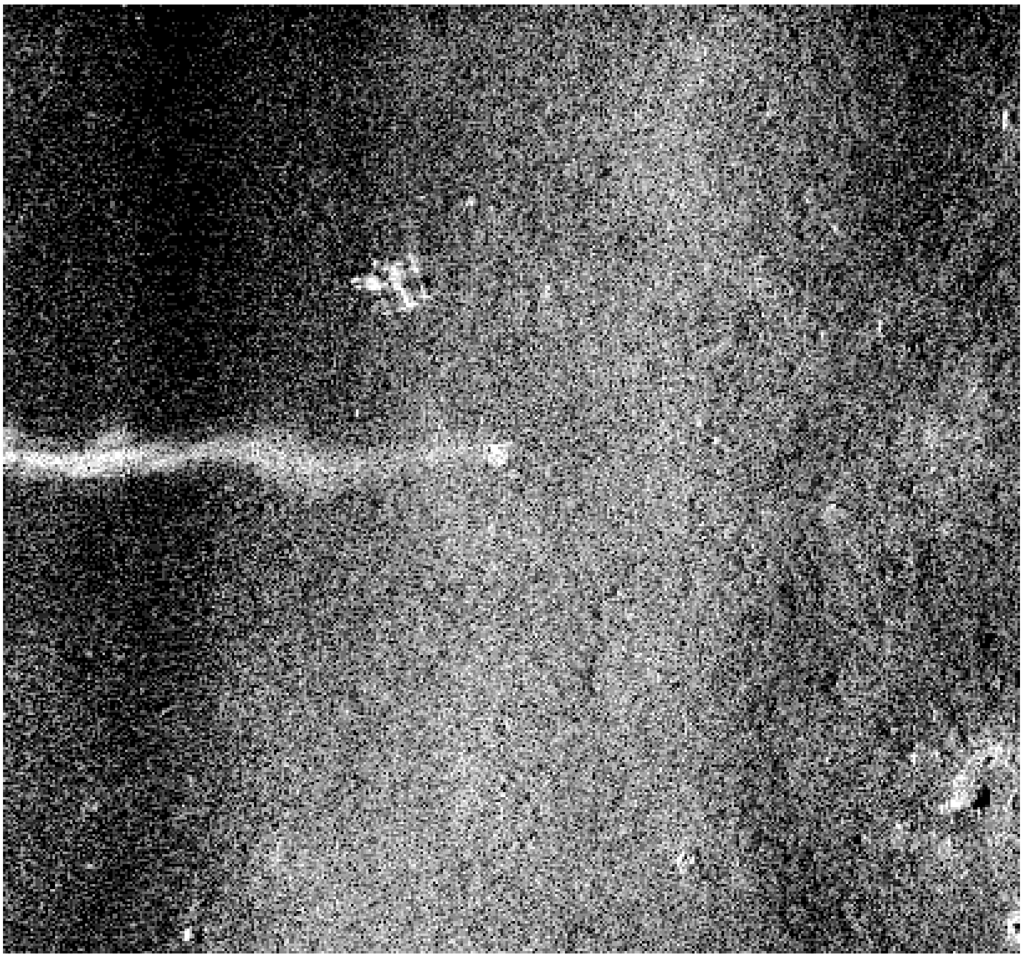


Figure A1.11 Example HISAS image showing the CO_2 gas plume during an 25 l/min release. In this case the AUV travelled 50 m above the seabed, and the distance between the AUV and the leak frame is 30 m.

Passive acoustic sensor/hydrophone: Gas bubbles emit several characteristic sounds in water; a distinct sound as the bubble enters the water column from the seabed, a characteristic sound caused by the oscillations of a gas-filled bubble in a fluid, and a high-frequent sound caused by a bubble as it bursts. Passive acoustic sensors (hydrophones) are able to measure these sounds, but the acoustic signal power is the power emitted from the bubbles alone, which is generally much lower than what is achievable using active acoustic systems. Consequently, hydrophones have limited sensitivity and operating range in areas with significant background noise. Passive acoustic sensors have low demands to power and data bandwidth. The technology is also relatively inexpensive, and the technology may be a candidate for leakage detection at sites with large spatial extension or for contingency monitoring at suspected emission sites for long-term monitoring and quantification.

A1.1.3 Other sensors technologies

Additional sensors potentially relevant for environmental include optical sensors, fibre optics, and recent sensor developments such as lab-on-a-chip for in situ automated chemical analysis of nutrients and other chemical species. Optical sensors (cameras) are useful in some cases and are standard equipment on ROVs. Their main limitation is the need for good light conditions and limited range. In practice, a camera must be placed within a few meters of the point of interest, and the image quality suffers when there are particles in the water.

A2 Sensor platforms

A dedicated marine monitoring program for GCS is likely to make use of several platforms, or sensor carriers. Stationary platforms are relevant for long-term monitoring of high-risk locations as well as background regions. Mobile platforms, including research vessels, AUVs and gliders are needed for large area coverage.

Sensor platforms are in rapid development, as are the sensors to be mounted on the platforms. Advancements in battery technology combined with sensors developed for low power consumption is making it possible to cover larger areas than before, and/or allowing an autonomous vehicle to carry more sensors. Further, "hybrid" platforms are appearing on the market, blurring the line between the different platforms. For monitoring purposes, these advancements allow for flexible, dedicated solutions, increased coverage rate, and more cost-efficient monitoring.

A2.1.1 Research- and survey vessels

Figure A2.1 Simrad Echo R/V equipped with MBES, SBES, sonars and a sub-bottom profiler. Image courtesy TU.no

Research- and survey vessels are regularly used to map the oceans and have the advantage of covering large areas. They are particularly well suited for screening surveys, mapping the occurrence of gas seeps as well as seafloor bathymetry including pockmarks. Operating a large vessel is costly, but the advantage is that large areas can be efficiently mapped. These vessels can be equipped with multibeam echo sounders such as the Kongsberg EM2040, with the ability to map the seabed with a swath of ~7.5 times the water depth. Additionally, a sub-bottom profiler (also known as shallow seismics) may be mounted on the hull of the vessel to map the upper sedimentary layer and identify signs of shallow gas or other risk structures. Chemical water sampling may also be performed using a CTD rosette and if relevant chemical sensors.

In order to reduce costs, a ship-of-opportunity concept may be implemented, allowing several users to benefit from one vessel's presence in an area of interest.

A2.1.2 Stationary platforms

Stationary platforms, or templates, may be strategically placed at the seabed for monitoring of an area of interest. The template can be equipped with different sensors tailored to the monitoring task. A major advantage of using a stationary seabed template is the ability to acquire data over time and document changes occurring over time. Another feature of stationary platforms is that the sensors are held at a very precisely fixed depth. Most chemical and oceanographic parameters in the sea have more pronounced variability vertically than horizontally caused by vertical density stratification. This means that the natural changes in these parameters measured on a stationary platform usually will be smaller that if measured with a mobile platform that will to some degree move vertically as well as horizontally. The changes measured on the stationary platform can be completely attributed to changes in the water masses at this fixed point and not to movement of the sensor. This also means that it is easier to detect anomalous changes in pCO_2 coming from sources other than the natural variability often caused by movement and mixing of slightly different water masses.

Key challenges include robust and affordable solutions for data communication and power supply. In remote areas battery packs may be used to supply the sensors with power, and integrated data processing used to reduce the recorded data into a smaller amount of useful information to be stored or transmitted via a combination of acoustic and satellite communication. Maintenance requirements of the sensors placed on the template needs to be considered.

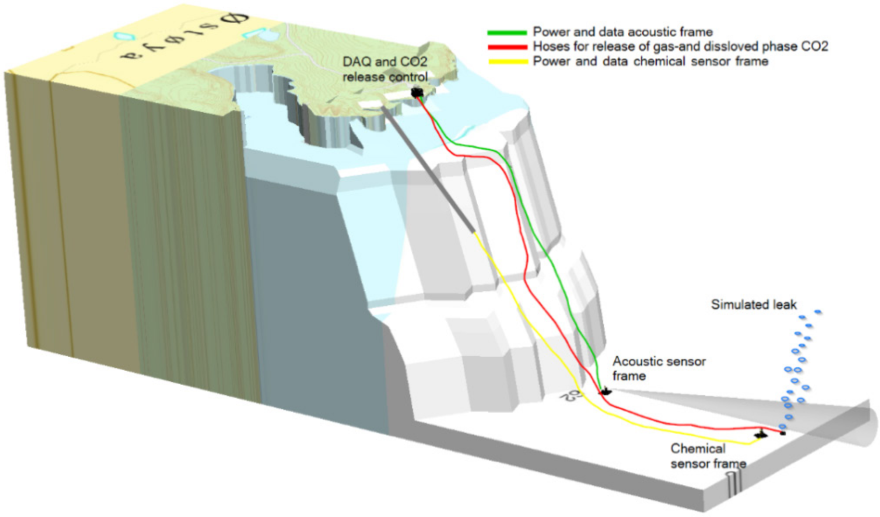


Figure A2.2 *Experimental setup during the ACT4storage controlled* CO_2 *release in 2019. The release frame is placed on the seabed in 65 m water depth, 100 m from shore. One sensor frame instrumented with* CO_2*,* O_2*, pH, salinity, temperature and ocean currents is placed a few meters from the release point (25 m during the first part of the experiment, then moved closer and placed at 10 m distance for the remainder of the experiment). Another frame with acoustic sensors (M3 multibeam sonar, EK80 echo sounder with 70 kHz and 333 kHz transducers, and a high-resolution scanning sonar) is placed 65 m from the release frame. The acoustic beam of the EK80 is indicated by the grey shaded area.*

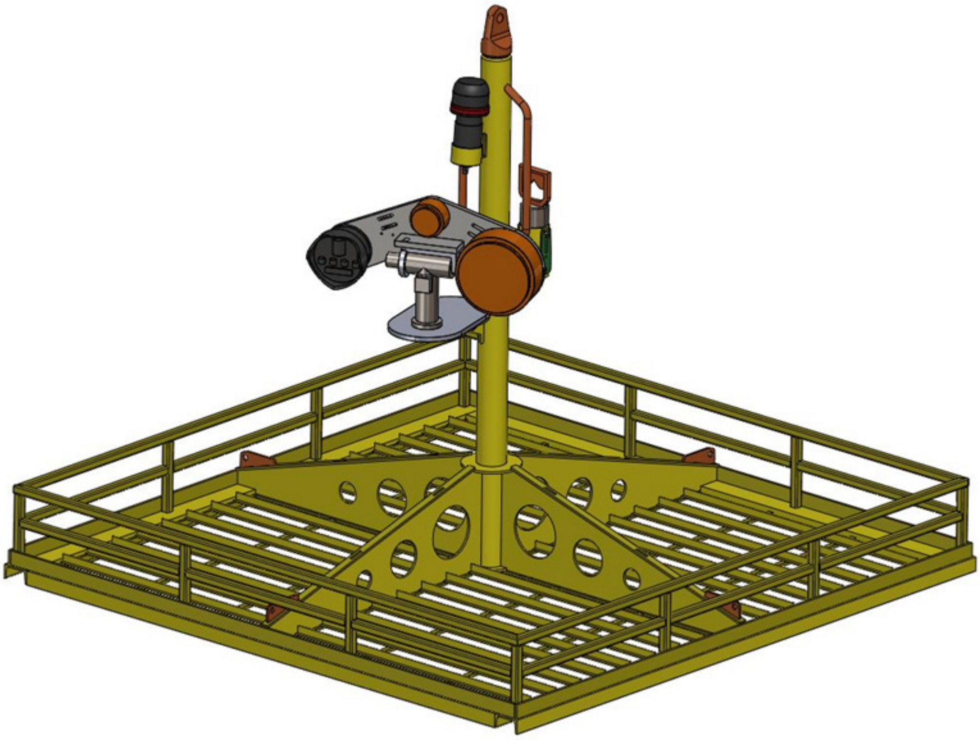


Figure A2.3 *ACT4storage seabed template with EK80 SBES, M3 MBES, and a single beam scanning sonar for bubble detection. The sensors are cabled to the surface for convenient data communication and power supply. For autonomous operation the template could be equipped with battery packs.*

Figure A2.4 *Kongsberg Maritime's K-Lander equipped with passive and active acoustic sensors, Kongsberg c-node for communication quad packs for power supply, and internal data processing.*

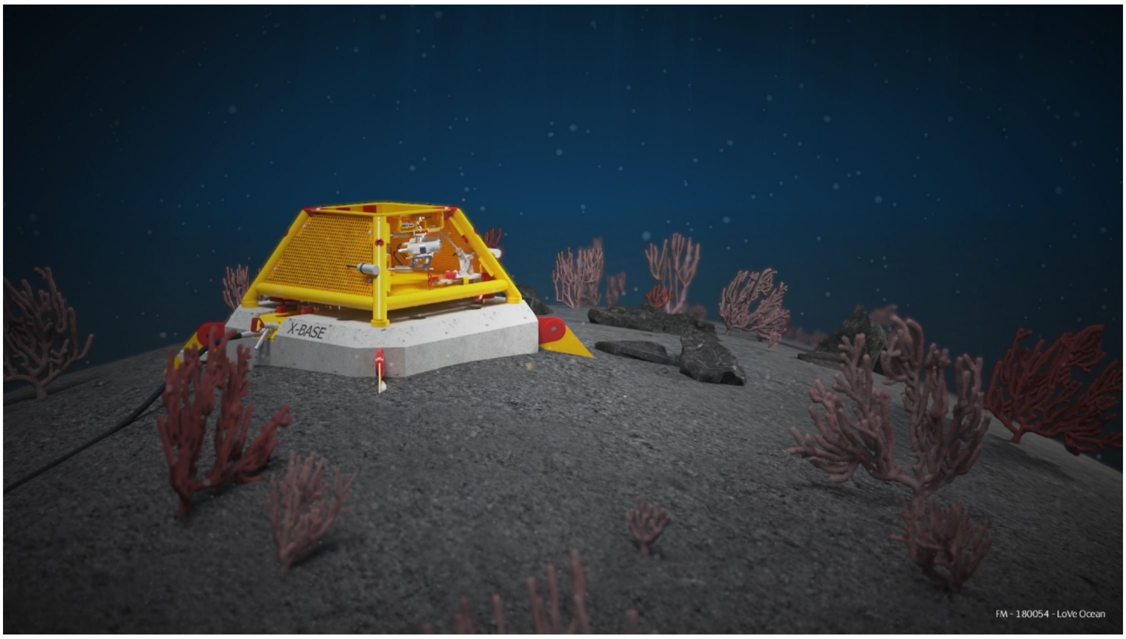


Figure A2.5 X-frame deployed at the LoVE observatory outside Lofoten. Image courtesy love.statoil.com

A2.1.3 ROVs

Remotely operated vehicles (ROVs) are routinely used during many offshore operations. For monitoring purposes, an ROV may be used to capture video recordings from a location of interest, and to acquire water- and sediment samples. In addition, an ROV may be equipped with many of the same sensors as one might place on a stationary template. The ROV can be a very useful tool as it can be moved around to cover a (limited) area or stay in a fixed position over time acting as a stationary template.

A2.1.4 AUVs

An autonomous underwater vehicle (AUV) is designed for remote surveying of large areas subsea. The AUV can be equipped with a number of sensors including active and passive acoustic sensors, chemical, oceanographic and optical sensors. The motion of an AUV is controlled by a combination of buoyancy control and thrusters. There are several types of AUVs on the market, designed for different applications. In general, larger AUVs have limited operational times (12-48 hours) but can carry more sensors including those with high power consumption. Smaller AUV's are less expensive and can have longer operational times but cannot carry the same sensor payloads. A key advantage of the AUV is the ability to operate close to the seabed, while covering a large area.

A2.1.5 Gliders

Traditionally, gliders are buoyancy propelled underwater vehicles which profile the water column in a sawtooth pattern. A few years ago, these where only used for monitoring physical (salinity, temperature, density) oceanography but in recent developments they are now used for biological (algea, microfauna) and chemical (CO_2, CH4, O_2, pH) oceanography.

Recently, several types of gliders have reached the market, where some operate at sea surface (sail buoy) and some operate submerged (wave glider). What these platforms have in common is a low power budget suited for battery operation and energy harvesting (solar panels, wave motion) and relatively long expedition times from a few days up to a year without human intervention. The range is directly linked to the power budget of the sensor payload.

The long range that many of these vehicles have means there is a potential to drastically decrease operation cost, since they can be deployed and recovered from shore (or platform). With some limitations given by the low power propulsion systems, these vehicles can be programmed with a survey plan including where and what to sample, and then operate autonomously for the entirety of the mission.

With the increased attention on ocean acidification, climate change and management of maritime resources, AUV and glider technology is rapidly evolving. Recent developments include gliders for specialized tasks such as deep-water gliders (e.g. Seaglider M6, Alseamar Deep Sea Explorer), and sensor technologies relevant for environmental monitoring including pH, pCO_2 (e.g. Pro Oceanus Mini CO_2 sensor), hydrocarbons (e.g. SeaOWL UV-A), CH4 (e.g. Franatech METS CH4), and acoustics (e.g. Kongsberg Maritime EK80 WBT Mini).

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