Long-term Monitoring of Relict Wells: The development of a real-time acoustic-chemical lander for Project Greensand

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Summary

The worldwide development of marine carbon capture and storage complexes necessitates sophisticated monitoring tools capable of detecting real-time changes. In coastal seas, there are growing tensions between wind farm developments and proposed carbon capture and storage complexes which underlie them. 3D seismic reflection surveys are not thought to be possible within the boundaries of wind farms, and while 4D seismic reflection can sometimes track large scale sub-surface gas migration, they struggle to detect small scale leaks and are expensive and environmentally unfriendly.

One of the most likely leakage pathways are relict wells which could be pathways for the rapid ascent of buried CO_2 to the seabed. As the location of relict wells in storage sites is well known it is possible to design a Measurement, Monitoring and Verification plan which incorporates a small number of landers to continuously monitor these “higher risk zones” throughout a complex’s life. Here we describe a lander developed as part of Project Greensand Phase 2, a large-scale CCS initiative offshore Denmark, and present results from a dockside experiment. The lander comprises chemical sensors to monitor pH, nitrate, alkalinity, local currents, and the salinity; a multibeam echosounder which can detect CO_2 bubble streams; battery and communication equipment.

Introduction

The large-scale adoption of Carbon dioxide Capture and Storage (CCS) has been identified as a key factor for reducing anthropogenic greenhouse gas emissions to reach climate goals[1]. During CCS activities, CO_2 gas produced during industrial processes is captured and stored in appropriate geological reservoirs deep beneath the surface to mitigate the potential greenhouse effects. Compared to other strategies, such as enhanced energy efficiency and the use of renewable energy sources, the crucial benefit of CCS lies in its potential to reduce (in a significant, timely, and cost-effective way) atmospheric CO_2 emissions, by utilizing existing infrastructure from oil and gas production[1]. Depleted hydrocarbon fields in the North Sea are prime candidates for CCS storage with the potential to hold 475–570 Mt of CO_2 [2].

While CO_2 escaping from a CCS site is unlikely[3] it is essential that the water column above CCS storage sites is continually monitored to ensure that successful storage is verified for the long term (years to decades) and to increase public confidence in the reliability of the technique. Therefore, with the growing scale of marine CCS complexes around the world there is an ever greater need to develop monitoring tools capable of reliable, autonomous, and long-term operation. Given its familiarity to the industrial sector much attention has been placed on the use of 3D seismic reflection surveys. Such surveys can track large scale sub-surface gas migration, studying overall reservoir integrity[4]. However, seismic surveys are of limited temporal resolution (typically biennial), struggle to detect small scale leaks (on the centimetre to metre scale), are expensive and environmentally costly. Such limitations are unfortunate given one of the most likely leakage scenarios has been identified as escape via relict wells (aka abandoned boreholes)[4]. Relict wells, if poorly sealed or later compromised, could allow for the rapid ascent of buried CO_2 to the seabed along a sub-seismic sized channel[4].

Fortunately, as the location of relict wells in storage sites is well known, it is possible to design a Measurement, Monitoring and Verification (MMV) plan which incorporates a small number of landers to continuously monitor these “higher risk zones” throughout a complex’s life (**Figure 1)**. These landers use a combination of chemical and acoustic systems to monitor the water-column near relict wells and would convey data to the surface in near real time. As part of Project Greensand, a large-scale CCS initiative in offshore Denmark, a joint team at the University of Southampton and National Oceanography Centre (UK) has developed a monitoring lander and demonstrated its capabilities in a recent dockside experiment.

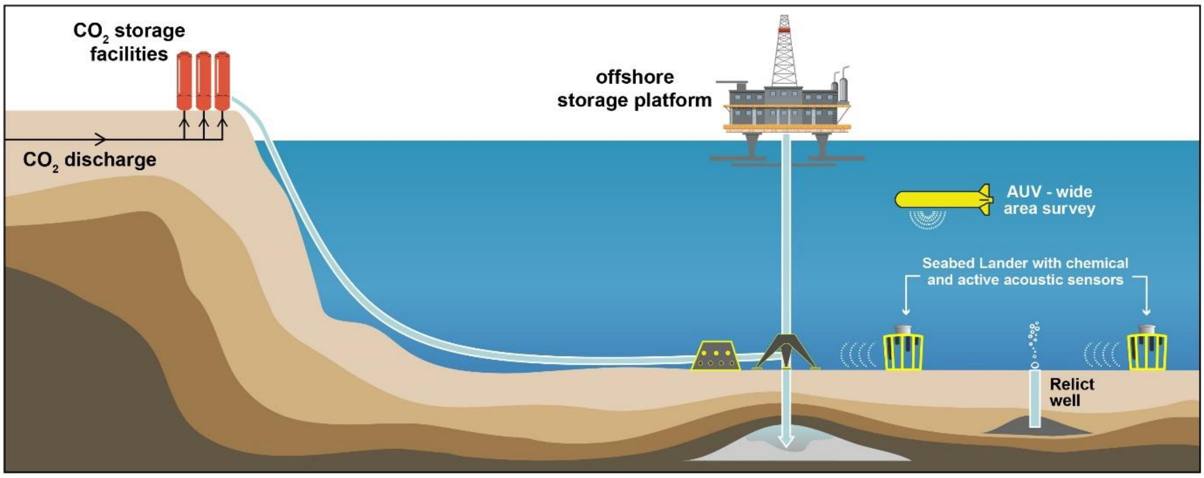


Figure 1 *A diagram illustrating the use of seabed landers to monitor relict well sites and injection points associated with CCS complexes. Wider area surveys could be completed using autonomous underwater vehicles.*

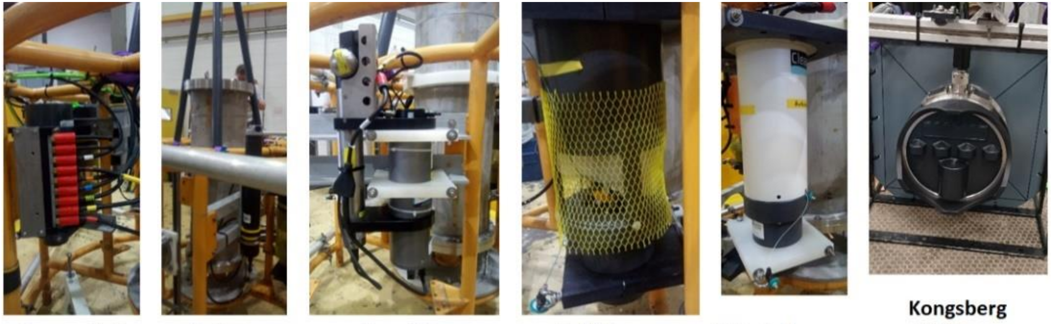
Theory *Lander Design*

The purpose of the Greensand Lander is to continuously monitor a given area on the seabed for signs of leakage from the underlying reservoir. It needs to be able to detect both gaseous and dissolved CO_2 seeps in a timely manner. The lander was designed to incorporate two complementary systems, acoustic and chemical, working in tandem to identify, verify, and quantify a potential leak.

The lander’s acoustic system uses an onboard multibeam echo sounder to regularly survey the area in front of the lander, sending out a high frequency (500 kHz) acoustic signal and measuring the strength of the returning echo as it bounces off objects in the water column. Gas bubbles produce very strong acoustic reflections, due to the high impedance contrast between them and surrounding water[5]. Consequently, gas seeps are easy to identify with multibeam systems. The echo sounder is positioned in a stationary horizontal position[5] permitting scanning of high-risk areas at set intervals. Each scan will then be exported to the surface as a single swath image and is placed into a time series. The difference between subsequent swaths is automatically calculated allowing for large changes (i.e., those caused by the sudden appearance of a gas seep) to be flagged for review by the surface team. The surface team will then examine the anomalous behaviour, in particular how mobile it is and if its size varies with tidal changes, to confirm whether or not it is a potential CCS leak or some other target (e.g., a school of fish). Active acoustic systems have the advantage of working in all conceivable marine settings with little to no site calibration required. It is unaffected by water quality, visibility, tidal height, current direction, and all but the most extreme forms of biological activity. Notably however they are unable to detect dissolved CO_2 or to determine anything about the chemistry of the imaged gas bubbles. This is particularly relevant in the North Sea, where natural methane seeps may cause false positives in a CCS monitoring system based only on bubble detection.

The lander's chemical monitoring capability addresses this limitation with a complementary monitoring tool, based on the specific detection of changes to the marine carbonate system caused by the dissolution of CO_2. It is enabled through sensors that monitor, pH, total alkalinity (TA), nitrate, local currents, oxygen, temperature, salinity, and pressure. CO_2 gas released from the seafloor will quickly dissolve into the water column, acidifying the seawater. The resultant reduction in pH is a principal indicator for CO_2 release. The local value of pH can also change for other reasons, such as change in source water masses with current direction, seasonal and tidal cycles, and biological processes. The nitrate, oxygen and physical parameters monitored from the lander make it possible to discriminate the effects of a CO_2 leak from these other processes. In addition, the presence of total alkalinity measurements means it is possible to calculate the concentration of dissolved inorganic carbon in the water, which can be coupled with hydrodynamic measurements to provide a quantification of the CO_2 emission[6]. Each of the sensors run on regular schedules enabling multiple readings across parameters each hour.

The pH, TA and nitrate sensors are “lab-on-chip" (LOC) devices: autonomous miniaturised instruments which perform spectrometric chemical assays in-situ with low power and reagent consumption[7]. The sensors draw in seawater, mix it with chemical reagents, and measure the reaction products optically. A proof-of-concept version of the setup has previously been used on a lander and on an ROV to detect, quantify, and map a controlled release of CO_2 in the North Sea[6,8].



Comms Hub   Battery   SeapHOx   pH, TA Sensors   Nitrate Sensor   Kongsberg M3 Sonar

Figure 2 *Photographs of the key components of the Greensands Lander*

Method *Dockside Experiment*

To demonstrate the capabilities of the Project Greensand Lander a two-week-long deployment was performed in Empress Dock, Southampton (UK) in late 2022. The lander was lowered via a crane to just above the seafloor next to the dock wall. Communication and power were supplied via direct cables to a nearby testing facility. Once baseline measurements had been established, a controlled amount of CO_2 was released through a hose connected to a short length of sintered pipe on the seafloor. Initially the injection was performed at 2 L/min (STP; 2000 kg/year) at a distance of 20 m from the lander. After observing this release across a number of tidal cycles the rate of gas was increased to 5 and then 10 L/min (5000 and 10000 kg/year). Following this the location of the release point was moved to a distance of 50 m and then 100 m from the lander.

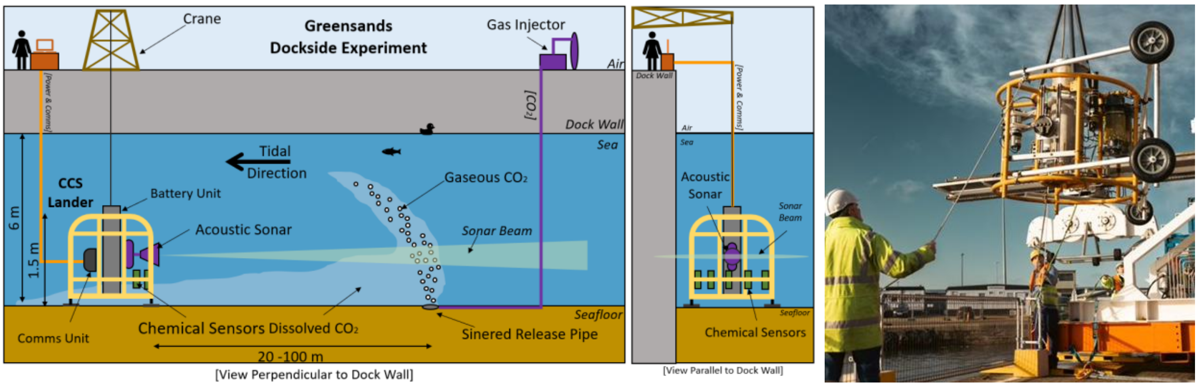


Figure 3 *a) Diagram of the dockside-controlled CO_2 release experiment as the tide flows towards the lander. b) Photo of the Greensands Lander being lowered into the Dock*

The acoustic results from the experiment are shown in **Figure 4**. Here one can see an example of an acoustic swath produced by the multibeam overlaid on a map of the release site. Clearly visible 20 m from the lander, near the dock wall, is the increased reflection strength caused by the presence of CO_2 gas bubbles. The artificial seep was easily identified in the acoustic data throughout the entire period of the experiment, with detection possible up to at least 100 m away at flow rates as low as 1 L/min (1000 kg/year). It was possible to observe the bubble plume flowing in different directions, which occurs as a natural result of the tidal cycle in this location.

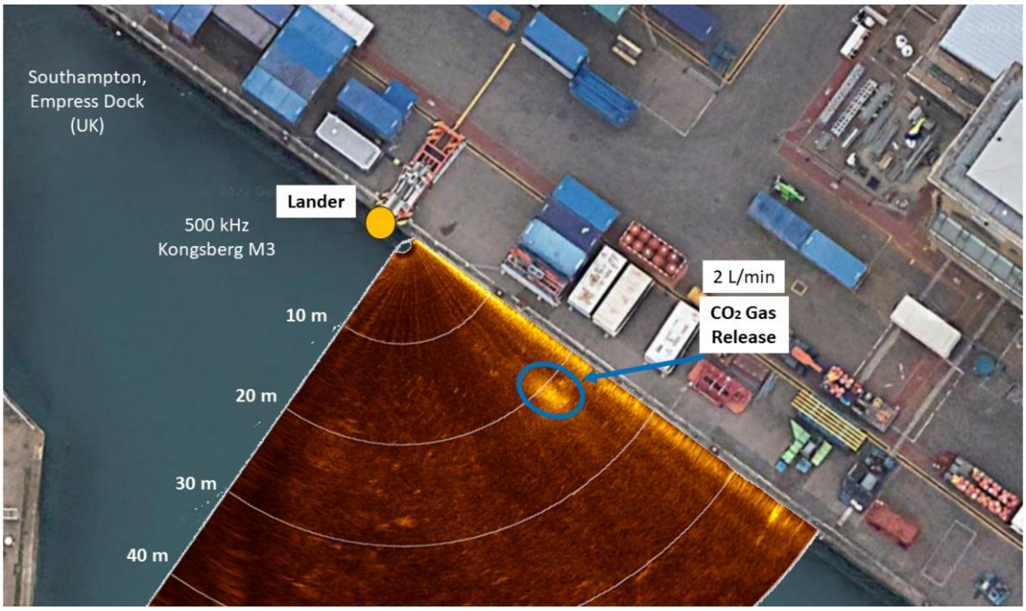


Figure 4 *Acoustic swath data collected by the landers multibeam echo sounder overlaid onto a map of the experiment site. Note the clear strong reflection caused by the simulated CO_2 seep.*

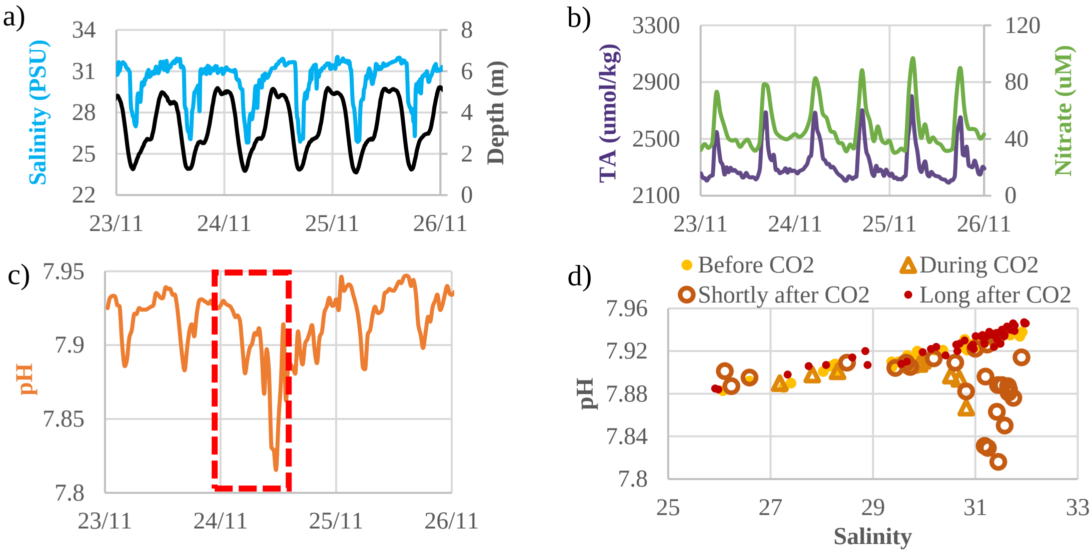


Figure 5 *Chemical time series from dockside experiment over 3 days showing tidal variation of a) salinity, b) total alkalinity (TA) and nitrate, and c) pH. The boxed area is the period of the* CO_2 *release and demonstrates the decrease in pH as a result of the* CO_2 *release. During the release and for 12 hours after, the pH is notably decreased away from the tidally-driven baseline, before recovering in the subsequent tidal cycle. d) Plot of the pH vs salinity before and during release.*

The lander's physical and chemical sensors revealed tidally-driven changes in water depth (> 4 m) and water chemistry (**Figure 5**). At low tide, we observe the expected decrease in salinity and increase of nitrate and total alkalinity from the input of highly alkaline, nutrient-rich freshwater from the local chalk river. Before and long after the release, the pH variability is only tidally driven. Upon the release of CO_2, we observe a decrease in the pH readings, compared to the normal pH-salinity relationship observed in this dynamic environment (**Figure 5**). As the test was done in a harbour with limited flushing, the low pH persisted for approximately 12 hours after the release ended.

Conclusions

As part of Project Greensand Phase 2, we have developed an acoustic chemical lander capable of continuously monitoring relict wells in marine CCS sites for signs of loss of containment. Following a successful controlled release experiment, we have demonstrated that this system allows for the detection of small-scale seeps, as low as 2 L/min (2000 kg/year). This represents a significant improvement over traditional seismic reflection techniques, in terms of minimum detection threshold and temporal resolution, at the cost of areal coverage. The lander incorporates an acoustic (sonar) system capable of detecting a gas seep at a distance of at least 100 m, performing regular surveys at a set interval (for example, every 15 minutes). The lander's chemical system can identify the specific changes in ocean chemistry caused by CO_2 seeps. Moving forward this lander design will be deployed to ensure the integrity of storage sites offshore Denmark.

Acknowledgements

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References

1. IPCC. Climate Change 2014: Synthesis Report (2014). **2.** Strachan, N. et al. IJGGC (2011). **3.** IEAGHG. Information Sheets (2013). **4.** Dean, M. & Tucker, O. IJGGC (2017). **5.** Li, J. et al. J Geophys Res Oceans (2020). **6.** Schaap, A. et al., IJGGC (2021) **7.** Beaton, A. et al., ACS Sens (2022) **8.** Monk, S. et al., IJGGC (2021)