# Next generation geophysical sensing: exploring a new wave of geophysical technologies for the energy transition

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Rapid changes in energy production and use together with increasing efforts to mitigate climate change mean that more accurate and more frequent monitoring of the Earth will be needed. The new Centre for Geophysical Forecasting (CGF) has set out a 'broad-band' research programme to respond to these challenges. CGF is one of several new 'research-based innovation' (SFI) centres, jointly funded by the Research Council of Norway and several industrial partners, officially opened in December 2020. Here we set out our vision for the CGF research programme using some early insights, hoping to stimulate others to work with us, directly or indirectly, in addressing these challenges.

Our vision is to apply geophysical sensing methods and ideas that have been historically developed for the oil and gas industry to respond to emerging challenges in sustainable geophysical applications. This will include ecosystem and environmental management, geohazard prediction and improved mapping and management of subsurface fluid resources (e.g. water, hydrocarbons, $CO_2$ and hydrogen). The Norwegian setting means we are especially interested in the offshore marine environment, but the group also has a strong focus on onshore hazards such as landslides. Our key innovation topics are:

- $CO_2$ storage management
- Reconfiguring hydrocarbon production processes
- Geohazard monitoring and forecasting

To address these challenges and to leverage new and emerging technologies, CGF has set up the following six research areas (work packages):

- Distributed Acoustic Sensing
- Storage of $CO_2$, gas and energy
- Effective monitoring and forecasting systems (offshore, coastal and onshore)
- Geohazard prediction and deep mapping of the Earth's crust
- Heterogeneous high-performance computing tools and techniques for model fitting of subsurface datasets
- Data assimilation and uncertainty quantification

Although in the early stages of developing these work packages, we are already able to illustrate some of the emerging concepts we are working on, highlighted below.

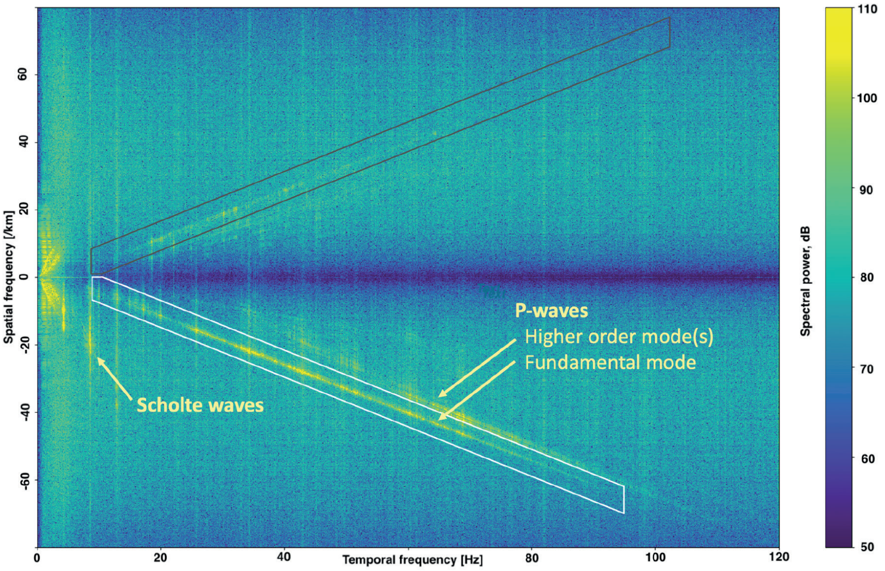

**Figure 1** DAS data from a FO telecommunication cable running from the UK to a platform in the North Sea. The f-k plot illustrates P- and Scholte waves excited by a bottom-trawl operating within 2 km of the cable.

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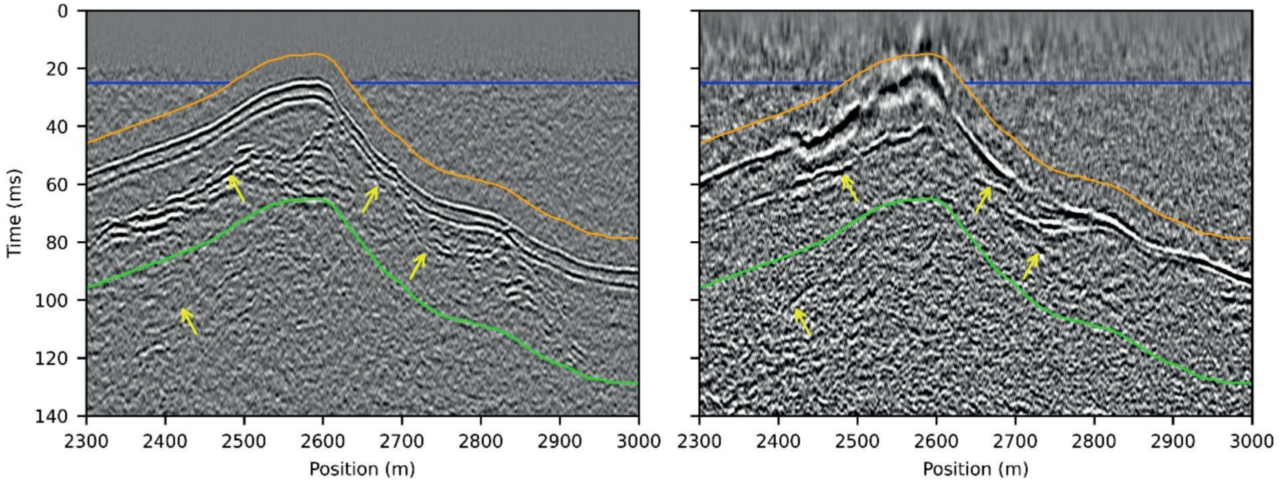

**Figure 2** Shallow subsurface profiling from a submarine FO telecommunication cable. The reference image on the left is from conventional seismic (a towed single-channel streamer with a 24-element hydrophone array of 7 m active length) while the image on the right is processed from a seabed telecommunication cable using DAS (with 4 m gauge length). Both images use the same signal enhancement. Yellow arrows indicate subsurface reflections seen in both acquisitions (the orange, green and blue horizons show the windows used for computing signal/noise ratios and spectra). Images from Taweesintananon et. al., 2021, reproduced with permission.

## Using fibre-optic telecommunication cables in novel ways

A major research focus at CGF is in using fibre-optic (FO) cables to sense acoustic fields by measuring modulations in the Rayleigh backscattering from impurities in the fibre caused by the stress-strain relationship as seismic P- and S-waves propagate across the cable, a technique known as Distributed Acoustic Sensing (DAS). Advances in interrogator technology now provide $10^{-12}$ resolution in strain out to ranges along the cable exceeding 100 km, offering strong potential for new applications.

In principle, existing FO telecommunication cables can be used in this way, providing a potential network of sensors with enormous geographical span and spatial resolution. We believe that DAS will be useful for detecting and tracking acoustic sources on the surface of both sea and land, within the water column, at the interface with the seabed and subsurface, including seismic events. Examples include traffic on land, ship at sea, storms, whales, trawls, subsurface structures, microseismic activity and distant earthquakes, opening up a whole new range of possibilities for monitoring the Earth.

## Seabed events and interface wave detection

Figure 1 shows a temporal/spatial -frequency (f-k) plot from DAS data collected from a FO telecommunication cable in the North Sea (Rønnekleiv, 2019). The different types of waves arriving at the FO cable are clearly separated. The figure shows Scholte interface waves, as well as fundamental and higher mode P-waves, from a nearby trawl scraping along the bottom. This demonstrates that DAS could be used for integrity monitoring of submarine telecommunication, power cables and associated infrastructure.

## Imaging the subsurface

CGF recently conducted a pilot feasibility test to investigate the use of an existing submarine telecommunication FO cable for shallow subsurface imaging. Figure 2 compares the DAS result with conventional seismic data. While the DAS result (right-hand panel) is generally of lower quality than the traditional seismic result on the left, the experiment demonstrates that this approach has the potential to be used in the future for low-cost monitoring of potential landslide hazards associated with sea-level rise or increased storm frequency, and for continuous monitoring of sub-surface structures as part of managing subsurface fluid resources.

## Clay monitoring and avalanche detection

CGF has also established a research site for geophysical clay monitoring using DAS (Figure 3), close to the construction of a new road in Rissa (an hour's drive from Trondheim across the fjord). The road will be built on quick clay and to stabilize the clay, rock masses will be deposited on the coastal side of the new road. CGF has installed a 2 km-long FO cable and drilled two 20 m deep wells. The wells will be instrumented with FO cables as well as conventional hydrophones. This project is a cooperation between several partners in CGF including Alcatel Submarine Networks, Magseis Fairfield and NTNU. The purpose is to investigate if it is possible to detect changes in the shear modulus in the clay during the road construction work, as suggested by Wehner et. al., 2021. Baseline surveys for DAS, nodes and hydrophones have already been acquired and humidity of the soil close to one of the shallow wells will be monitored by hygrometers. In addition to monitoring, we also plan to compare various monitoring methods (nodes, hydrophones and DAS).

**Figure 3** Deployment of a geophone node (white cylinder) close to one of the shallow wells (orange pipe) at Rissa. The DAS fibre is trenched approximately 40 cm into the ground approximately 1 m to the right of the geophone line.

Yet another planned CGF project focuses on using DAS for snow avalanche detection, working with Norsar and the Norwegian Public Roads Administration. To prepare for such measurements, Norsar has already conducted feasibility tests using FO cables deployed in different soil types and with different coupling of the FO cable to the ground. These tests were conducted at the NOR-FROST test-site (part of ECCSEL) at the Norsar premises, where a variety of interrogators and geophones can also be tested and compared with each other.

## Monitoring marine mammals using advanced signal processing

There is a long history of collaboration between the bioacoustics and geophysical scientific communities, for example, repurposing 'traditional' sensor systems such as ocean bottom seismometers (OBS), to monitor large baleen whales through their sounds.  An example of this reapplication of geophysical sensing networks is their use to detect and track large whales. CGF researchers have recently published an article that shows how a single OBS can be used to detect low-frequency vocalizations from a baleen whale, identify the species, estimate the range (from the acoustic multipath structure) and hence derive source levels and even infer the vocalizing depth of the animal from the near-surface multipath coherent interference effect (Bouffaut et. al., 2021). Teasing such a rich set of properties from a single OBS hydrophone data recording illustrates how much might be gained from pivoting our thinking about existing technologies and capabilities into new applications. The need to detect, identify and track large marine mammals is an important one, as we seek to understand how these charismatic megafauna are recovering from near extinction in the commercial whaling years and how they now interact with changing climate and anthropogenic use of the oceans. These dynamics are exacerbated at the doorstep of the Arctic, off the coast of Norway, which is currently under-sampled and poorly understood. CGF researchers foresee a significant contribution of DAS to monitor such areas, with the untapped potential to record, track and separate baleen whales.

## Using time-lapse seismic to detect migrating fingers of $CO_2$

A key aspect of ensuring safe storage of $CO_2$ storage in deep saline formations is effective and accurate monitoring of $CO_2$ using time-lapse (4D) seismic methods. 4D seismic monitoring at existing projects reveals that volumes as small as a few tens of kilotonnes (Harris et. al., 2017) or $CO_2$-layer thicknesses down to a few metres (White et. al., 2018) can be detected. The challenge is to improve these detection limits; both assure successful storage (termed conformance) and to verify insignificant risk of leakage (termed containment verification). One way to tackle this challenge is to use fluid dynamical forecasting combined with advanced analysis of seismic amplitude and seismic velocity changes for a thin $CO_2$ layer. Figure 4 illustrates this concept with reference to the high-quality seismic datasets at the Sleipner $CO_2$ storage site offshore Norway. In practice this means estimating the $CO_2$ saturation in thin layers below the seismic tuning thickness (Figure 4B, Ringrose et. al., 2021). Fluid dynamical models (Figure 4A) can be used to reduce the uncertainties in these seismic inversions. For thin horizontal $CO_2$ layers, especially in shallow formations, the use of long-offset data or repeated refraction-type seismic data offers a promising complement to conventional 4D seismic data. Full-wave inversion methods using both reflected and refracted waves can also offer an important way to stabilize and optimize the seismic inversion process (Raknes et. al., 2015).

A dedicated $CO_2$ test tank is under construction at NTNU with 300 transducers placed on a regular grid to simulate 4D seismic shooting above physical models that are placed on top of a sand layer in a water-filled tank. Air or $CO_2$ can be injected at the bottom of the tank to simulate $CO_2$-injection. This development is a part of ECCSEL (The European CCUS Research Infrastructure).

## Uncertainty quantification

The integration of new types of geophysical data, such as DAS, with more traditional geophysical data often requires a good understanding of the uncertainties. Only then can one provide tangible prediction intervals for the variables of interest

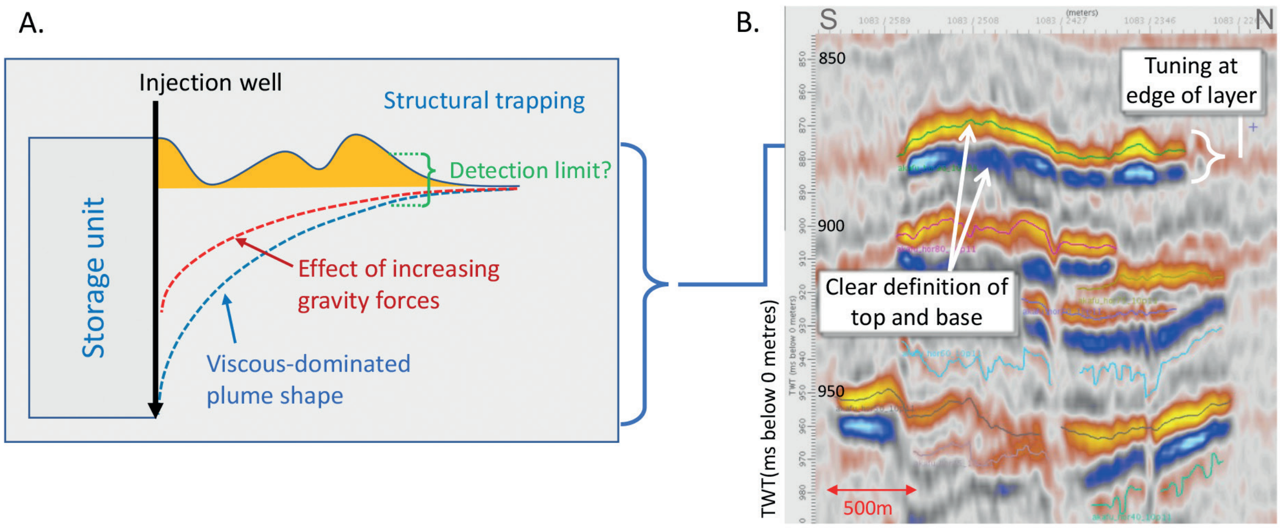

**Figure 4** Illustration of the challenges in edge detection of an expanding $CO_2$ plume. (A) Sketch of the fluid dynamical factors affecting the shape of an expanding $CO_2$ plume. (B) Cross-section through the 2010 seismic amplitude data at the Sleipner $CO_2$ storage site showing amplitude variation for the $CO_2$ plume in Layer 9 (top layer); modified from Ringrose et. al., 2021.

using all the available information, critical for decision support systems. As an example, we are interested in characterizing the injected $CO_2$ in space-time via multiple realizations to span the uncertainty in subsurface forecasts. With monitoring data, some realizations will be more likely than others, and knowing this can lead to improved injection strategies in the vicinity of faults, or potentially to stopping the injection earlier because of unacceptably high risks of leakage. In such a framework, one can also experiment with different data gathering designs and as a result implement cost-effective monitoring schemes that lead to better decisions. Anyosa et al. (2021) suggest a statistical machine learning approach based on geostatistical modelling, multiple reservoir simulations of the $CO_2$ plume in an aquifer and associated synthetic seismic data for both leak and seal scenarios. From a large set of simulations, leak and seal conditional probabilities are estimated over time, and these are used to assess the value of information from the seismic monitoring schemes.

In many physical processes it is also important to understand what is within natural variability so that we can reliably detect critical events. Statistical analysis reduces the false positives and negatives. With more nuanced training from data, it is also possible to classify events, for example various types of rock fall, and even link this to a physical cause which can influence downstream decision making.

## The way forward

The exciting new opportunities outlined in the previous sections point towards a rich landscape of future sensing and monitoring capabilities, leveraging existing systems, software and skillsets in new ways while integrating novel sensing methods to create opportunities for new products and services in the geophysical domain that will be critical for a successful energy transition and business pivot in Norway, as elsewhere. CGF invites stakeholders from all corners of the globe to engage and join us in developing these innovations.

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