D1.13 – Critical technology elements (WP1) Final Report

DigiMon – Digital monitoring of CO_2 storage projects

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1 Introduction

1.1 Overview of WP1 – Critical technology elements

The overall objective of the DigiMon project is to “accelerate the implementation of CCS by developing and demonstrating an affordable, flexible, societally embedded and smart Digital Monitoring early warning system”, for monitoring any CO2 storage reservoir and subsurface barrier system. Within the project the objective of WP1 was to develop individual technologies, data acquisition, analysis techniques and workflows in preparation for inclusion in the DigiMon system. The technologies and data processing techniques developed as part of WP1 include distributed fibre-optic sensing (DFOS) for seismic surveys and chemical sensing, 4D gravity and seafloor deformation measurements, a new seismic source and seismic monitoring survey design. For these technologies the key targets for WP1 were

- Develop individual components of the system to raise individual technology readiness levels (TRLs),
- Validate and optimise processing software for individual system components,
- Develop an effective Distributed Acoustic Sensing (DAS) data interpretation workflow.

This work was performed with the expected outcomes of

- Raising the DAS TRL for passive seismic monitoring,
- An assessment the feasibility of using Distributed Chemical Sensing (DCS) for CO_2 detection,
- Reducing the cost of 4D gravity and seafloor deformation measurements.

1.2 Document purpose

This document provides an overview of the work performed in WP1 and a summary of the significant results. Detailed descriptions and results from each of the task can be found in the task deliverables and associated papers. A list of WP1 deliverables and research outputs are given in Appendix A and B.

1.3 Document structure

The report contains a description of the datasets used in WP1 tasks (Section 2) and a brief description of individual task objectives and outcomes relating to individual technologies (Sections 3 to 8). Following this is a summary of the impact of WP1 in terms of raising TRLs and outcomes relevant to policy, regulatory and industry stakeholders (Section 9). This impact section also contains highlights of dissemination of the WP1 results to the wider community.

2 Datasets

A crucial component of WP1 are the datasets, which provide a basis on which to investigate some of the critical technology elements. Through the project, we have assessed the capability of different open-source modelling packages to simulate DAS datasets, reviewed the suitability of open-access DAS datasets and generated several real-world field datasets.

2.1 Synthetic dataset (Deliverable 1.3)

Of the many software options available for simulating seismic wave propagation, we choose two popular open-source software packages to include in our test: SW4 and SPECFEM3D Cartesian. SW4 uses a node based finite difference approach to solve the seismic wave equations to fourth-order accuracy. SPECFEM3D uses the spectral element method. Both packages are commonly used to model particle motion as measured on conventional seismometers. We are not aware of any examples where they have been applied to model DAS datasets. Additionally, for the simpler models we apply analytical and semi analytical modelling approaches (e.g., ray-theory and wavenumber integration methods) for benchmarking purposes.

Through a series of progressively more complex models we have shown that we can achieve reasonably consistent synthetic DAS data using both SW4 and SPECFEM3D (Figure 1). This gives confidence that the wavefields are accurately being modelled, such that either method can be used to create synthetic data for DigiMon. However, through this analysis we identified some differences in the capabilities of each modelling method such that, depending on the use case, one method may offer advantages over the other. These are summarised below:

Array geometry: One of the benefits of DAS systems is that they provide a very dense sampling of the wavefield, with channel spacing on the order of a metre. However, this close spacing presents a challenge for modelling DAS synthetics with SW4, as receivers must be at mesh nodes (e.g., a grid spacing of 8 means that the receivers cannot be closer than 8 metres). In contrast SPECFEM3D allows receivers to be placed at any location within the mesh, allowing for more flexibility in modelled array geometries.

Boundary effects: To suppress boundary effects at the lateral sides of the model geometry each model employed a form of absorbing boundary conditions. The SW4 models used supergrid boundaries and the SPECFEM3D models used Stacey boundary conditions. The SW4 models greatly outperformed SPECFEM in this respect. Clear boundary reflections could be seen in the SPECFEM models, which then interfered with later arrivals. The boundary conditions of SPECFEM models could possibly be improved by using more sophisticated absorbing boundary conditions like perfectly matched layer (PMLs).

Strain output: One of the major benefits of SW4 over SPECFEM is that it supports the direct output of strain seismograms for all 6 independent components of the strain tensor. In contrast, SPECFEM supports only the output of 3 component particle motion seismograms, and the conversion to strain must be done through numerical differentiation in post processing. This is not a significant weakness when simulating simple linear fibres, where only the axial strain needs to be modelled. However, there are scenarios where having the full strain tensor output would be desirable, for example in modelling the response of helically wound cables which are sensitive to strain in multiple directions.

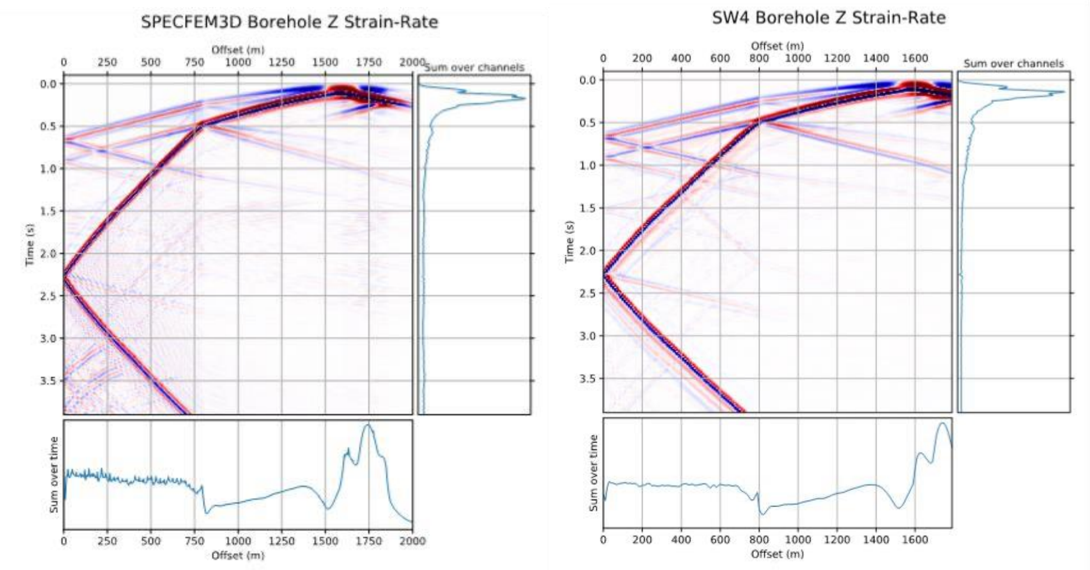

Figure 1. Strain-rate synthetics for the revised North Sea model recorded along the borehole array. Channel 0 is located at the surface, with the base of the array at 2000 m depth. The source is located at a depth of 1630 m.

2.2 Open access and existing datasets (Deliverable 1.2)

This deliverable was a suitability assessment of open-access DAS datasets with a focus on their suitability for microseismic and ambient noise interferometry (ANI). For this, the DAS field dataset of FORGE is recommended. FORGE is the Frontier Organization for Research in Geothermal Energy and is a field laboratory for developing an enhanced geothermal system in hot crystalline rock situated near the town of Milford in Utah, USA (https://utahforge.com/). The FORGE team is led by Joe Moore of Utah (and funded by the US Department of Energy) and is credited for this dataset. The dataset is completely open access, but obviously attribution would be appreciated in any publications. The FORGE dataset provides downhole DAS and geophone recordings of microseismic events and covers approximately two weeks of continuous DAS recordings that can be used to test the potential of DAS for the ANI method.

In addition to the FORGE dataset, various other DAS datasets have recently become publicly available that are recommended to consider for future work, since they can be valuable in addressing different research aspects of the application of DAS. Table 1 gives a summary of the different open access datasets considered for this deliverable. This table shows whether the datasets are suitable to be used for microseismic and ANI analysis. When compared against alternative datasets, the FORGE dataset is especially relevant for the DigiMon project, as it provides both microseismic event data and continuous DAS recordings from a borehole configuration spanning a relatively long duration (17 days). The borehole configuration is preferable for the purpose of detecting microseismicity since it allows measurements close to the reservoir and therefore able to detect weaker events compared to a trenched deployment at the surface. FORGE concerns an enhanced geothermal system and in this setting the mechanism driving seismicity is most likely different compared to the case of CO_2 injection and storage (DigiMon) since CO2 storage project will not intentionally induce seismicity. However, the performance of the DAS cable with respect to detected seismicity is expected to be similar for the case of monitoring CO_2 injection and storage as in a geothermal setting and therefore the FORGE dataset is expected to be suited for this purpose.

Dataset	**Location**	**Onshore/ offshore**	**Field operation**	**DAS configuration**	**DAS monitoring period**	**Microseismic/ Earthquake data**	**Ambient noise data***
POROTOMO	Brady hot springs, Nevada, USA	Onshore	Geothermal, natural lab	Surface/trench	15 days of continuous data	DAS, geophone	DAS, geophone
FORGE	Milford, Utah, USA	Onshore	Enhanced geothermal system	Permanently cemented into monitoring borehole	17 days of continuous data	DAS, geophone (40 microseismic events)	DAS
Antarctica	Antarctica	Onshore (ice)	Passive & Active seismic surveys	At surface (1km cable). Downhole VSP	jan-20	Icequakes	~3 days of continuous DAS data for 3 configurations each
Garner Valley	Garner Valley, CA	Onshore	Natural tectonics	Trenched	8 hours overnight data	No	DAS
Stanford phase 1	Stanford, CA, USA	Onshore	Urban	Telecommunication conduit. OptaSense ODH3	Only snippets of data available	DAS, geophone	No
Richmond Field Station and Fairbanks	Richmond Field Station at Richmond, CA, USA; Farmers Loop Road, Fairbanks, AK, USA	Onshore	Permafrost and geothermal	Trenched in Richmond. Trenched in Fairbanks. Silixa iDAS	Only snippets of data. late 2014 and early 2015 (Richmond), summer 2016 (Fairbanks)	DAS, geophone	No
Belgium DAS array	offshore Zeebrugge, Belgium	Offshore	Teleseismics, ocean noise	Trenched. Chirped pulse DAS	1 hr of raw strain data acquired on August 19, 2018 including the principle body wave phases from the M8.2 Fiji deep earthquake of the same date.	DAS, Teleseismics	No
Monterrey Bay Dark Fibre	Offshore Moss Landing, CA	Offshore	Plate tectonics	Silixa iDAS. Trenched	4 days, continuous	DAS (M=3.4)	Possibly
SAFOD DAS array (San Andreas)	San Andreas Fault, California, USA	Onshore	Plate tectonics	Permanently cemented into monitoring borehole. Optasense H-3	Earthquake events available within period of 22 days	DAS	No

Table 1. Overview of open access datasets containing DAS data and relevant for D 1.2.

2.3 DigiMon field datasets (Deliverable 1.1)

2.3.1 Antarctica dataset

This dataset was acquired by the British Antarctic Survey (BAS) and the University of Oxford in Antarctica during January 2020. Surveys were acquired at two different locations: the Rutford Ice Stream and Skytrain Ice Rise. At Rutford surface deployments of fibre were used to monitor icequakes and image the velocity structure of the firn layer, while the internal ice sheet structure was imaged at Skytrain using borehole installed cables.

During the Rutford deployment, three different array geometries using 1km of fibre optic cable were install between 11 and 21 January 2020 along two different orientations (Figure 2). Line 1 was positioned perpendicular to the flow of the ice stream, with both a linear and triangular geometry deployed. Line 2 was position in the direction of the ice stream flow, and along this line a linear and ’hockey stick’ configuration was installed. To compliment the survey, three conventional 3-C geophones were also deployed along Line 1.

Figure 2. Field deployment photo at Rutford Ice Stream (BEAMISH), left to right: the linear array with a distant flag marking one of the Reftek/geophone stations (station A000); the recording tent – the petrol generator was located 50m from the tent; ploughing a furrow for the cable; inside the recording tent.

In summary, the Rutford dataset comprise of continuous data recorded using three different array geometries for fibreoptic cable. The DAS network was complemented by 3-component geophones which were deployed along the DAS survey line, and during the survey period numerous icequakes were detected. Along with passive monitoring, a series of active seismic sources were made along linear DAS array. Some examples of applications for this dataset include:

- assessment of using DAS for active surveys, e.g., seismic refractions, MASW;
- sensitivity of straight fibreoptic cables to seismic signals;
- development of a microseismic workflow, e.g., event detection;
- research on the transfer function and response of DAS;
- seismic magnitudes estimation from DAS;
- development of ambient noise DAS processing workflow;
- optimum array geometries for DAS.

As part of the WACSWAIN project (https://www.esc.cam.ac.uk/research/research-groups/wacswain) a 650m deep borehole was drilled at Skytrain during the 2018/19 season. A multi-mode fibre optic cable was deployed in the borehole and used as a Distributed Temperature Sensor (DTS). The site was revisited in 2020, when a walkaway Vertical Seismic Profile (VSP) survey was acquired using DAS acquisition. DAS data was collected using a Silixa iDAS v2 interrogator connected to a DNS-4873 Sensornet fibre optic cable (Figure 3). Shots were acquired along three walk-away lines which were orientated at 40, 85 and 130 degrees from the borehole, with shot points located every 50m from 0 to 600m.

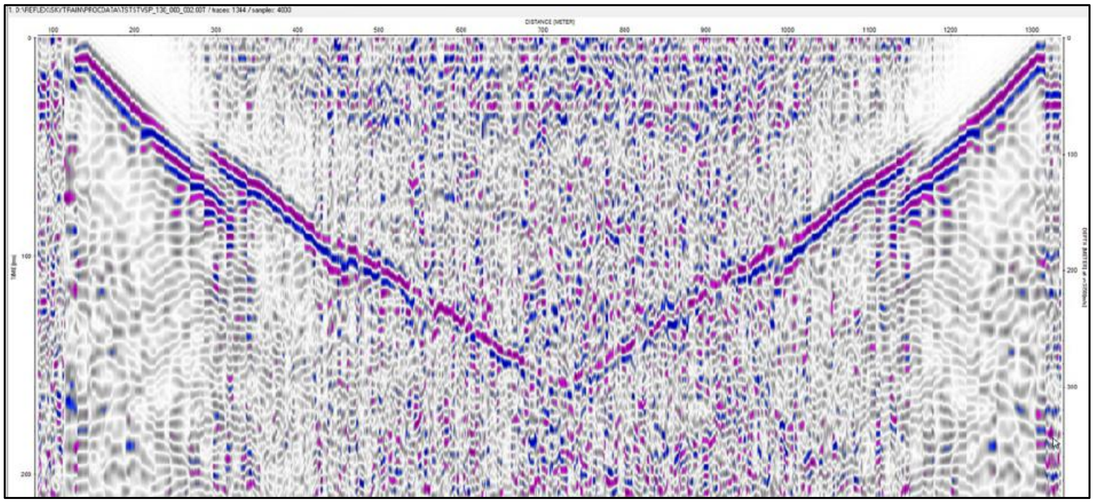

Figure 3. An example of the data recorded of a zero offset shot. Note that the data are reflected in the section, as the cable runs down and up the borehole. The hole was filled with drilling fluid up to a depth of ~300m. The hole above this is empty.

2.4 Svelvik CO_2 field laboratory, Norway

Between 13 and 22 September 2021 five different borehole survey configurations were acquired at Svelvik, Norway. The aim of the surveys was to provide a dataset to support DigiMon Tasks 1.2 & 1.3 and test a novel SV seismic source. Svelvik CO_2 Field Lab, near Drammen in Norway, consists of an injection well and four monitoring wells. The injection well is designed for injecting CO_2 and is equipped with a screen at 64-65 m depth. The four monitoring wells are 100 m deep and positioned at the corners of a rhombus with the injection well (#2) in the centre (Figure 4). The monitoring wells are located 9.9 m (M3 and M4) and 16.5 m (M1 and M2) from the injection well. The section between M1 and M2 is oriented in the EW direction, while the section between M3 and M4 is oriented in the NS direction. The monitoring wells are completed with PVC casing and instrumented behind the casing with:

- Sensors measuring pressure and temperature at the depth of injection
- Commercial fibre optic cables from SOLIFOS: Straight DTS (Distributed Temperature Sensing) and DAS (Distributed Acoustic Sensing)
- Helical fibre optic cables provided by Lawrence Berkley National Laboratory (LBNL).

The Svelvik dataset comprise of continuous data recorded over 8 days. The major component of the data relate to crosshole seismic experiments with P- and S-wave sources. Data were recorded on two DAS instruments, as well as hydrophone arrays and seismometers. DTS data was also recorded throughout the investigation. Some examples of applications for this dataset include:

- assessment of using DAS for active surveys, e.g., seismic refractions, MASW;
- sensitivity of straight/helical fibreoptic cables to seismic signals;
- development of a microseismic workflow, e.g., event detection;
- research on the transfer function and response of DAS;
- development of ambient noise DAS processing workflow.

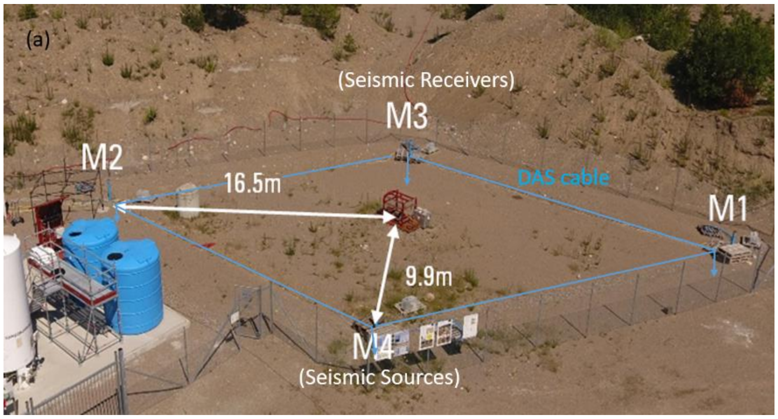

Figure 4. Svelvik site with monitoring boreholes marked (M1 – M4)

2.5 CaMI Field Research Station (FRS), Canada

This dataset was acquired by DigiMon partners at the Containment and Monitoring Institute's (CaMI) Field Research Station (FRS), Canada, between 6 to 10 September 2021. The CaMI FRS is located within the Canadian province of Alberta, approximately 30km south-west of Brooks in the County of Newell. The site is situated in relatively flat prairie lands, which have very minimal topographic variations. At the centre of the site is a fenced compound which contains the main CO_2 injection infrastructure, including the injection well, and two observation wells. Running through the compound is a 1.1km DAS trench which is centred on the injection well. Fibre-optic cables also run into two wells, creating a 5km loop (Figure 5). Outside of the compound, six broadband stations surround the injection well, which were previously installed by the University of Bristol to monitor microseismicity and changes in the ambient noise field resulting from the CO_2 injection.

The CaMi FRS dataset comprise of continuous data recorded over 3-4 days. The DAS network was complemented by 1- component and 3-component geophones which were deployed along the DAS survey line. In addition, broadband data is recorded outside of the 5km fibre loop. Along with passive monitoring, a series of active seismic sources were made along the linear trenched DAS array (Figure 5 and Figure 6). Some examples of applications for this dataset include:

- assessment of using DAS for active surveys, e.g., seismic refractions, MASW;
- sensitivity of straight fibreoptic cables to seismic signals;
- development of a microseismic workflow, e.g., event detection;
- research on the transfer function and response of DAS;
- seismic magnitudes estimation from DAS;
- development of ambient noise DAS processing workflow;
- optimum array geometries for DAS.

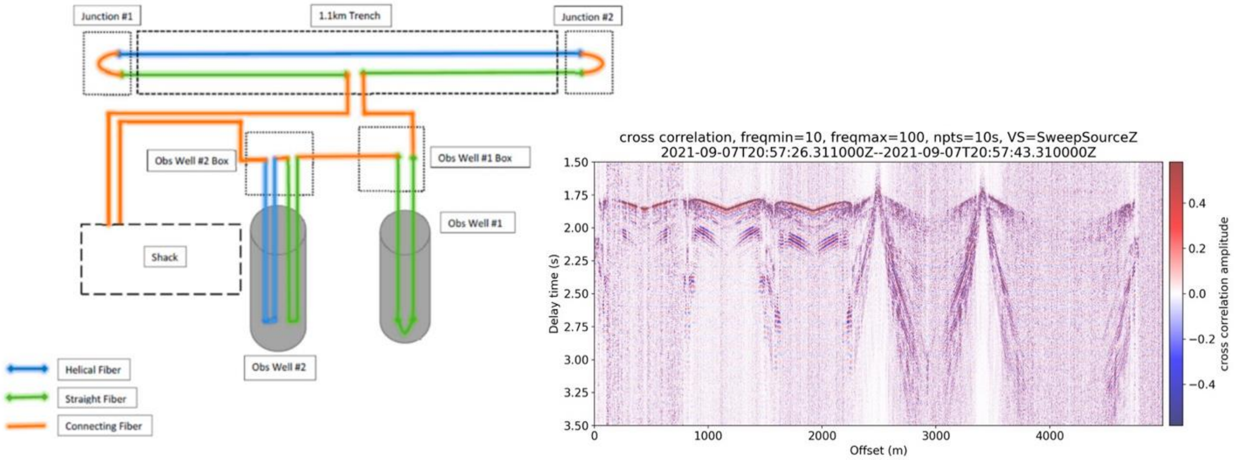

Figure 5. Schematic of DAS fibre configuration and cross-correlated vibroseis shot gather recorded on fibre-optic array.

Figure 6. Vibroseis surveys along the fibre optic trench at CaMi FRS.

2.6 Seafloor DAS in the Trondheimsfjord, Norway

To demonstrate DAS applications for seismic imaging, an optical cable on the seafloor in the Trondheimsfjord, Norway, was used by NTNU to perform an active seismic survey with two simultaneously recording systems was conducted. The two recording systems were as follows:

1) towed hydrophone streamer for conventional seismic recording.
2) fibre optic cable at the seafloor for DAS recording.

In addition, a controlled bubble gun source was towed by the same vessel that towed the hydrophone streamer.The vessel sailed above the fibre optic cable.

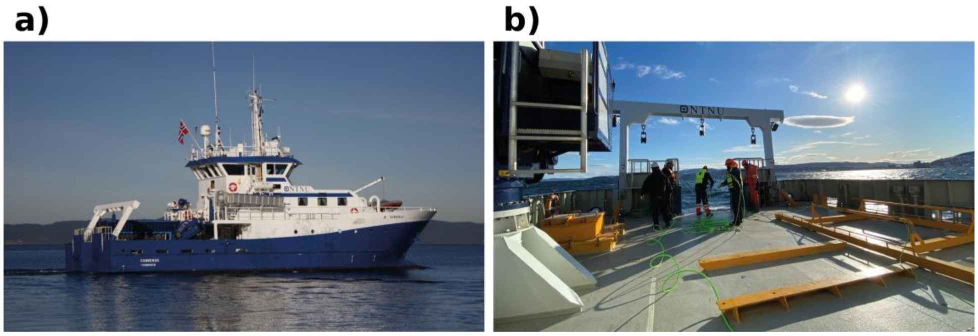

Figure 7. Photos of (a) NTNU's research vessel Gunnerus (retrieved from https://www.flickr.com/photos/trondheimhavn/5036332012/), and (b) the crew in action to recover the HMS-620 Bubble Gun source (Taweesintananon et al., 2021).

2.7 Laboratory-scale experiments of fibre optic vibration measurement

Using a small-scale (~20 cm by 30 cm) laboratory setup, we have developed methods to measure the exact strain response of a fibre to a known source. The source is a small metal ball on a pendulum that impacts the side of the testbed. The fibre is embedded in sand. The strain in the fibre is measured using a high SNR interferometric approach and represents total strain rather than a distributed measurement. The signal is also measured by a co-located geophone in the testbed. Tests show that the signal and the source is highly repeatable, and that the geophone signal (velocity) is consistent with the measured strain.

In parallel with the experimental lab-based tests, modelling is conducted using a finite-difference code to evaluate the accuracy of the modelling and to identify any systematic bias. The modelling includes a simple source, velocity model, and fibre geometry. We assume perfect coupling of the fibre to the media and focus on waveform shape rather than attempt to predict absolute amplitudes, although in principle this could be achieved. These initial 3D finite difference models demonstrate a reasonable fit to the measured data.

The main intention of this work is to gain understanding of the fibre transfer function as a function of the experimental conditions. Work is ongoing to build the dataset to cover a wider range of different situations such as different types of surround materials and different cable types.

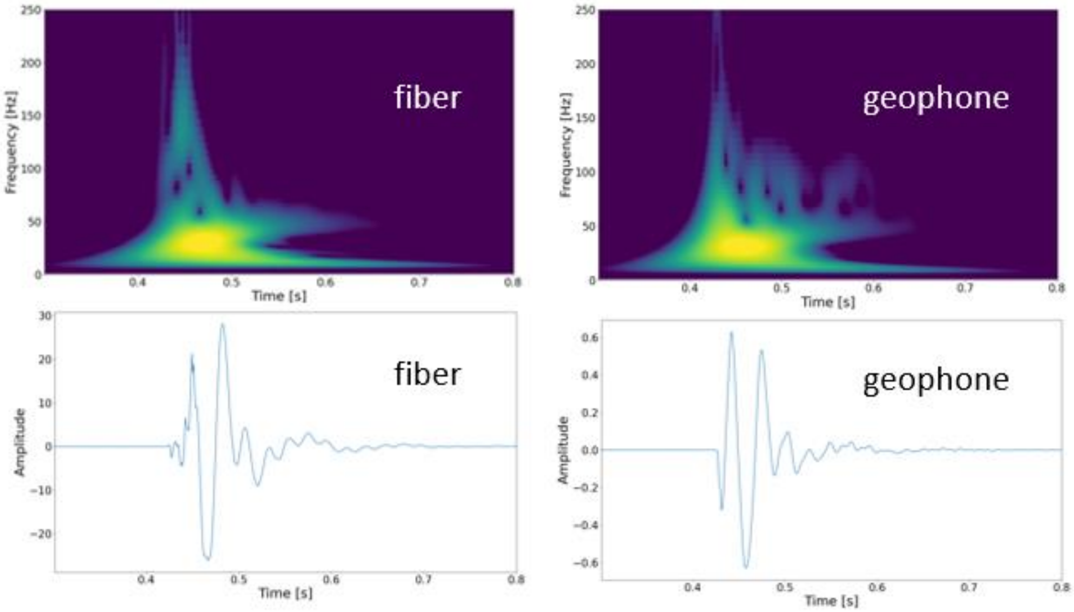

Figure 8. Wavelet transform and corresponding response for the fibre (top and bottom left) and the along axis-component of the response of the geophone (top and bottom right). The results correspond to a source impact directing along fibre direction, and with the fibre embedded in dry sand.

3 Task 1.2 – Determining the DAS transfer function

3.1 Aims and objectives

DAS measurements are measurements of optical phase changes which are then straightforwardly translated into the dynamical mechanical strain (or strain rate) of a fibre gauge length in the axial direction of the fibre (Lindsey et al., 2020). The resulting strain or strain rate measurements are typically expressed in nm/m or nm/m per second, respectively. Yet, the state-of-the-art algorithms of earthquake source parameter estimation rely on ground velocity measurements (expressed in m/s) as input data. Therefore, there is a strong interest to determine a transfer function that allows to convert the strain-based DAS measurements into ground velocity (or ground motion) measurements. To allow quantitative analysis of DAS data acquired for monitoring CO_2 storage fields, here we aimed to develop and test a method for determining the DAS transfer function

To develop the required knowledge in DigiMon, we defined the following objectives:

- Conduct a literature review on state-of-the-art of DAS and identify technical challenges in relation to the DAS transfer function
- Develop a method to achieve the conversion between the corresponding physical quantities
- Demonstrate the method using collocated seismic DAS and geophone records from a field site.

3.2 Outcomes and deliverables

First a literature review was conducted to find the main technical challenges and obstacles in relation to the DAS transfer function[1]. From this, the following key technical challenges were identified:

1. Strain(-rate)-to-particle velocity conversion: computational uncertainties.
2. Limited broadside sensitivity for straight DAS fibres.
3. Unknown cable-coupling requirements
    a. for elastic wave detection at the sea-bottom,
    b. for borehole acquisition: unknown signal attenuation due to casing, tubing, cementation and wash-outs.

These points can actually be (partially) tackled by determining and correcting for the DAS transfer function and this is where we placed our efforts. For this, we adopted and developed a state-of-the-art method for calculating the DAS transfer function according to the approach published by Lindsey et al. (2020), which is reported in Deliverable 1.6 (Butcher et al., 2022). This facilitated the conversion between the corresponding physical quantities and we demonstrate it using collocated seismic DAS and

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[1] *Verdel, 2020, DAS Geophysics – Literature Study (DIGIMON Task 1.2)*

geophone records from the geothermal FORGE site (Utah, USA; Section 2.2). The results show that DAS recordings can be successfully processed and translated to correct for the DAS instrument response by using a reference geophone station (see Figure 9 and Figure 10). The obtained DAS particle velocity recordings have a very good match with geophone ground velocity recordings.

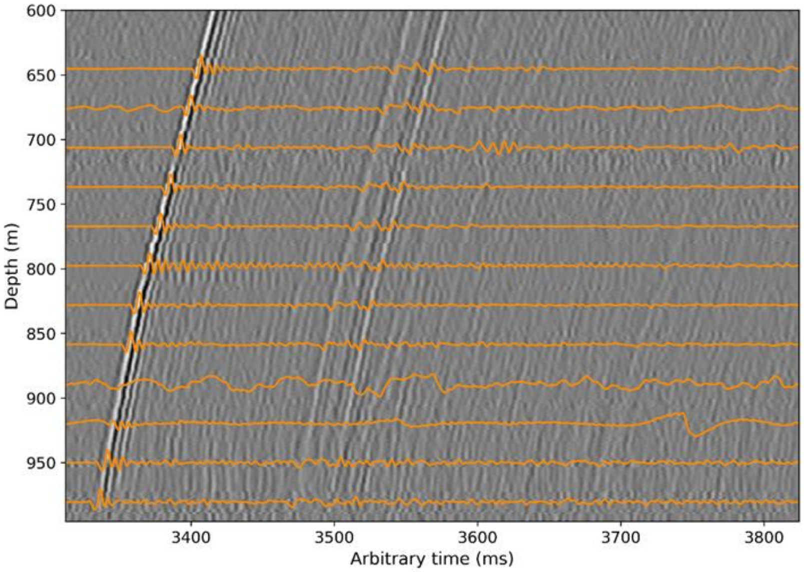


Figure 9. DAS and geophone perforation shot records from the FORGE site: pre-processed DAS strain rate measurements in the depth range beyond 600 meters (grayscale background mesh), with superimposed pre-processed vertical component of the particle velocity records from the 12 downhole geophones (in orange). For display purposes, the individual DAS and geophone traces are normalized by their root-mean-square and maximum values, respectively.

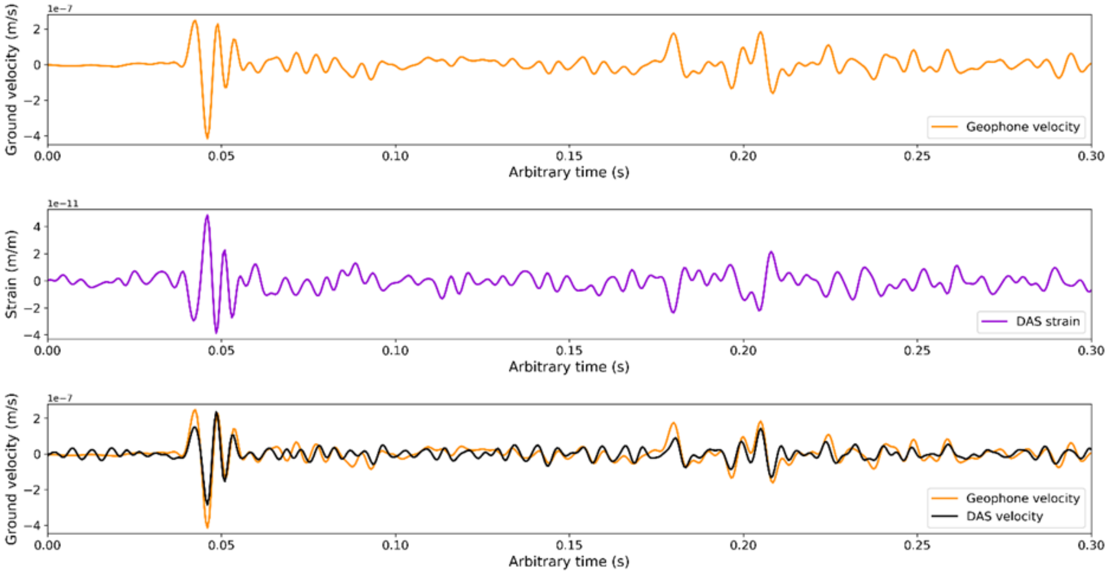


Figure 10. Application results of the F-K rescaling method on perforation shot from FORGE site: the geophone-based ground velocity record (in orange) is a collocated reference trace, the original DAS strain record (in violet) is obtained after integration of the pre-processed strain rate measurements and converted through the proposed method to the retrieved DAS-based ground velocity (in black).

3.3 Contribution to the DigiMon system

The developed method for determining and correcting for the DAS transfer function can be applied to any field dataset, including offshore CO_2 storage sites. It is an essential step within the DAS processing flow to allow quantitative use of DAS data, thereby allowing, for instance, estimation of magnitudes of recorded microseismic events and determining (changes of) physical reservoir properties from observed (time-lapse) DAS data.

4 Task 1.3 – Develop DAS data processing techniques and workflow

4.1 Aims and objectives

Through this task, we have developed data processing methods that seek to image CO_2 movement within a storage reservoir and potential breaches of the reservoir. The methods that we have focused on are microseismic monitoring and Ambient Noise Interferometry (ANI) methods, both of which are passive seismic methods which have the potential to provide cost-effective monitoring techniques.

Seismic activity in and around CCS reservoirs can provide valuable information on the movement of CO_2 and the characteristics of a storage reservoir. Any subsurface activity that alters the state of stress in the ground is capable of triggering seismic activity on pre-existing faults, and in the case of CCS, this can be caused by the movement of CO_2 within the subsurface. Microseismic monitoring, an established method to understand the effects of subsurface fluid injection for industrial applications, has been successfully deployed in several CCS projects and provides an important tool for monitoring CO_2 plumes and potential breaches from the containing reservoir. The position of seismic events provides valuable information on the extent of the CO_2 plume, while the waveforms can be used to characterise the fracture properties and stress regime within the reservoir. Task 1.3 aimed to develop microseismic monitoring processing techniques for DAS data.

ANI is a technique that reconstructs seismic signals from ambient noise recordings, the frequently discarded element of the seismic recording. Developed in the past 20 years, the technique itself is now mature and has been widely used in various conditions and scales from onshore to offshore, from applied geophysical exploration to continental imaging. The objective of ANI technique development is DigiMon was to advance data processing, particularly focussing on DAS data, with the aim of reducing monitoring costs by reducing the need for mobilisation of active seismic sources.

4.2 Outcomes and deliverables

4.2.1 Preprocessing Workflow (Deliverable 1.4)

We created a four-stage preprocessing workflow, which converts raw data into a dataset ready for the main processing workflows. For the purposes of this project, raw data represents the seismic data provided by the instrument supplier, which in this case is Silixa's TDMS file format recorded by the iDAS^{TM} system. The final output may either be waveforms files in a standard industry format, such as SEGY, or a numerical array passed to the main processing algorithm. The workflow is designed to be relatively generic to make it applicable to both active and passive seismic surveys (Figure 11).

Figure 11. Preprocessing workflow comprising of four stages to prepare the raw seismic data for the main processing stages.

4.2.2 Processing Workflow (Deliverable 1.6)

4.2.2.1 Microseismics

The primary goal of microseismic monitoring is to detect, locate and characterise very small earthquakes, which occur at or below the micro-scale of seismicity (M<2). The developed DAS processing workflow therefore consists of event detection, event location and source characterisation methods (Figure 12). Through DigiMon we have developed several DAS specific approaches to process DAS microseismic data. The Antarctic DAS and geophone dataset (Section 2.3.1) was used to perform this work.

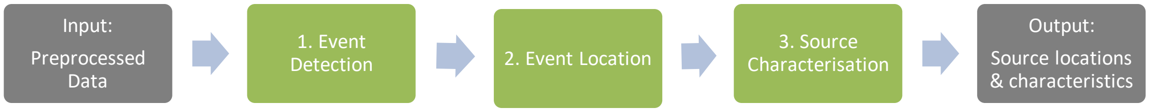


Figure 12. Microseismic processing workflow.

Amplitude-based methods, such as a Short-Term-Average to Long-Term-Average amplitude ratio (STA/LTA) algorithm, are commonly used to identify phase arrivals but they required high SNR to be effective. This is not always the case with DAS measurements and instead we have focused on two different processing approaches which exploit the spatial resolution of the DAS recording: a waveform-based migration method called QuakeMigrate and an approach based on slant-stack transforms named RadDetect (Butcher et al., 2021). Both approaches identify and pick microseismic events and then locate these events using the non-linear earthquake relocation software, NonLinLoc (Figure 13).

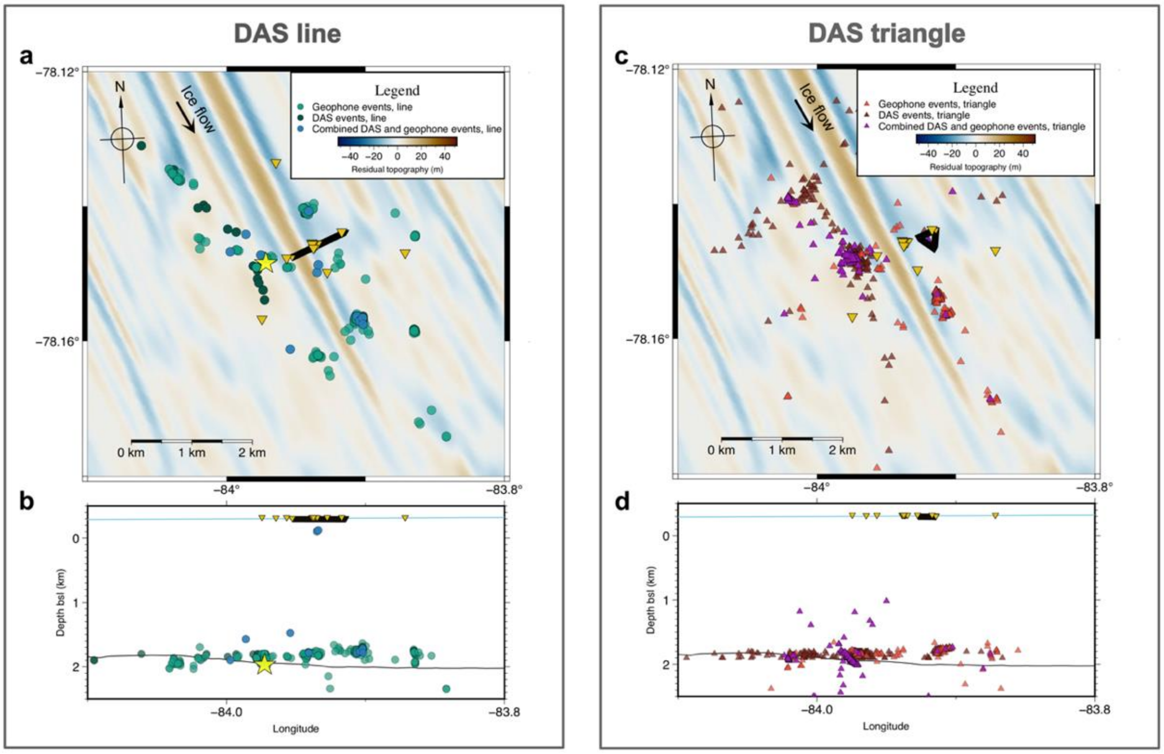


Figure 13. Detected icequake locations using DAS and geophones independently and together.

An earthquake source mechanism inversion involves using the observed radiation pattern of an earthquake to constrain the physical elastic failure mechanism that generates the earthquake. The earthquake source mechanism inversion for DAS data developed in the project is based upon the method described in Hudson et al. (2020) and available as the open-source package SeisSrcInv. This resulted in the first known publication of a seismic event source mechanism derived from DAS data.

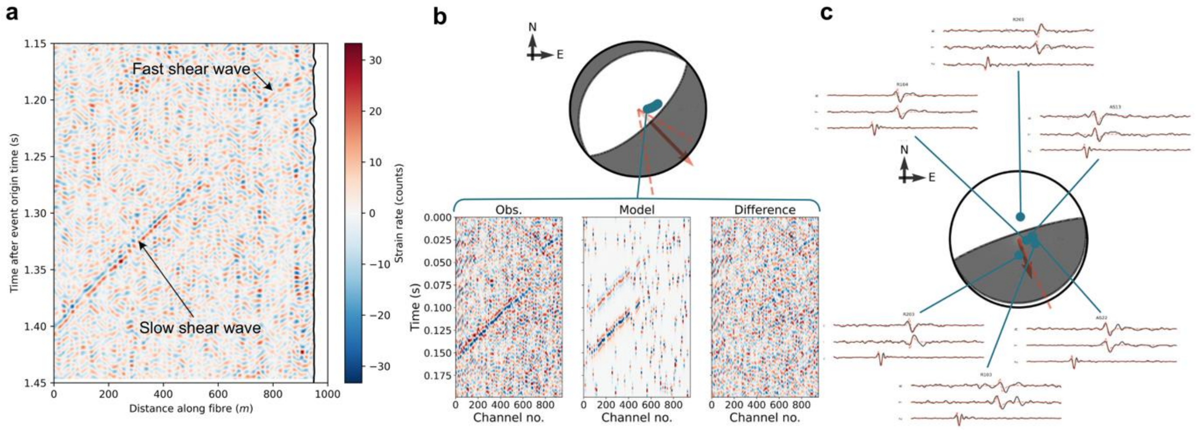


Figure 14. Example of icequake source mechanism inversion results using DAS compared to geophone observations (Hudson et al., 2021).

A methodology for estimating shear-wave splitting using the triangular DAS array was also developed. Shear-wave splitting occurs with propagation through an anisotropic medium, resulting in a slow and a fast shear-wave. Therefore, an analysis of the splitting provides information on the fracture characteristics of geological formations. The motivation for the study of this phenomenon as part of the DigiMon project was to provide a proof of concept demonstrating that a 2D DAS geometry can be effectively used as a multi-component sensor capable of measuring shear-wave splitting. A triangular surface DAS array partially alleviates for the inherent single component nature of DAS fibre because it records strain in a 2D plane rather than a 1D line, albeit with measurements at different orientations not at precisely the same location. However, if we assume that at the scale of the array the S-waves can be approximated as plane waves, we approximate the triangular array as a point sensor by correcting for the spatial distribution, similar to the approach of Innanen et al. (2019). If we estimate the orientation of the slowness vector, we can then invert for the polarization that best fits the observed data (Figure 15).

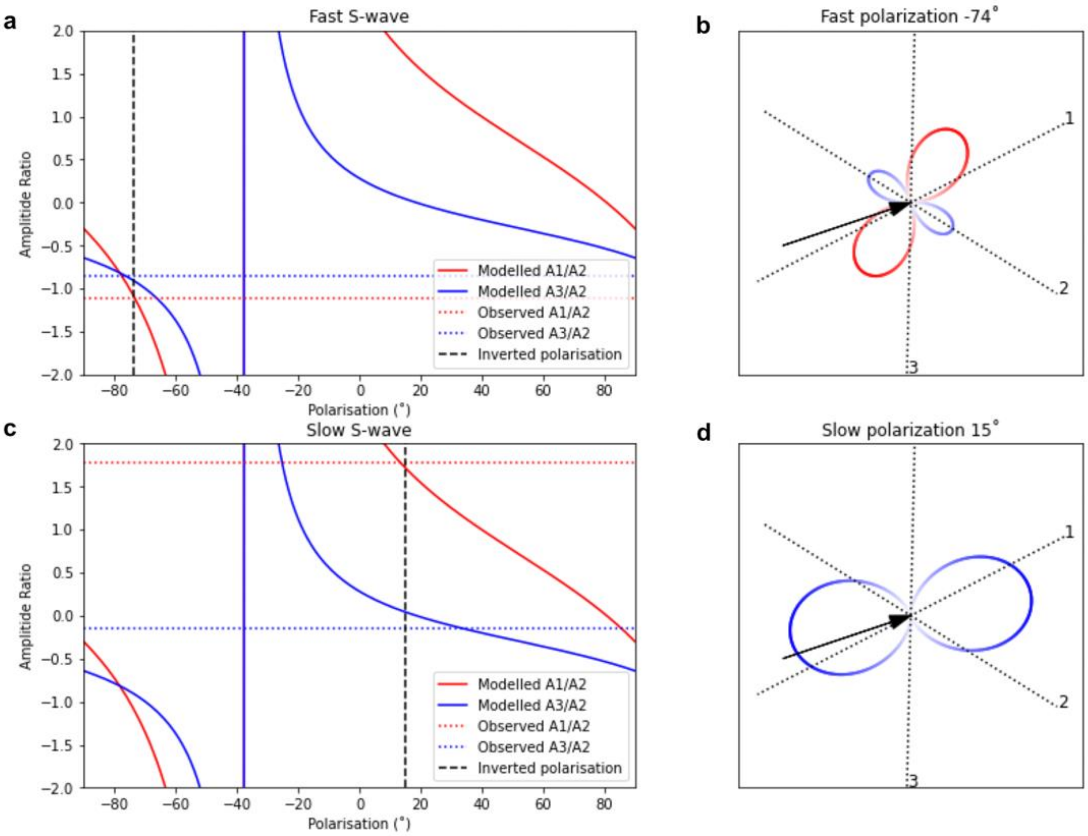


Figure 15. a) Results of the polarization inversion of the fast S-wave. Solid lines indicate modelled amplitude ratios as a function of polarization angle, dotted horizontal lines indicated the measured amplitude ratios and vertical dashed black line indicates the inverted polarization (-74˚). (b) Predicted strain sensitivity pattern for the inverted fast S arrival with polarization of 74˚. Dotted lines indicate the orientation of the three sides of the array, and black arrow indicates the horizontal projection of the propagation direction. (c) and (d) same as (a) and (b) but for the slow S-wave with inverted polarization of 15˚.

4.2.2.2 Ambient Noise Interferometry

The technique obtains velocity measurements from ambient seismic noise by extracting the Green's Function through cross correlating the seismic noise wavefield between two receivers and stacking over time (Figure 16). Seismic velocities and tomographic images of the subsurface can then be derived for site chracterisation and monitoring purposes. Where receivers are permanently installed and hence the receiver geometry is unchanged between surveys, a high degree of repeatability can be achieved which is ideal for monitoring CO_2 storage sites.

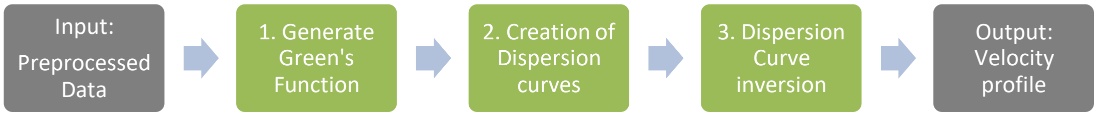


Figure 16. Ambient noise interferometry processing workflow.

Using the DigiMon Rutford dataset, a method combining a geophone virtual source and selective stacking of cross-correlation with DAS data (Figure 17) to use ANI and surface wave velocity inversion to build a shear-wave velocity model (Figure 19 and Zhou et al. 2022).

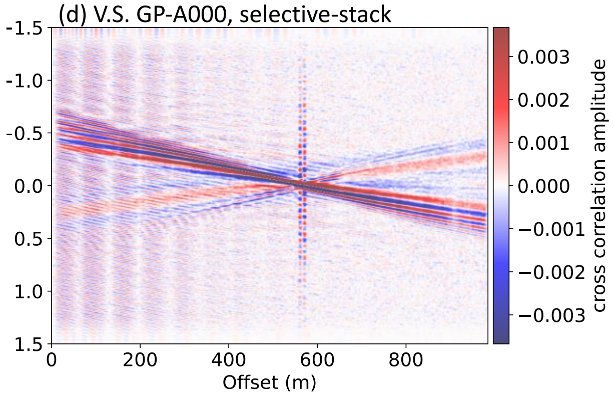


Figure 18. Selective-stacked cross-correlations using a geophone as a virtual source and DAS channels as receivers.

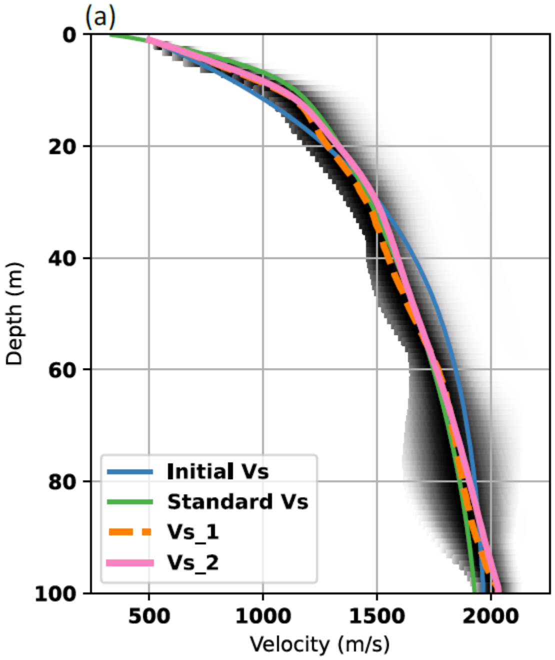


Figure 19. Two inverted shear-wave velocity (V_s) models for the upper 100m of ice in the Rutford ice-stream., Vs_1 from maximal PDF (greyscale) and Vs_2 from direct inversion of a fully selective stacked CCs virtual shot gather. The initial Vs model used in the inversion is in blue and for comparison, the Vs profile derived from the standard Vp refraction experiment is in green.

4.2.3 Machine Learning

Machine learning methods are likely to prove critical to DAS microseismic monitoring. The large data volumes and high levels of instrument noise recorded by DAS deployments mean that existing 'conventional' seismic processing techniques are prohibitively slow or ineffective for microseismic monitoring. Machine learning methods, on the other hand, are not restricted by any explicit statistical assumptions regarding signals of interest, and they can exploit the vast volumes of data acquired by DAS deployments to automatically discover useful data representations and features through model training. Model implementation is also heavily optimizable through use of GPUs and compression / pruning strategies, allowing for highly efficient signal processing over large sections of data.

A fully automated end-to-end machine learning method, called DAS-N2N, was developed for suppressing strong random noise processes in DAS data (Figure 20; Lapins et al., 2023, in prep.). The method requires only noisy, raw DAS data acquired by two spliced (joined together) fibres in the same cable for model training (Figure 20 A and B). Once the model is trained, it produces a completely 'denoised' copy of the data (Figure 20 C). The model is lightweight by deep learning standards, processing data from a 30 sec iDAS TDMS file in less than 1 sec. Advantageously, this method requires no manual data curation, meaning it can be applied to any DAS deployment. The method will be tested on other datasets to determine the scope for application of the method.

A second machine learning method was developed for detecting microseismic events from the denoised data above, using microseismic events from the DigiMon Rutford dataset detected by RadDetect (Butcher et al., 2021) for model training. The resulting model processes data from a 30 sec Silixa TDMS file in less than 1 sec, producing a highly efficient end-to-end workflow between raw data acquisition and microseismic event detection (Figure 21) that is suitable for real-time monitoring operations.

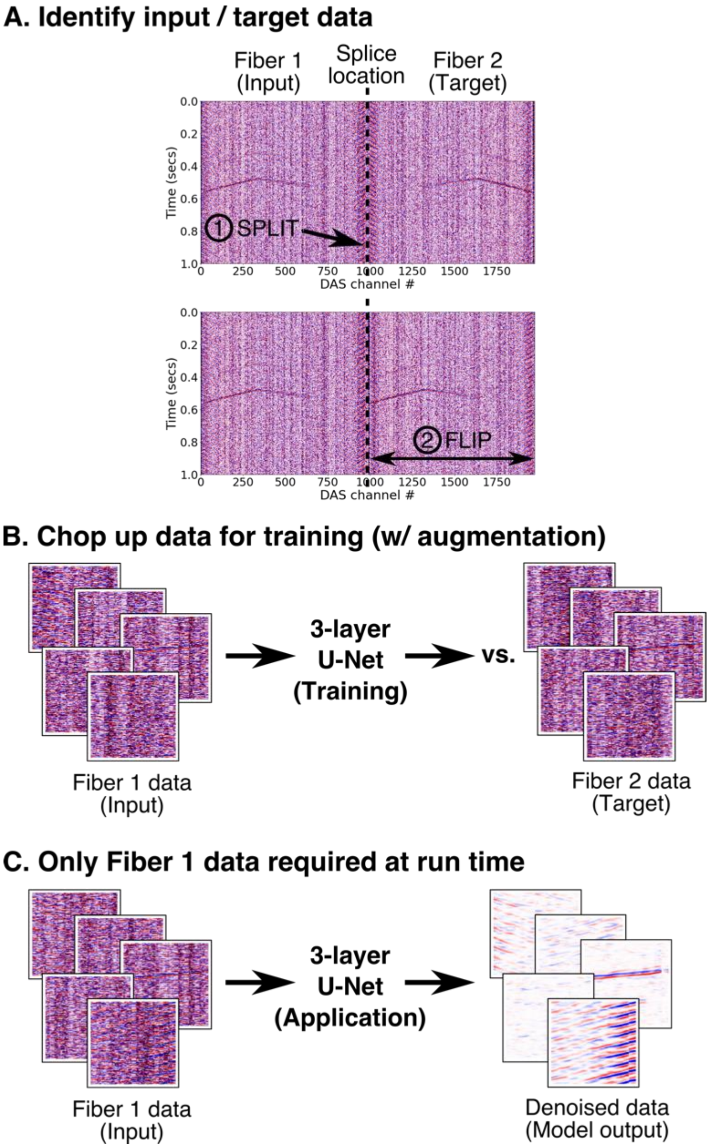


Figure 20. Schematic for fully automated training and implementation of DAS-N2N denoising model. A) Spliced fibres record two copies of underlying signal but with different random instrument noise. B) Data from one of the spliced fibres is used as input data for model training, with data from the other fibre used as target data (or training "labels"). C) Once trained, the model returns denoised data from a single (i.e., un-spliced) fibre. Figure after Lapins et al., 2023 (in prep.).

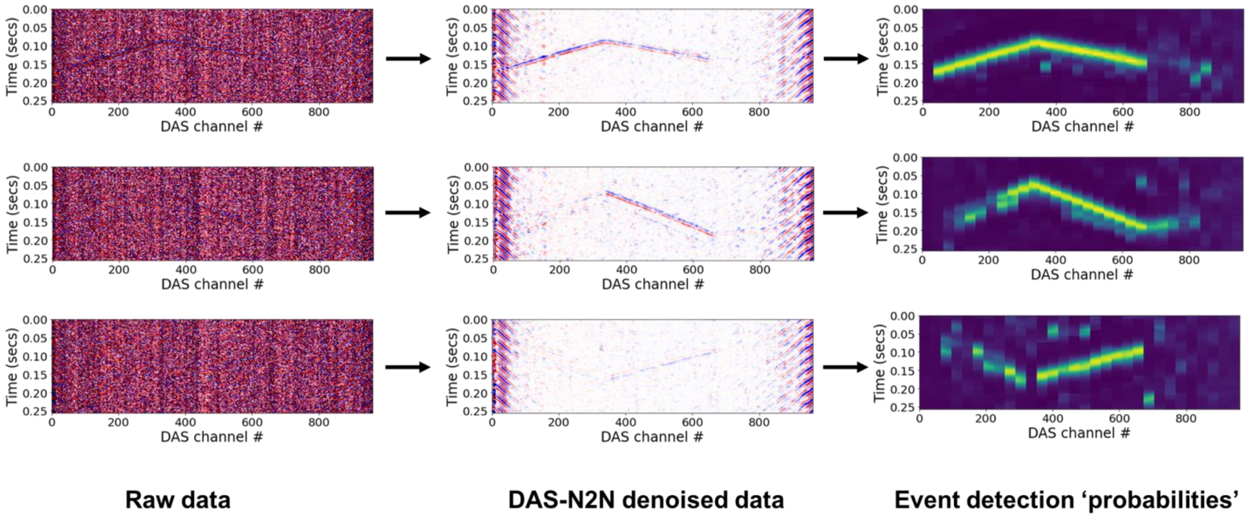


Figure 21. Proposed end-to-end machine learning workflow. Left: Raw DAS data from the DigiMon Rutford dataset. Middle: Data has been processed by DAS-N2N machine learning model to suppress background noise. Right: Data has been processed by event detection machine learning model to produce microseismic event ‘probability masks’ (areas in yellow have a high probability of being a microseismic event).

4.2.4 Processing Algorithms (Deliverable 1.5)

A Python library for processing DAS data has been developed, named DASpy. Python is a popular, widely supported language with a large range of dedicated libraries. We base the structure of the modules on the ObsPy library (Krischer et. al, 2015), an open-source library designed to facilitate the development of seismological software packages and workflows. Some of the DASpy workflows act as wrappers for existing programs, such as NonLinLoc (Lomax et. al, 2012) which is used to located seismic events. DASpy is hosted within a private GitHub repository call ‘DAStoolbox’ which also contains a number of example Jupyter notebooks and datasets which demonstrate the functionality of DASpy. Figure 22 describe the different modules contained within the DASpy library and its structure.

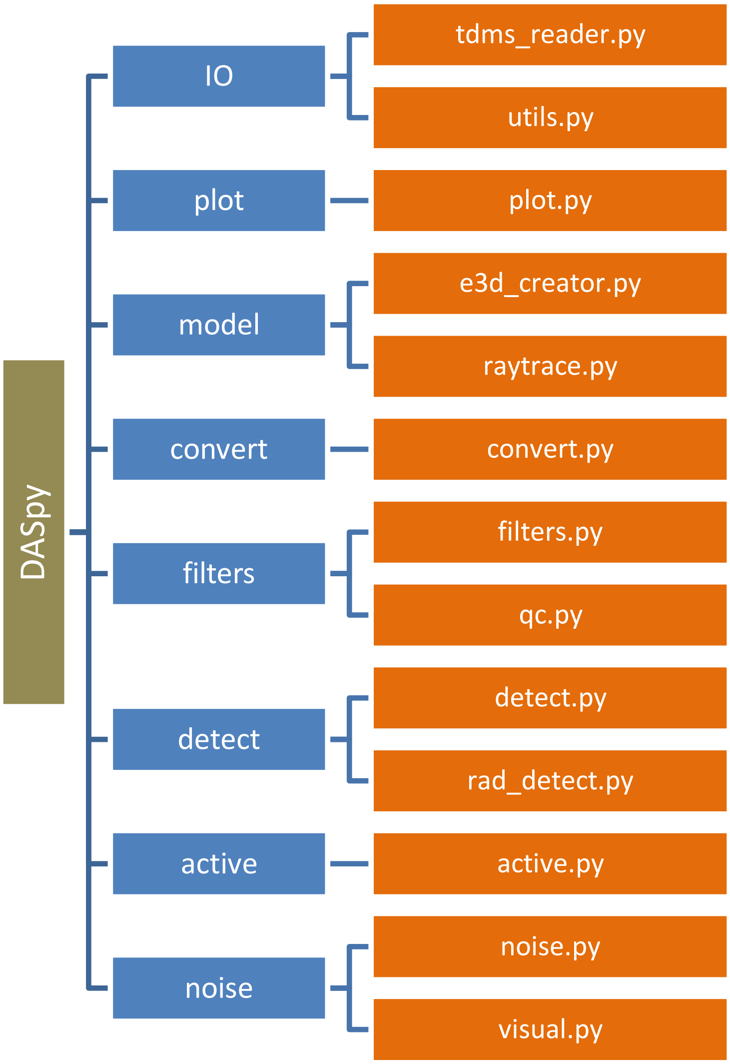


Figure 22. Structure of the DASpy library.

4.3 Contribution to the DigiMon system

Through this research, we have assessed and developed the capability of using DAS as a sensing instrument in active and passive seismic surveys. Some of the challenges of DAS originate from the one-component nature of the fibre, measuring strain instead of particle motion, and the volume of data recorded. We have addressed these issues by developing novel methods for passive methods, such as microseismic data processing (e.g., event detection and characterisation) and ambient noise interferometry (e.g., hybrid receiver and selective stacking). Alongside, this we advanced the efficiency of processing workflows by creating generic python processing functions and adopting machine learning methods to enable real-time processing of DAS data.

5 Task 1.4 - Active source technology development

5.1 Aims and objectives

Geotomographie GmbH developed a SV-wave source to increase its cross-hole tomography capabilities further because borehole SV-wave sources are not currently sufficient to enable complete imaging and understanding of injected CO_2 behaviour over large distances between boreholes. S-wave borehole measurements were carried out at different stages of CO_2 injection at the Svelvik field in Norway to measure the progress of injected CO_2 (Koedel et al., 2022).

The following development steps were carried out:

- Design of the SV-source and selecting appropriate material, manufacturing of the novel SV-source.
- Laboratory tests to gather information regarding the suitable operation principle and for an optimal probe design.
- Field tests to evaluate the performance of both prototypes and to find the suitable operation principle.
- Field test in Svelvik to receive a full tomographic dataset with high-quality P-, SH- and SV- data.

5.2 Outcomes and deliverables

The deliverable from this task was D1.7 (Project report on capabilities of new SV-wave source) and the outcomes in this task were:

- The design of the SV source based on two operating principles.
- The selection of one operating principle based on quality, range, and cleanliness during the first field tests in Germany.
- Successful deployment of this novel SV-wave source at the CCS test site in Svelvik.
- Successful generation of a full tomographic dataset with high-quality P-, SH- and SV-wave data to enable monitoring CO_2 injection with crosshole seismic surveys during different time stages and an assessment of potential stress changes caused by CO_2 injection.
- The SV-, P- and SH-wave sources produce highly repeatable signals for DAS data collection.
- Field use of the novel SV probe revealed problems with sustained operation and the construction has subsequently been modified.
- The SV-source improves the practicability of S-wave tomography by faster handling (up and down shooting), allowing rapid and detailed monitoring of the effects caused by CO_2 injection and reducing the costs.
- The Source Triplet (P-,SH- and SV-sources) is powered by the same high-voltage impulse generator, which leads to reduced costs.

- Horizontally and vertically polarized S-wave (SH-and SV-, respectively) velocity profiles can be used to evaluate the anisotropic properties of rock.

5.3 Contribution to the DigiMon system

The development of the SV-wave seismic source is a new, valuable tool for CO_2 injection monitoring.

SV-waves will be generated using the novel seismic borehole source. The performance of tomographic measurements with simultaneous acquisition of P-, SH- and SV-waves enables the provision of a complete data set for the calculation of elastic moduli, the change of stress states during, e.g., the injection of CO_2 as well as the measurement with fibre optic sensors. Due to its physical properties, the storage of CO_2 in a formation may result in a change in stress due to changes in the elastic properties of the soil (local uplift phenomena), and changes in stress states could potentially be detected with SH- and SV- wave measurements.

In addition, the novel SV-source improves the practicability of S-wave tomography by faster handling (up and down shooting) and each source in the Source Triplet (P-,SH- and SV-sources) is powered by the same impulse generator, which leads to reduced costs.

6 Task 1.5 - Feasibility studies for DCS

6.1 Aims and objectives

The feasibility study focused on the development of new fibre for distributed chemical sensing (DCS) that will allow direct detection of CO_2 leakages in the environment. This is particularly important for monitoring well integrity for CCS to provide early warning for an incoming well failure and potential CO_2 leaking through it. We proposed using optical spectroscopy in optical fibre for direct detection of CO_2 (Figure 23). The main approach is based on Raman interrogation within gas-filled Holey Fibres (HoFs), so that the location and concentration of the gases would be provided simultaneously via backscattering. Additionally, Infrared (IR) Absorption Spectroscopy could also be used, and the architecture would be more discrete since interleaving with standard solid core fibres and Fibre Bragg Grating (FBG) sections is required to enable reflection to the I/O controls. The possible Raman length or the IR numbers of sections would be defined based on signal to noise ratio. The optical spectroscopy methodology would overcome current roadblocks to CCS, as fibre optics will allow for CO_2 (and other gases) detection in wells with direct in-situ measurements of concentration along with other important parameters such as baseline temperature and pressure of environment.

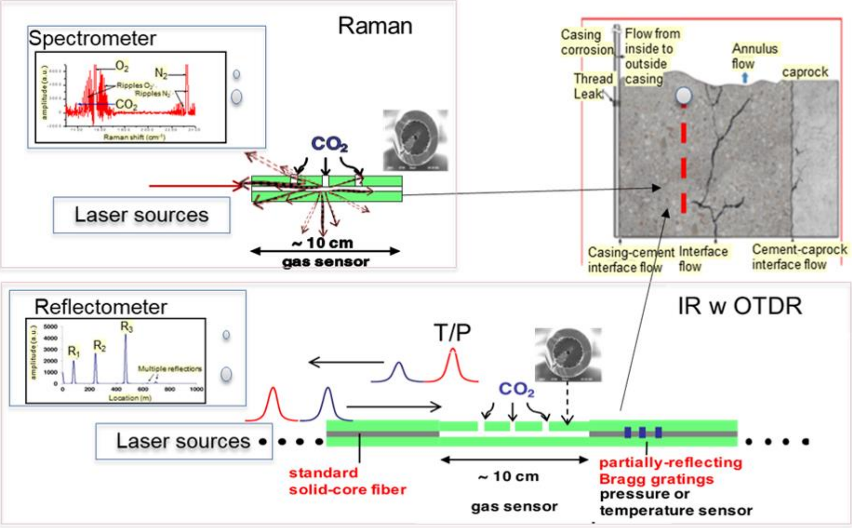


Figure 23. Schematics of CO_2 detection by Raman spectroscopy in slotted HCFs aided by FBGs for multipoint detection. A similar concept would apply for NIR absorption spectroscopy.

6.2 Outcomes and deliverables

We were able to assess commercially available IR/Raman hollow core fibre and demonstrated detection of CO_2 through them in our controlled environment setups (Figure 24). We have been able to measure the CO_2 at various pressures and built models demonstrating fill rates down to order of seconds to minutes, depending on section lengths. Both diffusion-only and pressurized fibre systems have been constructed following numerical simulations in COMSOL based semi-hybrid optical /fluido-dynamics models.

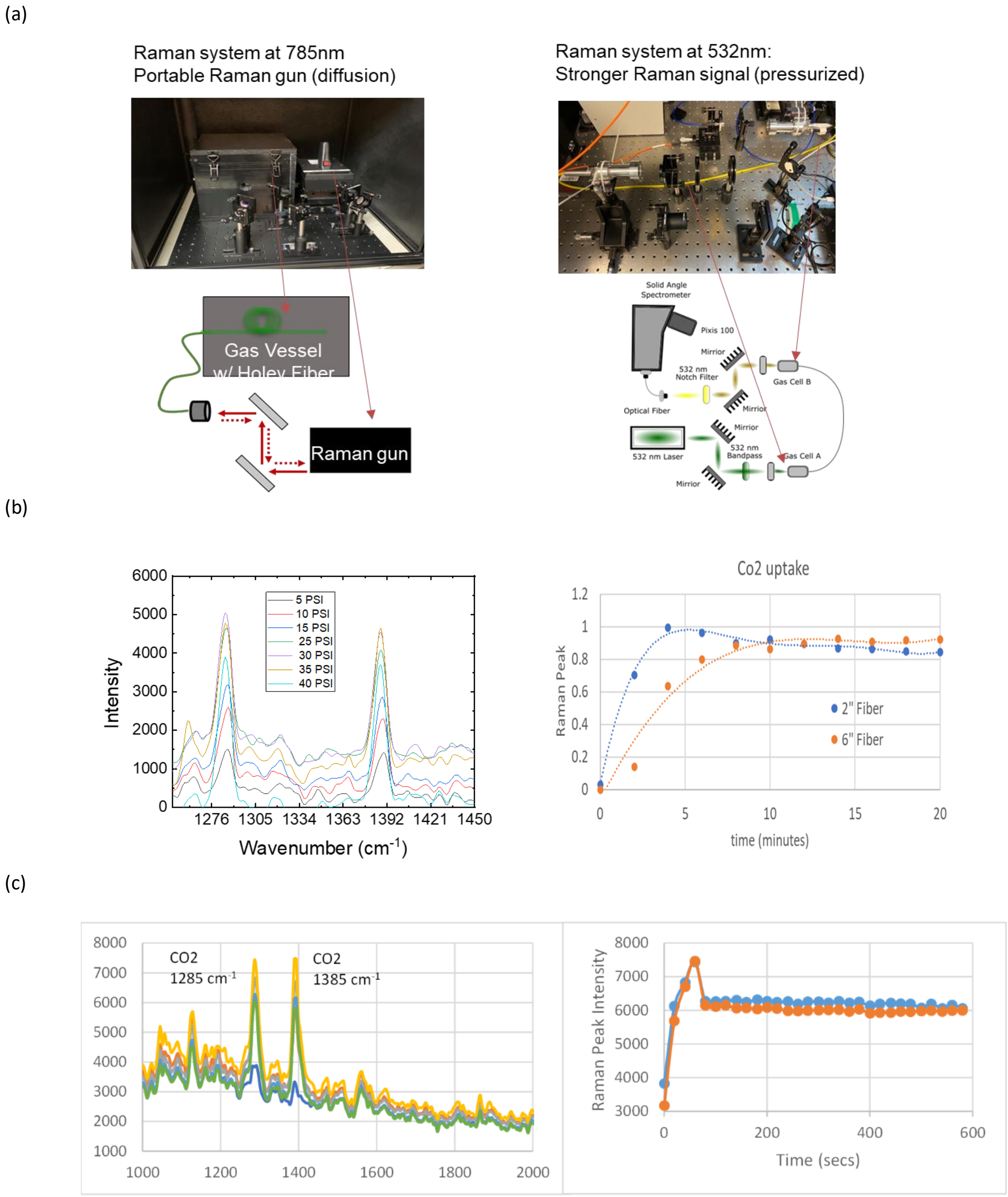


Figure 24. (a)Raman system at 785nm with a portable Raman gun (left) and 532nm Raman setup with pressure-controlled gas cell with Glophotonics PMC-C-Green-26 Microcell (right); (b) diffusion measurements: CO_2 doublet Raman peak trend (left) as a function of CO_2 exposure time, and filling time as function of length for peak 1385cm-1 CO_2 (right); (c) pressurized measurements: Raman detection of CO_2 at 50psi by 532nm HCF, showing time evolution of spectrum (left) and CO_2 doublet peak trend as function of CO_2 exposure time at inlet pressure of 50psi.

We have also established the ability of drilling precisely with pulsed femtoseconds (fs)-lasers side holes to enable penetration of CO_2 into the hollow core fibre and reduce diffusion rates (Figure 25). With a 40fs pulsed Ti:Sapphire 800nm laser 100 µJ, 20x @ 0.40 NA objective, 1 µm/s speed we were able to drill an array of 1-2 µm holes along 10cm fibre length.

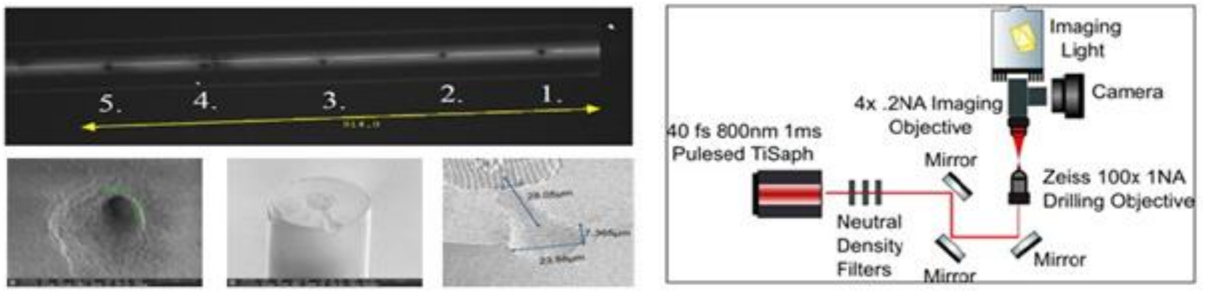
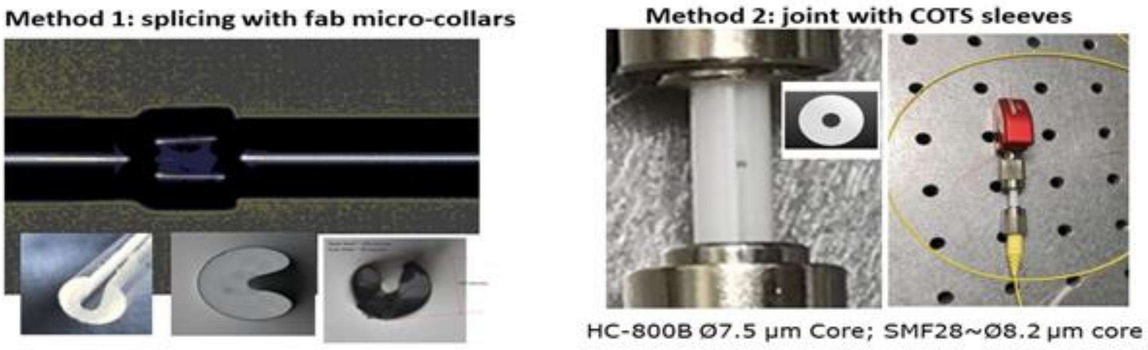


Figure 25. Image of 5 drilled holes in HCF HC-800C (top left); SEMs images of hole on the side and at cleaved facet showing etch depth control (bottom left); setup (right).

HoFs splicing with standard solid core fibres is important for support and field deployment. Open joint collars were also explored having a double functionality, adding gas ingress locations (Figure 26). Splicing or cleaving HCF is delicate given the hollow nature and the lattice morphology: any unwarranted stress can lead to fibre collapse, losing its optical properties or be completely clogged. Nevertheless, we were able to achieve splicing and manage losses of ~10%. We explored two methodologies: one by drawing and fusing a collar of only a few 10s of mm with a gap to enable gas ingress and just sliding the two ends into a mating sleeve off-the-shelf item (right) – this setup guaranteed 50% throughput. The ingress of CO_2 through the collar is being verified


Method 1: splicing with fab micro-collars

Method 2: joint with COTS sleeves

HC-800B Ø7.5 µm Core; SMF28~Ø8.2 µm core

Figure 26. (left) C-shaped preform out of a silica tube then drawn into a C shaped collar of ~60um that got spliced to the solid-core fibre; (right) joining of hollow-core and solid-core fibres by mating sleeve.

FBGs have been identified, procured, and characterized and being integrated. Along the work we leveraged internal modelling/design, photonics/laser characterization, optical fibre fabrication, and AM lab capabilities to design, develop and test in-house components or assemblies. Our results indicate the critical potential that the HoF would have in the direct detection of CO_2 downhole.

The results and conclusions are given in detail in Deliverable 1.8 (Project report on feasibility of using DCS for CO_2 leakage monitoring).

6.3 Contribution to the DigiMon system

We demonstrated most of the key elements to prove this technology has potential and that it is a monitoring technology worthwhile pursuing to increase its TRL levels to make it deployable and economically sound. HoF are commercially available but still quite expensive per unit length, longer lengths being prohibitive because of lack of market consequently inhibiting the overcome of fabrication and technological limitations. At this stage it is unequivocable that we need hybrid solutions, interleaving longer length of solid core fibre with shorter HoF sections at specific locations along the wells. If leak detection of CO_2 in CCS could be proved valid, then a larger market would boost the HoF industry, reduce cost and making our system more cost-effective. We are conducting work on the area of environmental effects (temperature, pressure) on the fibre and eventually such as optical and mechanical property changes.

The proposed technology can be applied to detect, locate, and quantify migration of CO_2 and formation fluids within and above the storage complex main seal through surface deployment within monitoring well. Given the large dynamic range of detection offered by the Raman approach (it is possible to easily tweak applied power or integration time), we could provide a means of detecting CO_2 trapped in hydrocarbons or formation water that would be at much higher levels – up to few mol %. Our short-term goal is to complete assessment of commercially available IR/Raman HCFs, FBGs, and time-domain reflectivity techniques to detect CO_2 leakage.

Longer term plans seek to enable highly sensitive CO_2 detection in the deep subsurface with high selectivity, stability, and sensitivity. More specifically, the proposed program targets to demonstrate the following by the end of the project conclusion: (1) Successful detection of <1% CO_2 in a complex gas mixture representative of subsurface environmental conditions at a length of >1km from the source and detector in a lab environment. (2) Successful demonstration of multi-point measurements of CO_2, consisting of at least 5 individual sensor elements spaced no more than 5m apart on a single optical fibre. (3) Successful field validation in a shallow monitoring well for controlled CO_2 gas release in the well. Ultimately, the proposed DCS technology is anticipated to be capable of selective monitoring of CO_2 in complex subsurface conditions at levels <100ppm and multi-km depths with at least 1m spatial resolution. Because near-IR and Raman spectroscopic techniques are being utilized, future research can also enable multi-component speciation, detection, and quantification of additional analytes of interest in subsurface environments through wavelength division multiplexing with multivariate data analytics methods. The proposed technology can be applied to detect, locate, and quantify migration of CO_2 and formation fluids within and above the storage complex main seal through surface deployment within monitoring wells.

7 Task 1.6 - 4D gravity and seafloor subsidence data acquisition development

7.1 Aims and objectives

The work within this task is part of the efforts to meet the following sub-objectives of the DigiMon project:

- Prepare for integration of the DigiMon system by developing and lifting individual components of the system to a common, high TRL.
- Secure optimal performance of the DigiMon system by optimisation and validation of processing software for DigiMon system components.
- Develop and implement efficient techniques for data acquisition and processing of gravity, seafloor deformation and seismic data.

More specifically, in this task, we have contributed to the further development of microgravity at the seafloor and seafloor deformation monitoring to enhance their applicability within CCS. The developments are directed along two main fronts: facilitating cost reductions and improving data accuracy.

7.2 Outcomes and deliverables

The outcome of Task 1.6 can be summarised in four individual developments listed below. For a more elaborate description of the different developments, we refer to Deliverable 1.9 within the DigiMon project, in addition to the listed publications (Ruiz, et al., 2020; Lien et al., 2023).

The first development is the validation of new functionality to reduce the thermal disturbances on the gravity sensor during data acquisition (standby mode) for offshore operations. This development keeps the instrumentation in mechanical and temperature equilibrium during data acquisition, which provides improved accuracy and reduced measurement time.

The second is the development of a new DepthView software package to facilitate standalone services for measuring seafloor deformations. The equipment for seafloor deformation monitoring is significantly smaller and lighter than that required for measuring gravity. Moreover, 2-mm accuracy can be obtained with a measurement time of five seconds. Hence, the measurement of seafloor deformation can now be combined with other measurements in any survey utilising an ROV or AUV.

The third is new functionality for image recognition to measure the placement of the frame at the concrete platform during measurements. This development is motivated by the ambition to improve data accuracy in addition to progress towards more autonomous operations where placing the instrumentation is based on image analysis.

And, as the last one, we have further developed software for conducting feasibility studies assessing the value of microgravimetry and seafloor deformation monitoring for depleted gas fields. This development contributes to expanding our service to new applications.

The Snøhvit gas field monitoring case demonstrates the enhanced data value to our customers with the improved gravity and subsidence monitoring accuracy obtained from the novel data processing algorithms in part developed through the DigiMon project (Ruiz, et al., 2020). During the 2020 survey at the Ormen Lange gas field, OCTIO reduced per-station measurement time by 15% and the overall number of measurements by 13%. Further, OCTIO delivered the lowest total station uncertainties to date on the field: 0.61 µGal for gravity and 3.7 mm for seabed depth (www.octio.com).

7.3 Contribution to the DigiMon system

The developments contribute to reducing the cost of gravimetry and seafloor deformation monitoring to make them more feasible for CO_2 sequestration applications, which are more price-sensitive than for the case of oil and gas. In addition, they aim to improve the accuracy of the data to facilitate refined quantitative estimates of the properties of the storage unit and improve CCS management. And finally, the developments are motivated by the ambition to progress towards more autonomous operations where data acquisitions can be performed remotely from onshore (https://reachsubsea.no/contract-signed-with-kongsberg-maritime-to-build-the-first-two-game-changing-reach-remote-unmanned-offshore-vessels).

8 Task 1.11 - Seismic monitoring design

8.1 Aims and objectives

The aim of Task 1.11 was to demonstrate the capabilities of DAS for seismic imaging in seafloor applications and determine a suitable design for such surveys in combination with the use of traditional seismic survey instrumentation. For this purpose, an active seismic survey with two simultaneously recording systems was conducted. The two recording systems were as follows:

3) towed hydrophone streamer for conventional seismic recording.
4) fibre optic cable at the seafloor for DAS recording.

In addition, a controlled bubble gun source was towed by the same vessel that towed the hydrophone streamer (see Figure 27). The vessel sailed above the fibre optic cable.

The objectives of this survey were:

- compare the signal-to-noise ratio of hydrophone and DAS data.
- develop data processing methods for both recording systems.
- produce seismic images of the seafloor and the underlaying near surface from both hydrophone and DAS data.

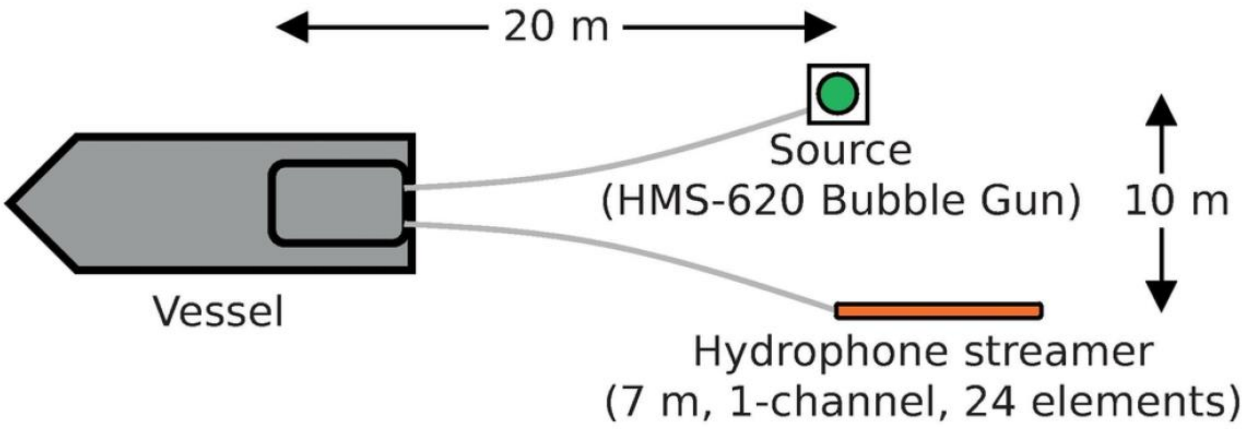


Figure 27. Top view of the acquisition layout. The source and the streamer are towed approximately 20 m behind the vessel. The diagram is not to scale.

8.2 Outcomes and deliverables

An extensive discussion of the survey, the data processing methods and the key findings are published by Taweesintananon et al. (2021). The main findings from this study are given in Deliverable 1.14 (Report on optimisation of seafloor deployments for PRM) and are summarized below:

- DAS and hydrophone data have a comparable signal-to-noise ratio (see Figure 28).

- DAS images can be improved by using a seismic source with sufficiently large energy within the frequency range that matches the spatial resolution of the DAS system.
- The temporal resolution of the DAS images can be increased by minimizing the crossline-offset between the seismic source and the DAS cable. This ensures the presence of near-offset information.

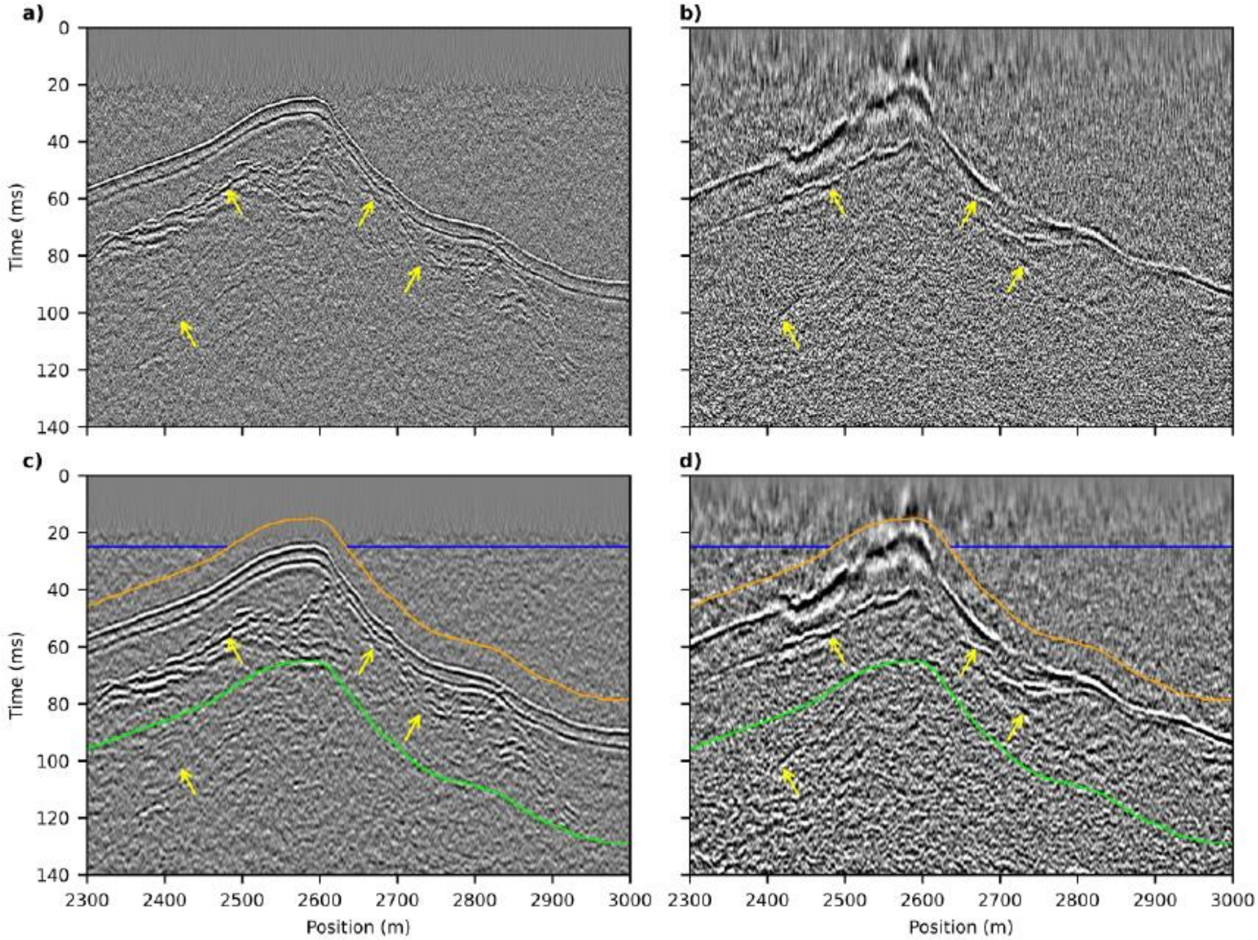


Figure 28. Poststack time-migrated seismic images from different datasets: a) the reference image from a towed single-channel streamer with 24-element hydrophone array of 7m active length, b) the image from seabed DAS with a 4 m gauge length, c) the of a) with additional trace mixing for signal enhancement applied, and d) the image of b) with the same enhancement applied. The seismic events associated with the arrows in comparison with the reference image. The horizontal axis is the distance along the cable. The horizons plotted in c) and d) define the signal and noise windows for computing S/N and spectrum. The signal window is defined between the orange and the green horizons, whereas the noise window is defined between the blue and orange horizons.

8.3 Contribution to the DigiMon system

The obtained insights on using DAS for subsurface imaging can be applied to any seismic acquisition where hydrophones are traditionally deployed. This includes the subsurface at offshore CO_2 storage sites. In addition, permanently deployed fibre optic cables at the seafloor allow for time-lapse DAS recordings.

9 WP1 Impact

9.1 Technology Readiness Level advances

Furre et al (2017) showed that due to the seismic velocity difference between supercritical CO_2, the CO_2 saturated brine and the in-situ brine, time-lapse P-wave active seismic tomography is an effective tool to map the CO_2 plume evolution at the CO_2 geological storage site of Sleipner. Seismic acquisition technologies applied were conventional seismic streamers and broad-band seismometers, which have the limitation of very high associated costs. A promising method which has the potential of reducing costs of such seismic surveys is by using fibre optic sensing using DAS. However, at the commencement of DigiMon project (September 2019) DAS technology was not widely applied in seismic surveys due to high noise levels of early instrumentation. However, DAS had been successfully applied to CO_2 storage sites since 2012 in the form of Vertical Seismic Profiling (VSP) surveys to characterise the storage site and image the CO_2 plume migration (e.g., Harris et al., 2016; Harris et al., 2017). DAS technology had also successfully applied to microseismic monitoring in the hydraulic fracturing industry but data processing routines were at an early stage of development (e.g., Verdon et al., 2019; Stork et al., 2020). Very few research projects were addressing the use of DAS for ambient noise imaging or surface seismic applications. The technology had been applied onshore to CCS projects but not offshore. Therefore, DAS had a TRL ranging from 3 – 8, depending on the application (Table 2). See Appendix C for the TRL criteria used for the assessment.

Application	TRL at DigiMon start	TRL brought forward by DigiMon
DAS surface and seabed seismic reflection	4	5-6
DAS Vertical Seismic Profiling (VSP)	8	8
DAS seismic crosshole tomography	3	5-6
DAS microseismic monitoring	5-6	7-8
DAS ambient noise interferometry (ANI)	3	4-5
Distributed chemical sensing (DCS)	2	3

Table 2. Summary of distributed fibre optic sensing TRL advancement by WP1 of the DigiMon project.

The research tasks carried out for WP1 of the DigiMon project produced new data processing methods and routines for DAS monitoring by using the pre-existing micro-seismicity dataset of FORGE geothermal system; the active and passive DAS dataset acquired by the British Antarctic Survey (BAS) and the University of Oxford in Antarctica during 2020; the laboratory experimental dataset acquired by NORCE; a synthetic micro seismic distributed acoustic sensing (DAS) dataset developed during the project; and the data of crosswell seismic measurements carried out at the Svelvik test site (see Section 2). By using the above datasets, a pre-processing workflow, processing algorithms, a transfer function and processing workflow were developed, which brought forward the technology for DAS microseismic monitoring, DAS ANI, 4D DAS active seismic tomography and DAS seismic reflection (Table 2).

The field testing of a novel SV-wave seismic source and a redesigned Multilevel Borhole Acquisition System (MBAS), aswell as acquistion of crosshole DAS data on straight and helical cables with P-, SH- and SV- seismic waves, took place at the Svelvik field laboratory. These tests demonstrate the technology in a relevant environment and so advanced the TRL level of SV-source crosswell surveys and also DAS crosswell surveys from TRL 3 to TRL 5-6.

Concerning DCS, design, fabrication, and characterisation of commercially available hollow core fibre for IR/Raman spectroscopy experiments carried out during the project advanced TRL from 2 (technology concept formulated) to TRL 3 (experimental proof-of-concept).

As microgravity and vertical seafloor deformation monitoring surveying were already at TRL 9 (actual system proved in operational environment) at project commencement (Furre et al 2017), developments carried out by the DigiMon project resulted in cost reductions and accuracy improvement rather than TRL development.

9.2 Stakeholder information

9.2.1 CCS industry

DigiMon advances in DAS technology can provide the next generation remote CO_2 injection monitoring, as fibre optic DAS could provide low-cost alternative to existing Permanent Reservoir Monitoring (PRM) seismic systems, allowing the replacement of streamer or Retrievable Ocean Bottom Seismic (OBS) surveys. Permanent DAS seismic systems in passive mode can provide real-time monitoring of the geomechanical effects of injection with microseismic events detection and analysis. Further developments in ANI techniques, with both traditional and fibre-optic sensors, could contribute towards imaging the CO_2 plume evolution without the need of expensive active seismic surveys.

DigiMon experiments indicate that there could be benefits of including small azimuthally varying 2D segments of DAS arrays as part of a larger aperture deployment to introduce some multi-component sensitivity, allowing monitoring geomechanical changes through shear-wave splitting and inversion towards CO_2 pressure and saturation.

Improvements in gravity and seafloor deformation surveying can provide reduced costs and clearer imaging of CO2 mass and pressure distribution within the storage complex.

DigiMon also highlighted the potential of using DCS in future CCS monitoring.

To sum up, the industry needs a low-cost system for monitoring subsurface CO_2 plume evolution and DigiMon WP1 provides developments in alternative technologies (DAS and gravity) to help reduce costs and improve monitoring effectiveness and accuracy over present state-of-the-art.

9.2.2 Policy makers and regulators

The needs of policy makers and regulators direct a CO_2 storage field monitoring system. A suitable monitoring system should monitor conformance and containment and be linked to a safety concept in case of CO_2 migration to nearby subsurface formations or to the atmosphere. DigiMon WP1 provides alternatives for such technologies (DAS and gravity). Permanent installation of these technologies can facilitate early warning, an essential part of the safety concept.

In addition, present monitoring regulations specify monitoring of reinjection parameters (pressure, temperature and flow) at the reinjection well. The future development of DCS can also provide monitoring of well integrity.

A summary report on the outcomes of WP1 for policy makers is given in Deliverable 1.12 (WP1 results summary report suitable for policy makers).

9.2.3 Research results

WP1 research results filled in essential knowledge gaps identified by IEA in their report, IEAGHG (2015), by improving:

- Cutting-edge fibre optic DAS data processing for seismic applications, in terms of spatial positioning, effective signal-to-noise improvements, development of microseismic monitoring and ambient noise interferometry processing techniques.
- Sea-bottom gravimetry and deformation measurements.
- Development of an SV-wave seismic source for crosshole seismic imaging.

In 2017, Mission Innovation published a report on Priority Research Directions (PRDs) for Carbon Capture, Utilisation and Storage[2]. The DigiMon project has made significant steps in addressing the storage and crosscutting PRDs, impacting on the cost, acceptability and efficiency of monitoring CO_2 storage sites. The specific PRDs tackled by WP1 are given in Table 3. A roadmap for commercial delivery and implementation of WP1 outcomes is given in Deliverable 1.10.

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[2] Mission Innovation Report on Accelerating Breakthrough Innovation in Carbon Capture, Utilization and Storage, (2017) Report of the Mission Innovation Carbon, Capture, Utilization, and Storage Experts’ Workshop, September 2017.

PRD		WP1 Outcomes
S-4	Developing Smart Convergence Monitoring to Demonstrate Containment and Enable Storage Site Closure	• Task 1.3 – Development of fibre-optic monitoring data processing techniques and workflows. • Task 1.6 – Improved algorithms to acquire and process gravity and deformation data.
S-5	Realising Smart Monitoring to Assess Anomalies and Provide Assurance	• Tasks 1.3 & 1.6 – Improved data processing efficiency of gravity, deformation and DAS data. • Task 1.3 – Development of machine learning processing techniques for DAS data.
S-6	Improving Characterisation of Fault and Fracture Systems	• Task 1.3 – Development of DAS data processing techniques for dense array processing. • Task 1.11 – Seismic monitoring design and optimization.
S-7	Achieving Next Generation Seismic Risk Forecasting	• Task 1.2 & 1.3 – Assessment & development of DAS data processing for seismic monitoring.
CC-1	Integrating Experiment, Simulation and Machine Learning across Multiple Length Scales to Guide Material Design and Process Development	• Task 1.3 – Development of machine learning techniques for DAS data.

Table 3. Mission Innovation PRDs addressed in WP1 of the DigiMon project.

9.3 Dissemination of results

Dissemination of WP1 results took place in a series of over 30 scientific publications in scientific journals, conferences and dedicated webinars organised for this purpose, as shown in Appendix B. Presentations were given at international conferences throughout the project to highlight the ongoing developments in the project.

10 Conclusions and Outlook

Work Package 1 of the DigiMon project has made a significant contribution to the development of multiple CO_2 storage monitoring technologies for different applications. The work performed provides

- Novel fibre optic Distributed Acoustic Sensing (DAS) data processing techniques and algorithms for passive seismic monitoring, including methods for data denoising with machine learning, microseismic monitoring processing and ambient noise interferometry (ANI) imaging of CO_2 injection.
- A new seismic SV-source to enable a source triplet (P-, SH- and SV-wave) crosswell seismic tomography investigation to detect CO_2.
- A successful feasibility study for seafloor DAS reflection seismic imaging.
- Improved accuracy and reduced number of measurements and measurement time for seabed gravity measurements.
- Software to facilitate standalone seafloor deformation measurements
- Software for conducting feasibility studies to assess the value of microgravimetry and seafloor deformation monitoring.
- An assessment and laboratory demonstration of the capabilities of Distributed Chemical Sensing (DCS) to detect CO_2.

The research and implementation of the scientific breakthroughs have enabled the DigiMon partners to successfully meet the key targets for WP1:

- Develop individual components of the system to raise individual technology readiness levels (TRLs),
- Validate and optimise processing software for individual system components,
- Develop an effective Distributed Acoustic Sensing (DAS) data interpretation workflow.

The expected outcomes of WP1 have been achieved:

- Raising the DAS TRL for passive seismic monitoring,
- An assessment the feasibility of using Distributed Chemical Sensing (DCS) for CO_2 detection,
- Reducing the cost of 4D gravity and seafloor deformation measurements.

There have also been additional outcomes, including

- The application of DAS in a crosswell seismic survey to understand the response of different cable designs.
- A successful feasibility study for seismic reflection imaging using a fibre-optic seabed cable.

There continues to be significant research and development into distributed fibre optic sensing methods as the characteristics, advantages and limitations of the technology are assessed for different applications. One significant benefit of fibre optic sensing is that multi-parameter sensing can be conducted with one sensing element. Combining DAS, Distributed Temperature Sensing (DTS) and

Distributed Strain Sensing (DSS) data collection and interpretation is an ongoing and upcoming area of investigation.

Further automation and autonomy of seafloor gravity and deformation measurements continue to improve efficiency and reduce costs.

The next step for DCS is to test the technology in a field trial.

A roadmap for commercial delivery and implementation of WP1 outcomes is given in Deliverable 1.10.

11 References

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Appendix A WP1 Deliverables

The following are WP1 deliverables, available as reports from the DigiMon project.

- D1.1 - DAS field datasets
- D1.2 - DAS dataset suitable for microseismic and ANI analysis
- D1.3 - DAS synthetic dataset
- D1.4 – Project report on DAS preprocessing workflow
- D1.5 – Algorithms to process DAS data
- D1.6 – DAS processing workflow
- D1.7 – Project report on capabilities of new SV-wave source
- D1.8 – Project report on feasibility of using DCS for CO_2 leakage monitoring
- D1.9 – Improved algorithms to acquire and process gravity and deformation data
- D1.10 – A roadmap for commercial delivery and implementation of WP1 outcomes
- D1.11 - Project report on WP1 outcomes relevant to other WP
- D1.12 – WP1 results summary report suitable for policy makers.
- D1.13 – WP1 final report
- D1.14 - Report on optimisation of seafloor deployments for PRM

Appendix B WP1 Publications and Dissemination Activities

Author(s)	Title	Reference	Project partners involved
Baird	Modelling the Response of Helically Wound DAS Cables to Microseismic Arrivals	First EAGE Workshop on Fibre Optic Sensing, Amsterdam, 9-11 March 2020 doi: https://doi.org/10.3997/2214-4609.202030019	UoB
Ruiz & Lien	Cost-effective reservoir monitoring using seafloor measurements of gravity changes and subsidence,	Norwegian Petroleum Society, Biennial Geophysical Seminar, Oslo, Norway, 9-11 March 2020	Octio EM
Kendall	Detection of micro-seismicity by DAS - field data from Antarctica	DigiMon open webinar, 5 November 2020	UoO
Fagerås	Gravimetric monitoring of CCS	DigiMon open webinar, 5 November 2020	Octio EM
Kendall, Brisbourne, Hudson, Kufner, Butcher, Smith, Chalari, Clarke	Interrogating the cryosphere using distributed acoustic sensing (DAS): examples of active and passive surveys in West Antarctica	AGU Annual Fall Meeting, Dec 2020	UoO, UoB, Silixa
Hudson, Baird, Kendall, Kufner, Brisbourne, Smith, Butcher, Chalari, Clarke	Distributed Acoustic Sensing (DAS) for natural microseismicity studies: A case study from Antarctica	Journal of Geophysical Research: Solid Earth, 2021, 126, e2020JB021493. https://doi.org/10.1029/2020JB021493	UoB, UoO, Silixa
Brisbourne, Kendall, Kufner, Hudson, Smith	Downhole distributed acoustic seismic profiling at Skytrain Ice Rise, West Antarctica	The Cryosphere, 15, 3443–3458, 2021, https://doi.org/10.5194/tc-15-3443-2021	UoO

Author(s)	Title	Reference	Project partners involved
Nøttvedt, Midttømme, Stork, Lien, Puts	Digital monitoring of CO2 storage projects (DigiMon)	Climit 2021 Digits, 10 February 2021 https://www.norceresearch.no/en/insight/DigiMon-ccs-project-at-climit-digit-2021	NORCE, Silixa, Octio EM, TNO
Kendall, Brisbourne, Hudson, Kufner, Butcher, Baird, Smith, Chalari, Clarke	Listening to Ice Sheets - Fibre Optic Cables as Seismic Sensors in the Antarctic (Keynote)	Second EAGE Workshop on Distributed Fibre Optic Sensing, 1-4 March 2021 (online) doi: https://doi.org/10.3997/2214-4609.202131076	UoB UoO, Silixa
Butcher, Hudson, Kendall, Kufner, Brisbourne, Stork	Radon transform-based detection of microseismicity on DAS networks: A case study from Antarctica.	Second EAGE Workshop on Distributed Fibre Optic Sensing,1-4 March 2021 (online) doi: https://doi.org/10.3997/2214-4609.202131039	UoB UoO, Silixa
Hudson, Baird, Kendall, Kufner, Brisbourne, Smith, Butcher, Chalari, Clarke	Distributed Acoustic Sensing in Antarctica: What we can learn for studying microseismicity elsewhere	Second EAGE Workshop on Distributed Fibre Optic Sensing, 1-4 March 2021 (online) doi: https://doi.org/10.3997/2214-4609.202131037	UoB UoO, Silixa
Kendall	Passive seismic monitoring and the geomechanical response to CO2 storage (Invited)	Recent progress with CO2 storage monitoring and development of integrated methods, Universitsy of Oslo Seminar, 9 March 2021	UoO
Nøttvedt, Lien, Midttømme, Puts, Stork	Digital monitoring of CO2 storage projects (DigiMon)	15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, http://ssrn.com/abstract=3823153	NORCE, Silixa, Octio EM, TNO
Vandeweijer, Paap, Verdel, Mellors, Baird, Stork, Butcher	Modelling the DAS response for offshore CO2 storage sites	15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, https://ssrn.com/abstract=3820913	TNO, LLC, UoB, Silixa
Nøttvedt, Lien, Midttømme, Puts, Stork	DigiMon	SPE Virtual Workshop: Offshore CCUS - The Size of the Prize and the Way Forward, 6-13 April 2021	NORCE, OCTIO EM, TNO, SIlixa

Author(s)	Title	Reference	Project partners involved
Pitarka, Thomas, Paap, Heggelund, Butcher, Matzel, Mellors	Understanding Fibre Response with Lab-Scale Tests and Modelling	SSA Seismological Society of America Annual Meeting, 19-23 April 2021	LLNL, NORCE , TNO, UoB
Hudson, Butcher, Baird, Kendall, Kufner, Brisbourne, Smith, Stork, Chalari, Clarke	Antarctic icequakes shed light on the applicability of DAS for microseismic monitoring	SSA Seismological Society of America Annual Meeting 19-23 April 2021	UoB, UoO, Silixa
Stork	Passive seismic monitoring with DAS	DigiMon open webinar, 16 June 2021	Silixa
Landrø	Using DAS-data for geophysical monitoring,	DigiMon open webinar, 16 June 2021	NTNU
Taweesintananon, Landrø, Brenne, Haukanes	Distributed acoustic sensing for near-surface imaging using submarine telecommunication cable: A case study in the Trondheimsfjord, Norway	Geophysics, Volume 86, Issue 5, Sept 2021 https://doi.org/10.1190/geo2020-0834.1	NTNU
Stork, Butcher, Hudson, Kendall, Lapins, Zhou, Paap, Boullenger	Advances in Distributed Acoustic Sensing (DAS) monitoring for CCS projects: The DigiMon project	SPE CCUS Conference, 22-24 February 2022	Silixa, UoB, UoO, TNO
Zhou, Butcher, Brisbourne, Kufner, Kendall, Stork	Ambient Seismic Recordings and Distributed Acoustic Sensing (DAS): Imaging the firn layer on Rutford Ice Stream, Antarctica	Accepted for publication in Journal of Geophysical Research – Earth Surface.	UoB, UoO, Silixa

Author(s)	Title	Reference	Project partners involved
Zhou, Butcher, Kendall, Stork	Enhancing Ambient Noise Interferometry for Das: Selective Stacking and Hybrid Seismic Receivers	EAGE GeoTech 2022 Third EAGE Workshop on Distributed Fibre Optic Sensing, Apr 2022 doi: https://doi.org/10.3997/2214-4609.20224027	UoB, UoO, Silixa
Paap, Bhakta, Vandeweijer, Mannseth	Modelling approach for evaluating time-lapse effects of CO_2 storage on particle velocity and strain rate data	EAGE GeoTech 2022 Third EAGE Workshop on Distributed Fibre Optic Sensing, Apr 2022 doi: https://doi.org/10.3997/2214-4609.20224009	TNO, NORCE
Zhou, Antony Butcher, Kendall, Kufner, Brisbourne	S-wave velocity profile of an Antarctic ice stream firn layer with ambient seismic recording using Distributed Acoustic Sensing	EGU General Assembly, EGU22-7409, May 2022 doi: https://doi.org/10.5194/egusphere-egu22-7409	UoB, UoO
Butcher, Zhou, Kendall, Stork, Vandeweijer, Macquet, Lawton	Near-surface monitoring of CO2 storage sites: Case study from CaMI FRS	EAGE Asia Pacific Workshop on CO2 Geological Storage, Aug 2022. doi: https://doi.org/10.3997/2214-4609.202275038	UoB, TNO, Silixa
Delmas, Sahota, Chang, Heyrich, Khitrov, Bond	Hollow-core photonics crystal fiber for CO_2 leakage monitoring	Spie Optics and Photonics, San Diego, August 2022	LLNL
Butcher and Zhou	Enhancing seismic noise interferometry methods for DAS	DigiMon open webinar, 5 October 2022	UoB
Lapins	Using weakly supervised machine learning to suppress strong random noise in DAS recording	DigiMon open webinar, 5 October 2022	UoB
Boullenger	Estimation of the DAS transfer function and retrieval of true ground motion: application to a downhole experiment	DigiMon open webinar, 5 October 2022	TNO

Author(s)	Title	Reference	Project partners involved
Bond	Distributed chemical sensing (DCS) for CO2 leakage monitoring	DigiMon open webinar, 5 October 2022	LLC
Lapins, Butcher Kendall, Hudson, Stork, Werner	Machine learning DAS signal denoising without clean ground-truth signals	12th Statistical Seismology (StatSei) International Conference, 17th – 21st October 2022, Cargèse, France	UoB, UoO, Silixa
Butcher, Zhou, Vandeweijer, Lapins, Kendall, Boullenger, Paap Broman, Stork, Macquet, Lawton	Monitoring CO2 injection at CAMI FRS using Distributed Acoustic Sensing networks	16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, 23rd -27th October 2022, Lyon, France	UoB, TNO, UoO, Silixa
Koedel, Stork, Thomas, Zhou, David, Maurer, Soeding, Fechner	Seismic Cross-hole Surveying to Monitor a CO2 Injection at the Svelvik Test-site in Norway	16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, 23rd -27th October 2022, Lyon, France	Geotomographie, Silixa, NORCE
Bond, Chang, Sahota, Arteag, Heyrich, Delmas, Tumkur, Khitrov	Distributed chemical sensing for CO_2 leakage monitoring	16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, 23rd -27th October 2022, Lyon, France	LLNL

Appendix C TRL Assessment Criteria

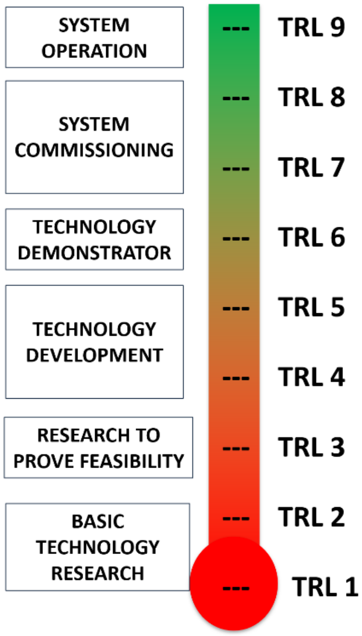

Figure 29. Nine-level TRL scale after DOE (2011)

Top-level question	
TRL 9	Has the actual equipment/process successfully operated in the full operational environment?
TRL 8	Has the actual equipment/process successfully operated in a limited operational environment?
TRL 7	Has the actual equipment/process successfully operated in the relevant operational environment?
TRL 6	Has prototypical engineering scale equipment/process testing been demonstrated in a relevant environment; to include testing of safety function?
TRL 5	Has bench-scale equipment/process testing been demonstrated in a relevant environment?
TRL 4	Has laboratory-scale testing of similar equipment systems been completed in a simulated environment?
TRL 3	Has equipment and process analysis and proof of concept been demonstrated in a simulated environment?
TRL 2	Has an equipment and process concept been formulated?
TRL 1	Have the basic process technology process principles been observed and reported?

Figure 30. Questions to aid TRL assessment.