Deliverable 1.1 Addendum 4:

Data from lab-scale experiments of fibre optic vibration measurement

DigiMon

Digital monitoring of CO_2 storage projects

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DigiMon Deliverable D.1.1 Version 1,
November 2021

Revision

Version	Date	Change	Page
1.0			All

Document distribution

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Table of contents

1 Introduction

Understanding the exact nature of the coupling of the optical fiber in response to seismic waves in a variety of settings is key to quantitative interpretation and modelling of seismic data recorded by Distributed Acoustic Sensors (DAS). While field experiments are very useful for gaining understanding their interpretation is complicated by variations in the conditions along the fibre, such how “straight” the fibre is at a given location, and the properties of the surrounding material. Lab-scale experiment can be useful for investigating specific parameters, since they allow for precise control over the local conditions over short lengths of fibre. This activity works towards the establishment of a lab-scale test bed for characterizing fibre optic response to seismic disturbances.

Using a small-scale (~20 cm by 30 cm) laboratory setup, we measure the exact strain response of a fiber to a known source. The source is a small metal ball on a pendulum that impacts the side of the testbed. The fiber is embedded in sand. The strain in the fiber 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, modeling is conducted using a finite-difference code to evaluate the accuracy of the modeling and to identify any systematic bias. The modeling 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.

2 Description of Dataset

2.1 Experimental setup

The aim of the experiment is to measure the seismic response of a single 0.2 m length of optical fiber. This length is shorter than a typical gauge length for a Distributed Acoustic Sensor (DAS), which is ~ 10m. For the sensor response measurements, we used a fiber-based interferometric measurement to measure changes in the fiber length as a function of time. The interferometry (passive homodyne) is implemented with a 3x3 coupler, two-photodetector phase recovery scheme. The fiber was embedded in sand. A geophone was used to provide reference velocity measurements and to measure uniformity of the impact signals between different experiments. A steel ball bearing pendulum impacting on the side of the container was used to generate the seismic signals.

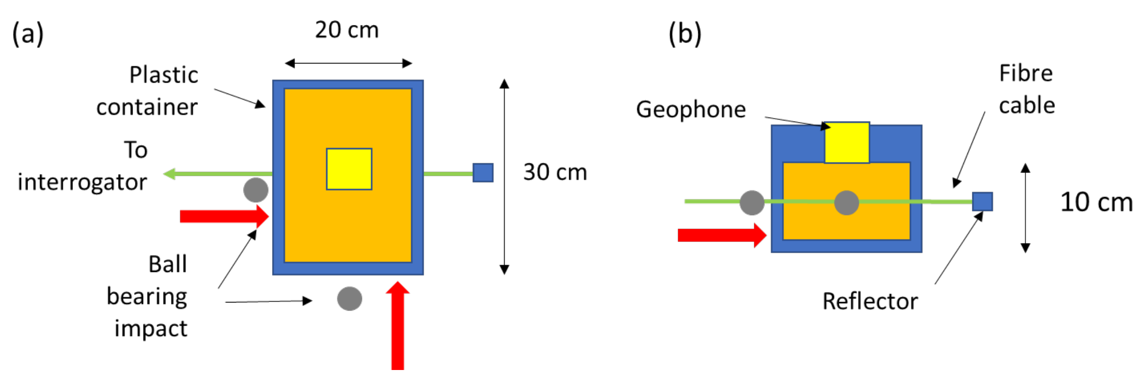


Figure 1) Experimental setup (a) Top view (b) side view

2.2 Variables tested

The cable type was held fixed throughout the investigations, and was a BRUsens DAS AC4 fiber cable that is specifically designed for DAS applications, see the appendix. The sand was also a constant throughout the experiments. 10kg was used, the following distribution of particle sizes was measured using a series of sieves:

Size >2.36 mm : 27%
1.00 mm < Size < 2.36 mm : 21%
250μm < Size <1.00 mm : 40%
Size < 250μm : 12%

The variables that were controlled were:

- The angle between the swing arm impact axis and the fibre. (0°,45° and 90°)
- The sand saturation (wet/dry)

Some example datasets comparing the fibre optic sensor data against the geophone data is shown in figure 2). The data shows the influence of impact incidence angle and sand moisture content on the measurements.

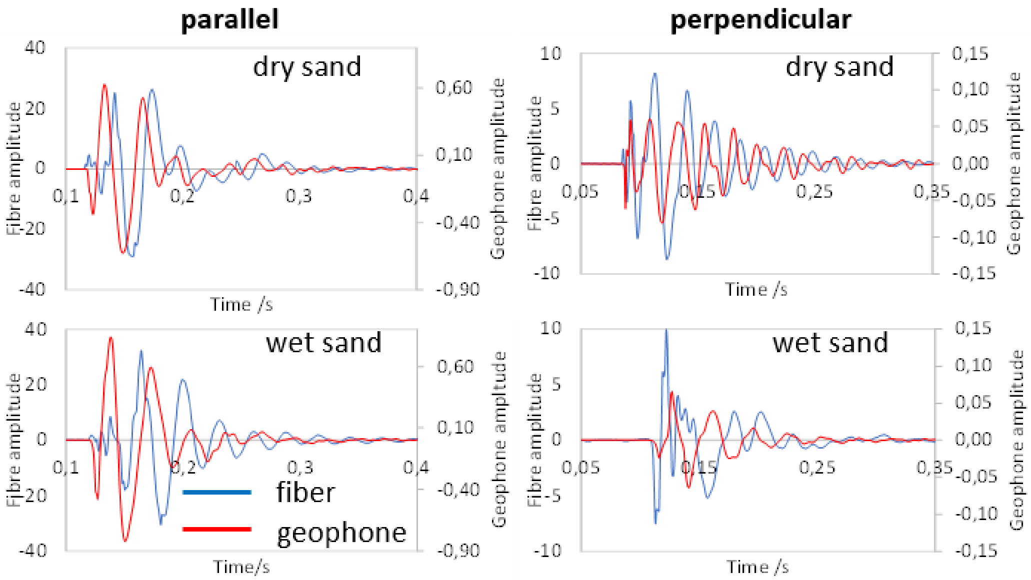


Figure 2) Response of optical fiber (blue) and geophone (red) component parallel fiber axis. Top left: Impact along fiber axis, dry sand, Top right Impact across fiber axis, dry sand. Bottom left: Impact along fiber axis, wet sand. Bottom right: Impact across fiber, wet sand.

To gain more insight into how the frequency content of the response varies over time, we performed continuous wavelet transforms of the signals. Figure 3 shows results using the Morlet wavelet. The impact is characterized by an initial contribution of a broad frequency which then later settles into a periodic response at around 50 Hz. The wave propagates parallel to the fiber in this case. The wavelet transform is similar for the perpendicular case.

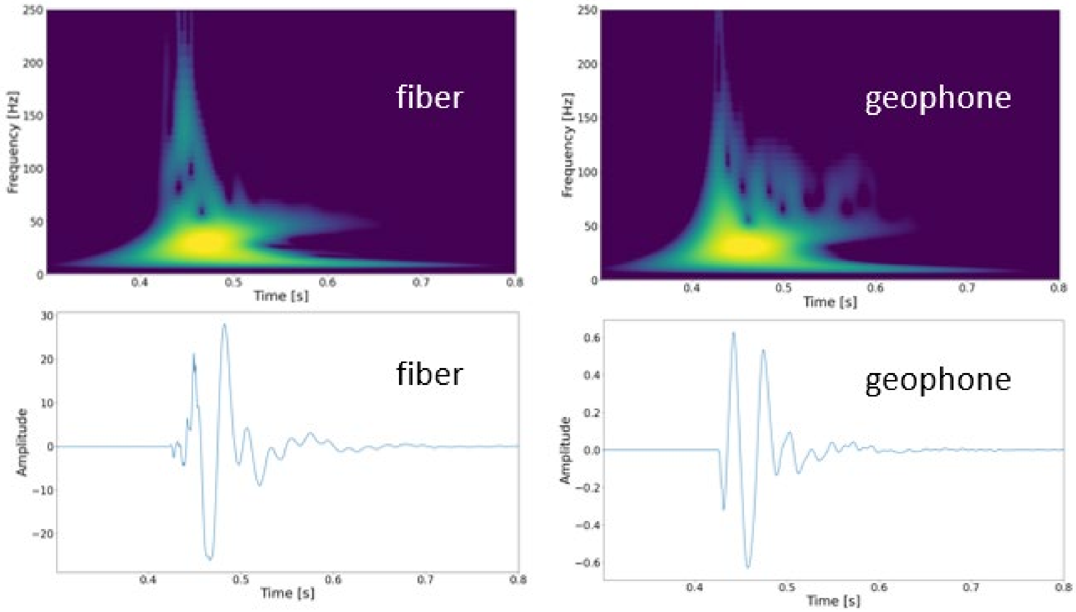
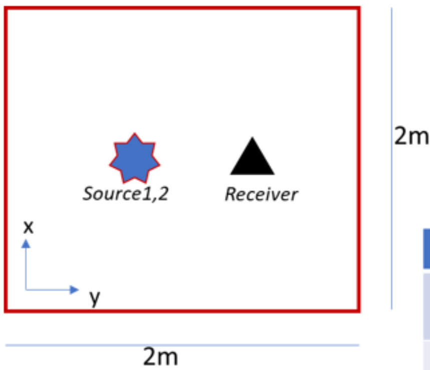


Figure 3) Wavelet transform and corresponding response for the fiber (top and bottom left) and the along axis-component of the response of the geophone (top and bottom right). The results correspond to a source impact directing along fiber direction, and with the fiber embedded in dry sand.

2.3 Modelling work

We used SW4, a 3D finite-difference code, and a point source to calculate time histories of the strain (as measured by the fiber) and particle velocity (as measured by the geophone). For the inital case, a homogenous velocity model with high (2.25) Vs/Vp ratio was assumed on a computational domain that approximated the testbed (Figure 4). Several point source functions were tested and we settled on a combination of two Ricker wavelets separated in time by 0.13 s.

SW4 can generate both the full strain tensor as well as the three components of the particle velocity. We chose the strain component (Syy) along the fibre and the particle velocity along the fiber. We note that in theory, the strain and the velocity time series should be related by the apparent velocity of the seismic waveform (e.g. Lior et al., 2021) and this is apparent in the synthetics. Comparison of the synthetics and the recorded data, after lowpass filtering at 40 Hz, show a reasonable match (Figure 5).



Computational Domain : 2 x 2 x 1.2 m
Rigid boundaries, except for free surface
grid spacing = 0.01 m
fmax= 1000 Hz
Velocity Model
Vp=1800m/s;Vs=800m/s; density=1.6g/cm^3

Source Model

	Moment Tensor	fo	Depth	delay
Source1 Rickert	Mxx=0.2 Myy=1.2, Mzz=0.2 Mxy=0.0 Mxz=0.0 Myz=0.0	25 Hz	0.1 m	0
Source2 Rickert	Mxx=0.2 Myy=1.2, Mzz=0.2 Mxy=0.0 Mxz=0.0 Myz=0.0	25 Hz	0.1m	0.13s

Figure 4) Schematic of modelled system

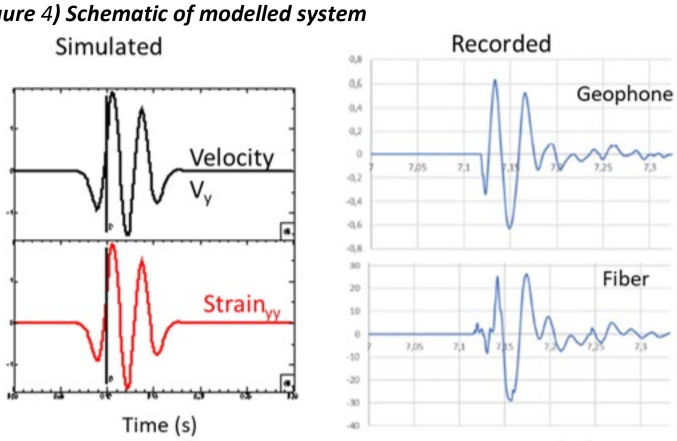


Figure 5) Simulated and recorded waveforms, low passed filtered > 40 Hz

3 Data Access

3.1 NORCE

All data recorded by NORCE are backed up on NORCE's archives. Any requests for data should be made to NORCE.

3.2 LLNL

The SW4 code is open source and available at: https://geodynamics.org/cig/software/sw4/

4 References

Lior, I., Sladen, A., Mercerat, D., Ampuero, J.-P., Rivet, D., and Sambolian, S.: Strain to ground motion conversion of distributed acoustic sensing data for earthquake magnitude and stress drop determination, Solid Earth, 12, 1421–1442, https://doi.org/10.5194/se-12-1421-2021, 2021.

Sjogreen B., and N. A. Petersson. A fourth order accurate finite difference scheme for the elastic wave equation in second order formulation. J. Sci. Comput., 52:17–48, 2012. DOI 10.1007/s10915-011-9531-1.

Thomas, P. J., Paap, B., Heggelund, Y., Butcher, A. C., Pitarka, A, Matzel, E., and Mellors, R., Understanding Fiber Response with Lab-Scale Tests and Modeling, SSA 2021 Annual Meeting Seismological Research Letters (2021) 92 (2B): 1213–1479. https://doi.org/10.1785/0220210025

5 Applications

The main intention of the 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.

Appendix: AC4 fiber optic cable

BRUsens DAS 6.5 mm AC4 non-metallic

3_50_4_004

Fiber optic acoustic sensing cable, non metallic, with tight buffered optical fibers, aramid strain relief and PUR outer sheath, good acoustic response, for up to 4 fibers.

Description

- Compact design, high flexibility, small bending radius
- Outer sheath halogen free
- Outer sheath, robust, abrasion resistant, with special acoustic interlocking system, PUR
- High tensile strength
- High chemical resistance
- Standard rodent protection
- Good acoustic sensitivity
- Extra large diameter for better acoustic sensitivity
- Easy deployment

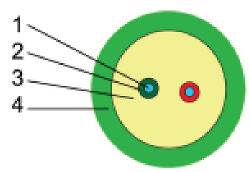
Application

- Acoustic
- Temperature mobile
- Rayleigh scattering
- Outdoors, harsh environment
- Attached to structures or in conduits

Remarks

- Accessories such as mounting brackets, loops, fan-outs, splice enclosures, connectors, patch-panels, repair kits etc. are available
- Deployment training upon request
- Standard cable marking with meter marks, special labeling of outer sheath upon request
- Other cable designs and temperature ranges upon request
- Standard fiber color code: 1 red, 2 green, 3 yellow, 4 blue

LLK-BSAC 6...6.5 mm AC4



Technical data

Type	Max. no. of fibres units	Cable ø mm	Weight kg/km	Installation Max. tensile strength N	Operation Max. tensile strength N
2F	2	6.0	31	2000	800
4F	4	6.5	34	2000	800

Type	with tensile load Min. bending radius mm	without tensile load Min. bending radius mm	Max. crush resistance N/cm	Repeated bending Cycles
2F	15xD	10xD	450	450
4F	15xD	10xD	450	450