Field tests of multicomponent seismic optical fiber sensor deployments

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Summary

Can we deploy DAS fibers in such a way that we locally sense multiple components of a seismic wavefield, increasing the information derived from a seismic experiment, but at the same time maintain its simplicity, and avoid introducing fundamentally new devices or pre-processing? To answer this, we installed and tested a buried experimental multi-component fiber sensor called the "Pretzel" at the Carbon Management Canada Newell County Facility in 2018, consisting of two 10x10 m horizontal squares of fiber. The 10 m sides of the Pretzel are longer than the 7 m gauge length that we typically use, such that we can be assured of acquiring at least one data trace that is unaffected by the corners of the sensor. The Pretzel is too large to either permit a vertical component or to be considered a point sensor, motivating us to install and test a smaller multi-component fiber sensor that could incorporate a vertical component. Three 1x1x1 m sensors (the "Croissant") were installed and tested in 2023. Initial results show good comparability to Pretzel data as well as to surface geophone data converted to strain-rate.

Introduction

Fiber optic seismic sensing (Distributed Acoustic Sensing, or DAS) is playing an increasingly important role in geophysical monitoring, both passive and active, and is poised to be a critical part of a wide range of next generation "energy transition" efforts, including monitoring of geothermal production, and long-term verification of containment and conformance of CO_2 in geo-storage. Especially in the latter application, practical monitoring campaigns will need to put a serious premium on low cost and automation, and DAS is an enabler of this. However, it is also true that every bit of information from data gathered in such monitoring will need to be used. Sensing of the full elastic field, rather than individual components, may be critical for characterization of an evolving subsurface state. Assuming that the standard single component DAS measurement is in this sense insufficient, and that some set of (possibly sparse) point measurements of a 3C particle velocity or 6C strain field is important, some choices exist. We could envision:

- A standard DAS system coupled with sparsely deployed 3C sensors
- An augmented DAS system including multiple fibers (e.g., straight and/or helical) with geometries that sample the wave with variable directionality (e.g., Ning and Sava, 2016; Innanen, 2017)
- Abandonment of fiberoptic systems entirely

to name a few options. However, each of these involves a departure from the fundamental simplicity of the DAS system, and (except for the last) the introduction of complex registration and preprocessing steps with unknown degrees of uncertainty. Acknowledging this – though conceding that these alternatives may well be needed – we seek candidate DAS configurations which retain its inherent simplicity, introduce point sensing of multiple wavefield components, and can be deployed at relatively low-cost.

To this end, we installed an experimental buried multi-component fiber sensor called the Pretzel at the Carbon Management Canada Newell County Facility in 2018 (Innanen et al., 2019), which consists of two 10x10 m squares at 45 degrees buried at 2 m depth. The 10 m sides of the Pretzel were chosen to be longer than the gauge lengths we typically use for DAS acquisition. This was so we could be assured of acquiring at least one data trace that was entirely recorded on a linear segment of fiber and unaffected by gauge-length effects from the corners and other sides of the squares. Due to the size of the Pretzel, it was not feasible to add a vertical component.

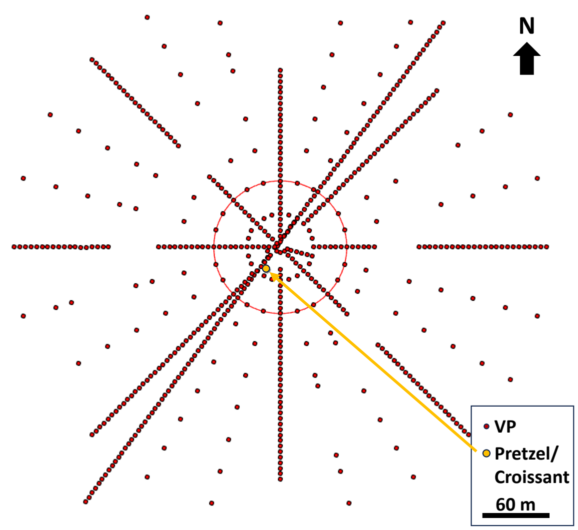

FIG. 1. Vibe Point map showing Pretzel and Croissant location (orange), VP recorded on the Pretzel in 2022, and VP recorded on the Pretzel and the Croissant in 2023 (Line 41, highlighted with a 60 m radius red circle).

The Pretzel is too large to be considered a point receiver, and significant changes in the recorded wavefield, particularly ground-roll, can be observed on a trace-to-trace basis, even when sampling the fiber at a 1 m trace spacing. A single period of ground-roll recorded on the Pretzel for four test vibe points was visually compared to horizontal component data from surface geophones converted to strain-rate (Hall et al., 2020) with good results. More recently, a method to estimate horizontal component tensor strain-rate that was first proposed by Innanen et al. (2019) was applied to 549 Vibe Points that were recorded on the Pretzel during the Snowflake 2 multi-offset multi-azimuth walkaway VSP survey (Figure 1; Hall et al, 2021, 2023), who were able to show horizontal wavefield propagation in map view from multi-component receiver gathers as a result.

It remained to design a sensor along these lines that is small enough to be considered a point receiver and include vertical as well as horizontal components. Takekawa et al. (2022) created and tested such a sensor. Like the Pretzel, they used a gauge length that was shorter (20 cm) than the sides of their sensor (25 cm). Unlike the Pretzel, which was constructed by directly burying fiber cables that are specifically designed for burial, the fiber was wrapped around a 3D plastic frame while under tension. While this design is small enough to be buried, extreme care had to be taken to not break the fiber in the process of burial. A number of these sensors were buried, and Takekawa et al. (2022) show comparisons to hammer source geophone data. Furthermore, 25 cm gauge lengths are not common in DAS sensing, and imply moving quite far from current practice.

At around the same time, we were considering construction of a similar sensor we call the Croissant. Our design involves wrapping a direct burial rated fiber cable around two 1x1 m plastic frames before burying the frames vertically at each sensor location. A critical question in this process is: Can we record meaningful seismic data on 1 m lengths of fiber when the gauge length is greater than the size of the sensor? Initial testing in 2022 consisted of constructing a 1x1 m 10 plastic frame and putting a single wrap of fiber on the frame. Note that the fiber cable was not tensioned on the frame. The frame was merely present to shape the wrap at a specific length and to keep the corners of the wrap from collapsing. The frame was placed on the ground with the fiber wrap in-line with a Vibe, with coupling provided by piling seismic batteries on top of the cable, and test sweeps were recorded using a 7 m gauge length. The frame was then rotated so the wrap was cross-line to the Vibe and more test sweeps were recorded. These tests confirmed that differences observed in the data at the frame location could only be explained by the change in the frame orientation. However, no data was recorded on other sensors for comparison.

Lab Tests

An extension ladder, to make adjustment of the length of the sensor easier, was placed on the floor with geophone planting pole handles passed through two of the rungs. Two scrap pieces of ~10 cm diameter ABS sewer pipe were placed over the planting pole handles to maintain a minimum diameter for the corners of the fiber wrap. Fiber cable was wrapped around the sewer pipes for each of two configurations: 7 m of fiber of the floor, and 1 m of fiber on the floor. A total of twenty-eight meters of fiber was used for each configuration. This was chosen because it is the same length as four 7 m gauge-lengths, giving us three 7 m gauge-lengths worth of data from the wrap uninfluenced by the rest of the fiber in the 7 m configuration.

As in the earlier 1 m frame field test, coupling was provided by placing seismic batteries on top of the fiber. Two source points were used: one in-line with the sensor located 5.5 m from the center of the sensor (SP1), and the other located 3.5 m cross-line from the center of the sensor (SP2). The source was a trailer tire that was lifted to waist height and dropped on the floor five times for each source point. The tire was caught after each hit to prevent a double bounce. Since we have no way to know precisely when the tire hit the floor, shot gathers were extracted from the continuous data using first break pick times. The detrended unstacked data show remarkably good consistency for this source and stacking does not significantly change the quality of the data. Figure 2 shows detrended, extracted, and stacked data for source points 1 (left) and 2 (right) for a 7 m sensor length and 7 m gauge length. Data were also acquired for a 7 m sensor length and a 4 m gauge length, a 1 m sensor length and 7 m gauge length, and a 1 m sensor length and 4 m gauge length. Data recorded with gauge lengths greater than the length of the sensor appear to be functionally identical to data acquired with a gauge length less than or equal to the length of the sensor (not shown).

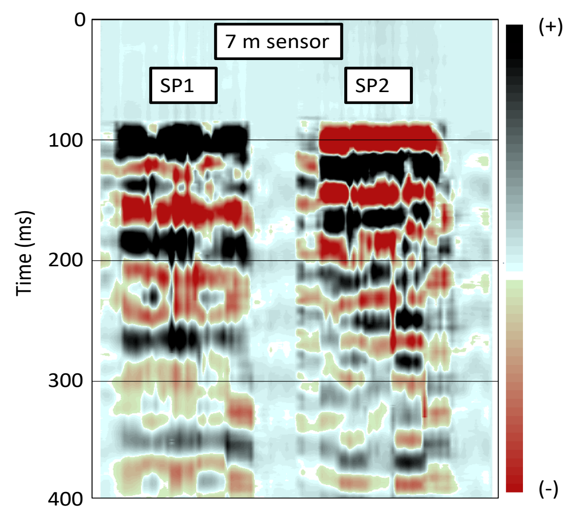

FIG. 2. Source gathers were aligned to 100 ms using first-break picks prior to stacking five tire drops per SP.

While amplitude dimming and brightening along the fiber in the sensor can be observed for each test, we attribute this to poor coupling where untensioned fiber was wrapped around the sewer pipe at each end of the sensor. As previously observed in field data, we do not observe any polarity changes in DAS data recorded on a given interrogator, even when the laser light is travelling in opposite directions as it traverses the fiber. However, the direct arrivals from SP1 (in-line) are a peak and direct arrivals from SP2 (cross-line) are a trough in these tests (Figure 2). This may be due to axial strain on the fiber for in-line shots and dilatational effects on the fiber for the cross-line shots. Further, prior to this experiment, we expected the amplitude of the direct arrivals to be significantly less for the cross-line shots due to broadside insensitivity (eg. Mateeva et al, 2012). of the DAS system. This was not observed, likely due to a complicated near source wavefield coupled with the proximity of the source to the sensor.

Field Installation

Croissant installation began with GPS locates of existing Pretzel fiber. One of the three Croissant stations (C1) is centered in the Pretzel, and the other two (C2 and C3) are located just outside the Pretzel to the SE and SW., at a 10 m station spacing (Figure 3). All trenching for fiber burial was completed at 15 cm width and a 15-30 cm depth between Croissant stations, increasing to 1.2 m depth at Croissant station locations.

Six 1x1 m plastic frames were constructed using ~10 cm diameter plastic pipe. One frame at each Croissant station has two fiber wraps, one horizontal and one vertical, and the other frame just has one horizontal wrap. Like the lab tests, each component contains 28 m of direct burial rated fiber cable. The wraps are offset from the center of the frames, so that the vertical component is close to the junction of the two frames, and the horizontal wraps are as far below the surface as possible (thin blue double-arrow lines; Figure 3). Fiber cable was wrapped around the plastic frames prior to the frames being placed in the trenches. No excess cable was left between components. There is no physical connection between the two frames at each station. They are held vertically by the trenches, and close to each other by the fill. Nine Inova SM-7 10 Hz three-component geophones and Hawk nodes were installed near the corners of the frames (three per Croissant station), with geophone horizontal components oriented parallel to the frames (orange, Figure 3).

Results

While it is difficult to interpret Pretzel data and pick a single trace to represent the center of each of its eight sides, picking a central trace to represent each Croissant component is very easy (Figure 4). Data amplitudes are more consistent trace-to-trace than seen in the lab tests. Multiple Croissant data traces could easily be stacked to improve the S/N ratio, but this does not appear to be necessary for our field data. Note that horizontal component Pretzel and Croissant field data show evidence of broadside insensitivity (cf. Mateeva et. al, 2012) for VP that are in-line with the fiber axis (not shown).

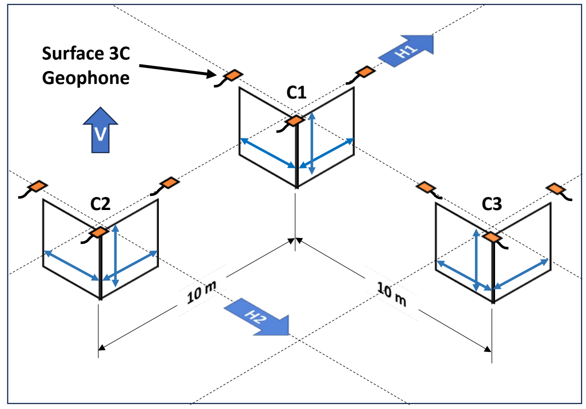

FIG. 3. Schematic showing fiber wrapped (blue arrows) buried vertical frames and surface geophones (orange) at Croissant stations C1-C3.

Two vibe points with 4 sweep per VP were recorded on optical fiber and geophones for testing. A 16 s 10-150 Hz sweep with a 0.5 s start taper and a 0.25 s end taper was used. Figure 5 surface geophone field data (left) and horizontal component Croissant data traces plotted beside geophone horizontal component data that have been converted to strain-rate by subtracting two adjacent traces (right). We were unable to use this method to convert and compare the vertical component geophone data to vertical component Croissant data because we did not bury any geophones. In this plot, each group of four traces contains (from left to right) a geophone H2 component strain-rate trace, a Croissant H2 component trace, a geophone H1 component strain-rate trace, and a Croissant H1 component trace. The geophone strain-rate traces have been arbitrarily bulk shifted trace-by-trace to better align with Croissant traces, with shifts ranging from 1 to 20 ms. We are attributing the need for bulk shifts to receiver statics, where both the geophones and the Croissant were installed in backfilled clay that had not had a chance to settle yet. Additionally, the Croissant horizontal component fiber wraps are located about a meter below the surface geophones.

To compare Pretzel and Croissant data, Line 41 (red circle; Figure 1) radial, and transverse component receiver gathers were computed for the Pretzel and the Croissant (Figure 6). Strain-rate tensors were estimated from eight component Pretzel data (cf. Hall et. al, 2021; 2023), and rotated to radial and transverse components using angles calculated from source and receiver GPS data. Croissant H1 and H2 components were also rotated to radial and transverse components. First impressions are that the Croissant data contain higher frequencies, including air blast) than the Pretzel data.

Discussion

In our continuing quest to develop low cost, directly buried, permanent, multi-component fiber-based sensors, we designed a 1x1x1 m sensor (the Croissant) that is comprised of two horizontal components and a vertical component. This design is smaller, cheaper, and easier to install than our older Pretzel design, which was too large to incorporate a vertical component, or to be considered a point receiver. Lab tests showed that we could acquire data on the Croissant, which has sides that are shorter than the DAS interrogator gauge length, that are comparable to data acquired on a sensor whose sides are greater than or equal to the gauge length. We installed the Croissant at the Newell County Facility in November of 2023, and recorded simultaneous data on the main fiber loop, the Pretzel, and the Croissant, as well as on nine temporary surface 3C geophones located at the corners of each Croissant sensor. Initial results show that it will be easier to create radial and transverse component data from Croissant field data than from Pretzel field data. The Croissant data show good comparability to surface geophone data converted to strain-rate. They are also comparable to Pretzel data converted to radial and transverse component gathers, although the frequency content differs, likely due to the Pretzel fiber being buried at twice the depth of the Croissant horizontal component fiber wraps.

Future Work

We intend to conduct further quantitative analysis and modelling of all data recorded to date on our two shaped fiber sensors. We are expecting to be able to acquire higher quality data after the fill settles around the Croissant post-burial. We also intend to continue thinking about and testing other designs, for example helical fiber cable formed into multi-component sensors.

Acknowledgments

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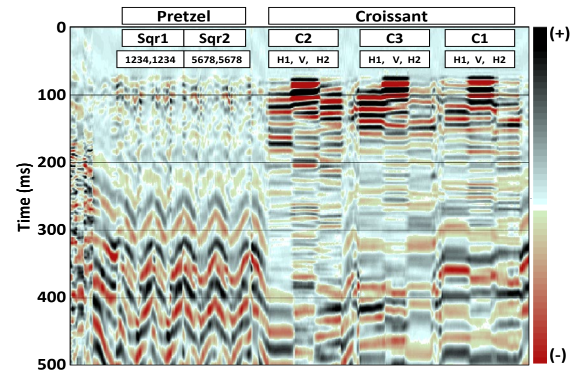

FIG. 4. Pretzel and Croissant field data for a single VP. Four stacked and correlated sweeps (16 s sweep, 10-150 Hz).

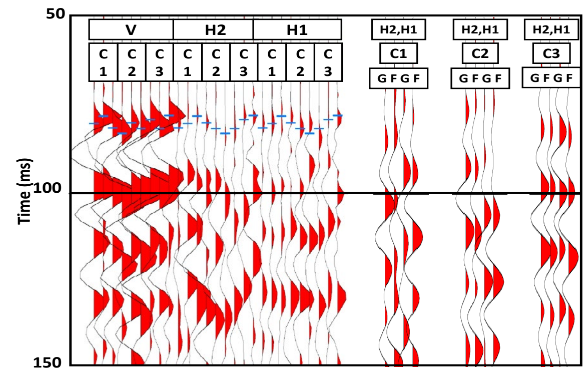

FIG. 5. Geophone field data sorted by component, Croissant station (C1-C3), and geophone station (left) for a single VP. Geophone horizontal components were converted to strain rate (G) and interleaved with equivalent Croissant traces (F) for each Croissant station (right).

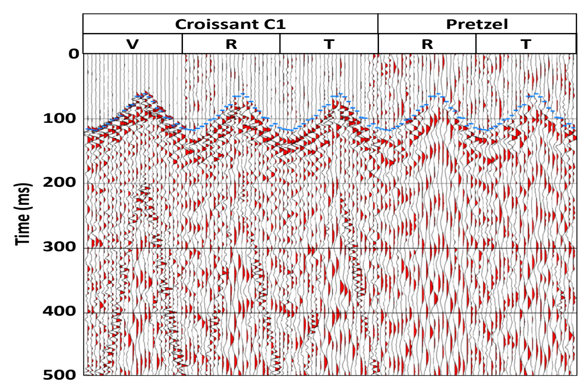

FIG. 6. Croissant station C1 and Pretzel receiver gathers for source line 41 (red circle; Figure 1) with a 150 ms AGC and no filters.