Vertical seismic profiling using distributed acoustic sensing

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ABSTRACT

We explain the methods behind distributed acoustic sensing (DAS) using fibre optic cables. We consider the application of DAS in the acquisition of vertical seismic profile (VSP) data. After conversion from optical backscatter to a strain measurement in terms of time and space, we apply common processing techniques to the VSP data acquired from the Containment and Monitoring Institute (CaMI) site in Newell County, AB using Fotech Solutions DAS technology.

INTRODUCTION

Interest in acquiring geophysical data using fibre-optic cables has increased over the last several years. With regards to data acquisition using fiber-optic cables, several techniques are available; however, in this paper, we focus on the use of distributed acoustic sensing (DAS). We apply this process to acquiring vertical sesimic profiles in boreholes located at the CaMI site in Newell County, AB.

DISTRIBUTED ACOUSTIC SENSING AND FIBRE OPTICS

Distributed acoustic sensing uses a measurement technique called interferometry. Interferometry is based upon the superposition of waves that uses the combination of the waves to infer something about their state.

To create optical interference within the fibre, a pulse of light is launched into the fibre, is reflected back, and interferes with itself. Figure 1 shows a simple case of the geometry required for interference to occur.

Between times 0 and t_0, light is introduced and propagates down the fibre, represented as the red parallelogram. When the forward propagating light reaches the first scatter point x_0, light is reflected back, represented by the green parallelogram. When the forward propagating light reaches the second scatter point x_1, it again reflects back, represented here by the blue parallelogram. When the backscattered light from x_1 overlaps with the backscattered light from x_0, interference occurs. The purple parallelogram represents the overlap of the backscattered light from x_0 and x_1.

The intensity of the backscattered light is measured as a function of time. This intensity of the backscattered light relates to the elastic strain that the fibre experiences through interference patterns in the Rayleigh portion of the backscatter, and so can be interpreted as an

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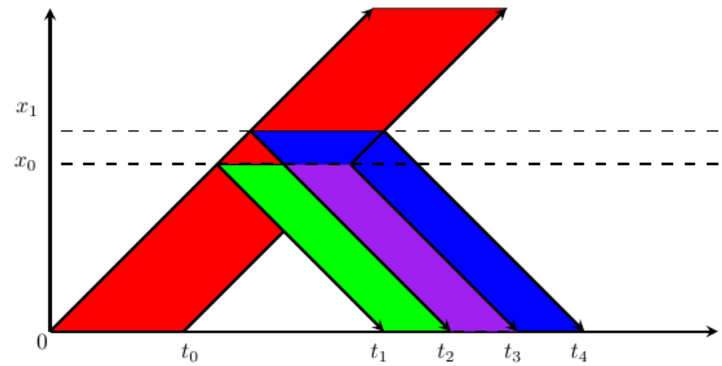

FIG. 1. Interference from multiple scattering points.

acoustic measurement under certain assumptions. As such, two-way travel time in the fibre is used to relate to space and produce a measurement to estimate strain on the fibre with typical sample spacing of approximately two-thirds of a meter. The backscattered light is associated with spatial locations along the fibre using two-way travel-times. Thus, solving the two-way travel time problem with regards to two scatter points x_0 and x_1 provides the following equation for the output intensity

$$I = r_0^2 + r_1^2 + 2r_0 r_1 \cos(2k\Delta x) \tag{1}$$

where r_0 and r_1 are the reflection coefficients at the scatter points x_0 and x_1 respectively, $k = \omega/c$ for frequency ω and velocity c, and $\Delta x = x_1 - x_0$.

The intent is to measure Δx. Using the output intensity, it becomes apparent that it is required that $2k\Delta x \in [0, \pi]$, or $\Delta x \leq \pi/2k$. Therefore, the wavelength of the source must be very stable for the sensor to be reliable.

Measuring Δx by the output intensity puts a limit on sample-rates. As such, we must consider the pulse-repetition-frequency (PRF) when conducting an experiment using DAS. The PRF is the fastest rate at which we may launch a pulse of light into the fibre if we would like the backscattered light to exit the fibre before we launch the next pulse. Therefore, it is important to calculate the time it would take for a pulse of light to reach the end of the fibre and return. Adding this value to the temporal length of the pulse provides us with the PRF.

EXAMPLES

We used DAS to acquire seismic data from the Field Research Station of the Containment and Monitoring Insitute (CaMI) in Newell County, AB. CaMI is a research institute which focuses on subsurface monitoring (CMC Research Institutes, 2015). Specifically, they study methods for containment of carbon and other subsurface fluids. For more information, see (CMC Research Institutes, 2015).

Figure 2 shows a schematic of the fibre loop at the Field Research Station. The fibre leaves the shed and goes down and up well 2 in a helical spiral, then down and back up well 2 in a straight fibre. It then goes to well 1 where it goes down and back up in a straight

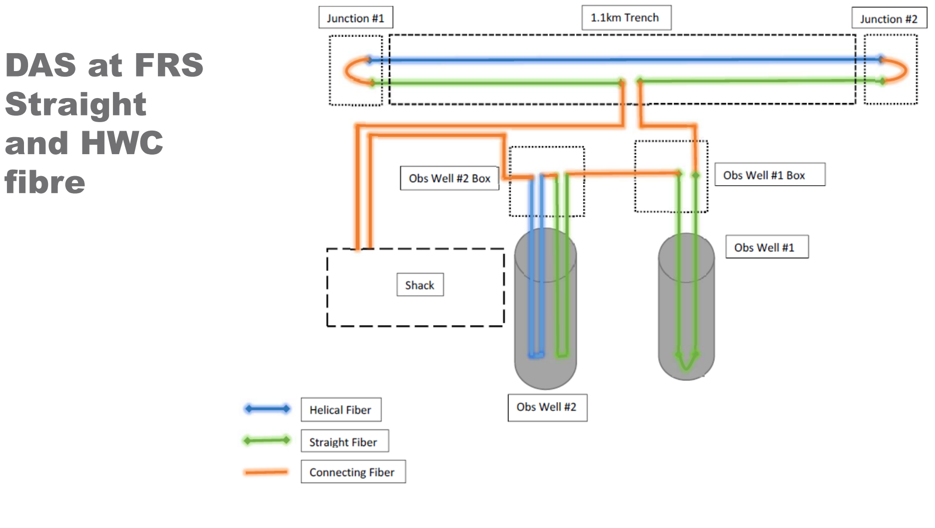

FIG. 2. A schematic of the fibre at the site in Newell County, AB.

fibre. After the wells, the fibre moves to the middle of the trench where it is laid straight for half the trench and then helically for the entire trench, then straight again for half the trench before returning back to the shed. The straight fibre is marked in green while the helical fibre is marked in blue.

The experiment consisted of 270 shots over 49 locations along 2 full lines. Five source locations, numbered 101 to 105, along the length of the trench on line 35, and 44 locations along a a line intersecting well 1 on line 23. Only line 35 is considered here due to time constraints, but further processing is underway on the entire dataset. The source location 103 resided between wells 1 and 2 and was approximately 500m from source locations 101 and 105. The wells reach a depth of approximately 300m. Processing is applied to the raw backscatter data to obtain the optical phase, and then each shot is cross-correlated with the pilot sweep and then stacked. There are 10 shots per stack.

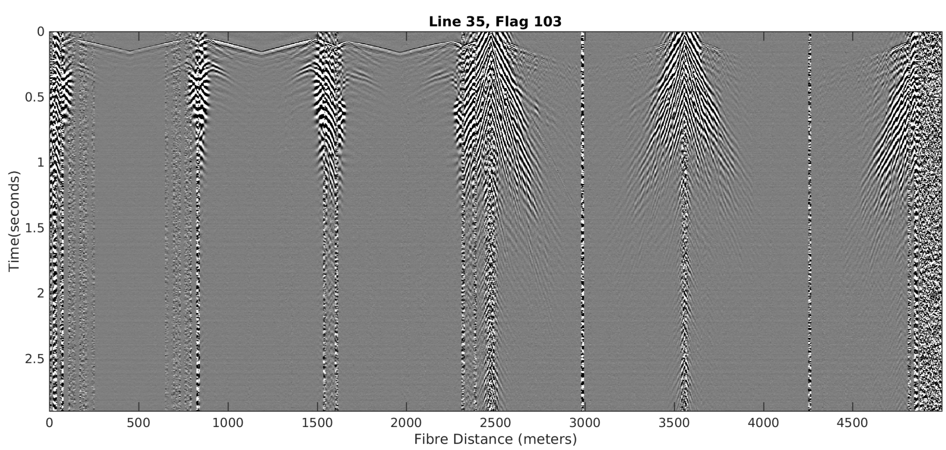

FIG. 3. Full fibre data for line 35 flag 103

Fig. 3 shows the resulting data when the vibroseis truck was at flag 103 for the full fibre. From approximately 0 to 750 meters we see that the helical fibre senses much more of the surface noise than the straight fibres (which go from around 800 to 2400 meters). On the day of acquisition, there was an extreme wind warning in the area so this likely accounts for the source of the noise. Why the helical fibre appears more sensitive to the wind noise than the straight fibre is unknown, but it could perhaps be due to differences in the coupling between the two fibres and the well. Counter-intuitively perhaps, it then seems as though the helical fibre is less sensitive to the vibe signal both in the wells and along the trench.

Fig. 4 and 5 show the results at each source location of well 1 and well 2. In this case, it focuses on the fibre which goes straight down well 2 before returning to the surface, moving to well 1, and extending down the straight fibre in well 1 before returning. From these images we clearly can the P and S wave response of the fibre as well as AVO effects and the position of several prominent reflectors.

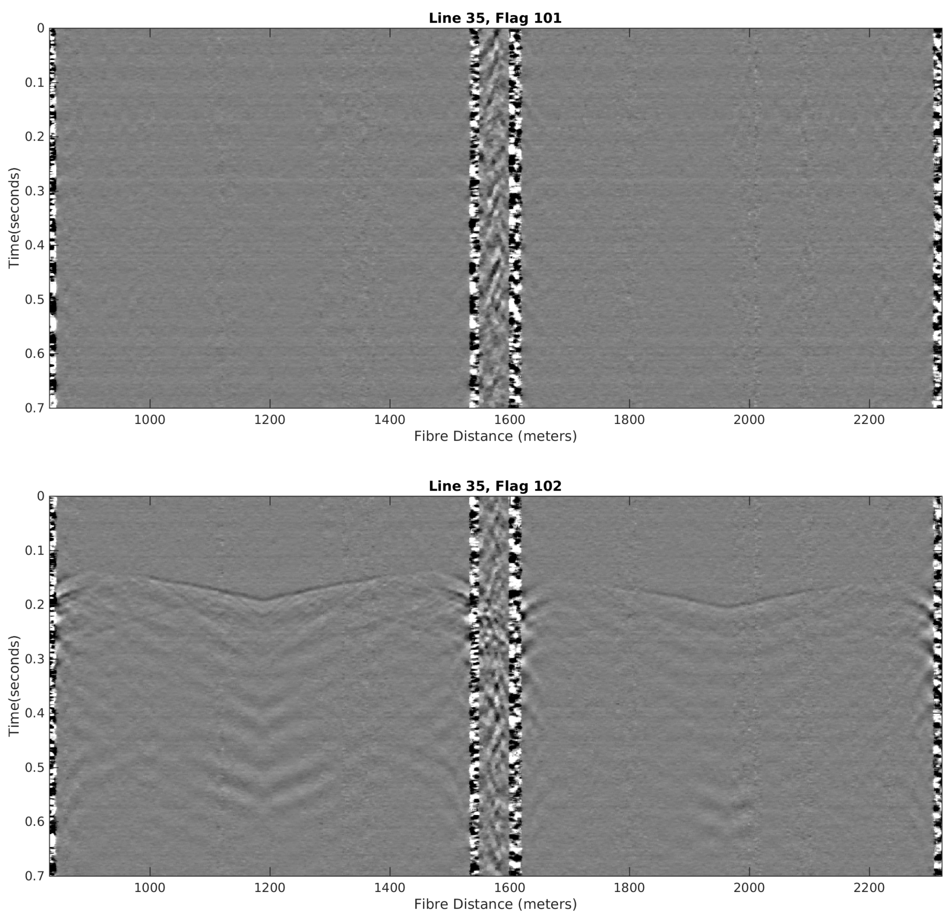

FIG. 4. The straight-fibre from well 2 to the straight fibre in well 1 acquired when the vibroseis truck was at source locations 101 (top) and 102 (bottom).

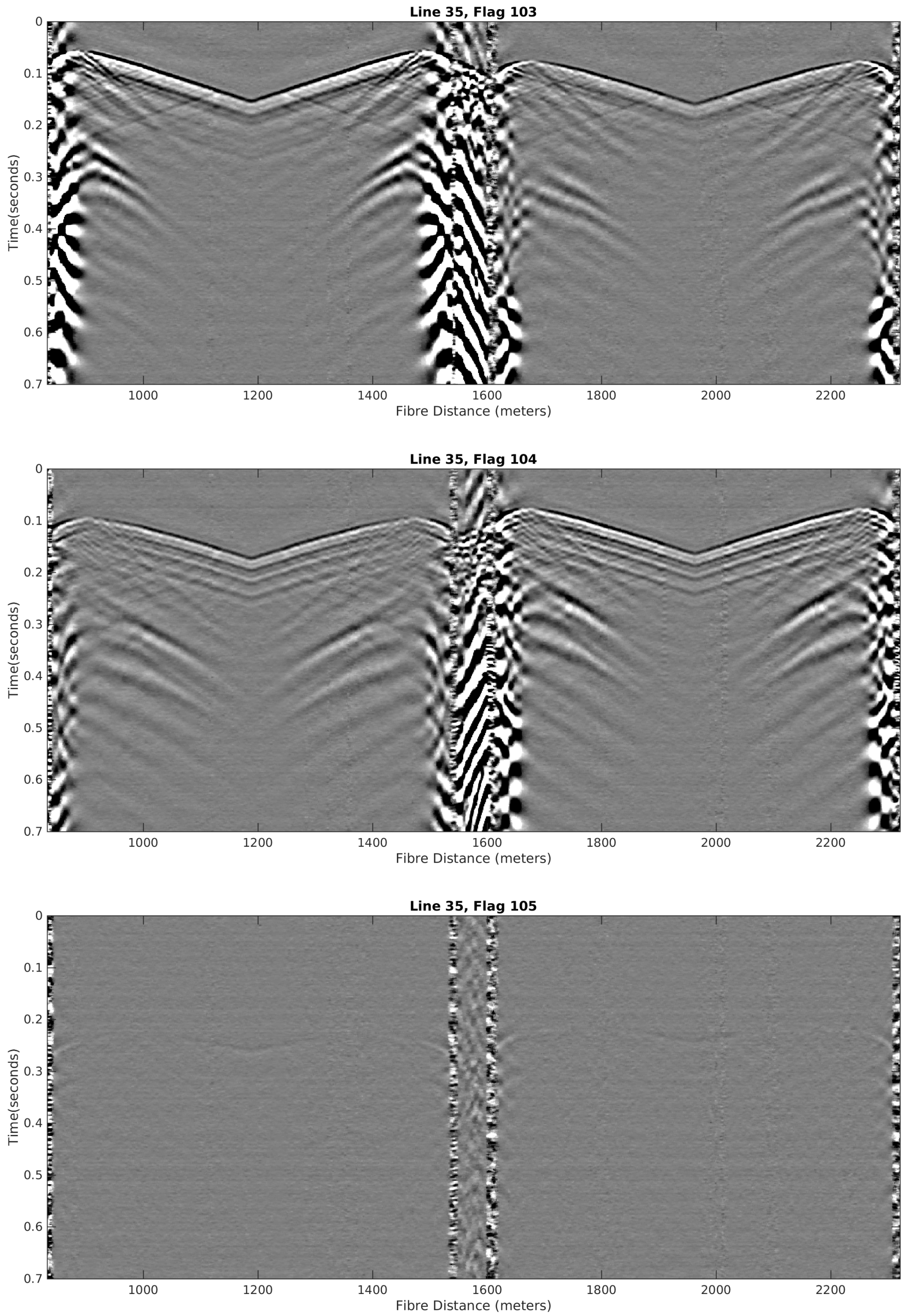

FIG. 5. The straight-fibre from well 2 to the straight fibre in well 1 acquired when the vibroseis truck was at source locations 103(top), 104 (middle) and 105 (bottom)

CONCLUSIONS

We explained the process of acquiring DAS data using fibre-optics and we showed that it can be used to acquire seismic data. We then considered the data acquired from the CaMI site in Newell County, AB and looked at the full fibre data for line 35 at source location 103 as well as the data from the two wells. With regard to the wells 1 and 2, we compared the results when the fibre goes straight down well 2 and returns to the surface before going straight down well 1 and returning to the surface at each source location. The source location 103 provided the best results of the subsurface in all three types of data. This fact is probably because it resides in the middle of both wells and beside the trench.

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