# High-resolution Distributed Acoustic Sensor Using Engineered Fiber for Hydraulic Fracture Monitoring and Optimization in Unconventional Completions

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## Summary

We present the benefits of an advanced high-resolution Distributed Acoustic Sensor that utilizes the new generation of engineered optical fibers for hydraulic fracture monitoring and optimisation in unconventional completions. We have also developed a retrievable engineered wireline fiber optic cable that can be economically deployed for crosswell strain measurement and identification of frac hits, microseismic monitoring, and time-lapse Vertical Seismic Profiling (VSP) acquisition with unprecedented data quality.

## Introduction

Monitoring the fracture geometry and estimating stimulated rock volume (SRV) is the goal for a better understanding of how wells and completions interact with each other.

The Distributed Acoustic Sensor (DAS) and Distributed Temperature Sensor (DTS) are used for multiple measurements along the entire wellbore. During the hydraulic fracturing treatment, the acoustic energy distribution and temperature profiling are recorded in real-time to analyse the fluid allocations per cluster.

The utilization of distributed fiber measurements has been increasing over the past few years. By installing a permanent fiber cable on the outside of a casing string, measurements along the entire wellbore can be achieved. However, the requirements for the cable orientation and directional perforation adds additional complexity and costs for the installation of the fiber and, therefore, limits the number of wells that can be instrumented with fiber and monitored simultaneously.

The high-resolution Distributed Acoustic Sensor system (called Carina) utilizes a new generation of engineered optical fibers (called Constellation fibers) and offers 100x (20dB) improved sensitivity compared to that of standard fibers.

The improved sensitivity has also led to the development of a retrievable wireline cable with engineered fiber that can be economically deployed in offset wells to provide addition measurements axes simultaneously with the data acquired on the permanently installed fibers with unprecedented data quality. The combined data provides a wide volume coverage for fracture monitoring and completion diagnostics.

## High-resolution DAS with engineered fiber

The existing DAS systems utilize standard single mode fiber (Parker T. et al. 2014). However, a transformative improvement in the measurement sensitivity has been achieved by advancing the state of the DAS optoelectronics interrogator architecture, together with the introduction of next generation engineered fiber. This fiber is engineered with bright scatter centres along its length to capture and reflect more light back to the interrogator, as indicated in *Figure 1*. This is

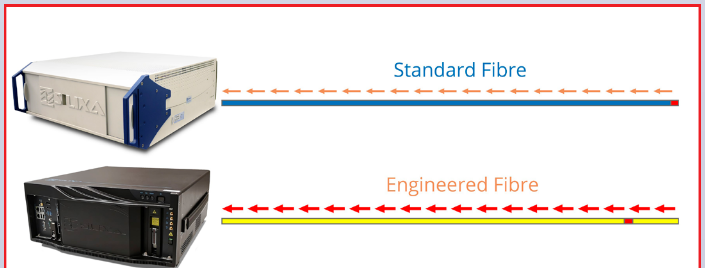


*Figure 1. The DAS system using standard and engineered sensing fiber*

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achieved without introducing significant loss to the forward propagating laser pulses.

The DAS noise performance with engineered fiber is 100x (20dB) lower compared to that when using standard fiber. The DAS performance is comparable to that of geophones around 10Hz but can far exceed the response of geophones in the range below 1Hz. The highly sensitive low-frequency strain measurement provides valuable data for monitoring the crosswell poroelastic build up within the reservoir and the detection of frac hits in the offset well.

The high sensitivity and wide dynamic range of the engineered fiber with its broadband and wide-aperture response can provide unprecedented data quality for both the permanently installed and intervention cables for fracture monitoring and completion diagnostics in multiple wells.

## Field deployment

*Figure 2* shows the fiber field deployment setup in unconventional multiple wells. Two of the wells have a permanent engineered fiber cable cemented behind the casing. In complex projects, it is recognized that acquiring addition data between the wells can be valuable in understanding the crosswell interference. This was achieved using a new engineered intervention wireline cable pumped down in to an already completed well. The wireline cable also has a mono-conductor for being tractored downhole.


*Figure 2. Multiple well monitoring using permanent and intervention engineered sensing cables. Intervention engineered fiber cable provides a new accessible dimension for crosswell monitoring*

With the introduction of the wireline intervention cable, we have added flexibility in designing the fracture monitoring program. By utilizing a retrievable cable, we can now eliminate drilling risks associated with the permanent fiber installation behind the casing and also reduce the overall cost.

The high data recorded both on the permanent and intervention cables can be combined and fed into the completion design in near real time in order to optimize the operations on the current well pad and for future development plans.

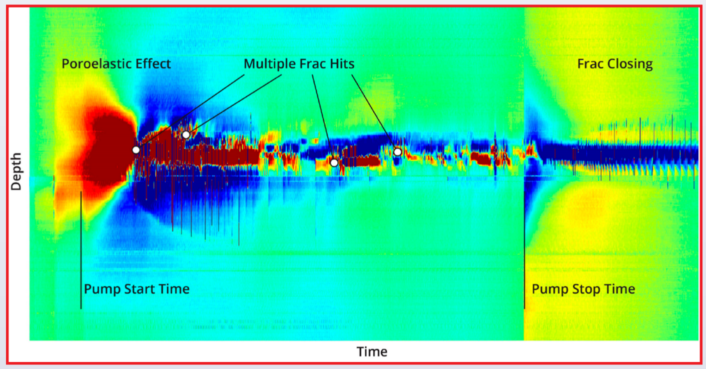


*Figure 3. Colour map of the crosswell strain at depth versus time (600m wide over few hours)*

## Monitoring the crosswell strain and the build-up of poroelastic effect

The crosswell strain data, shown in *Figure 3*, was acquired on the wireline intervention cable utilizing the engineered fiber. As indicated, we can easily identify critical strain effects and treatment processes including pump start time, poroelastic effect, frac hits, pump stop time, and fracture closure in such a intervention deployment with unprecedented clarity. This new data allows completion engineers to map the depth, azimuth and speed of the fractures and feed that information back into the fracture models to validate and optimize the designs for the snext operation.

To further validate the intervention response, the wireline cable was pumped down in the same well that has been instrumented with a permanent fiber behind the casing. As it can be seen in *Figure 4*, we can observe a strong similarity in the response of the both cables.

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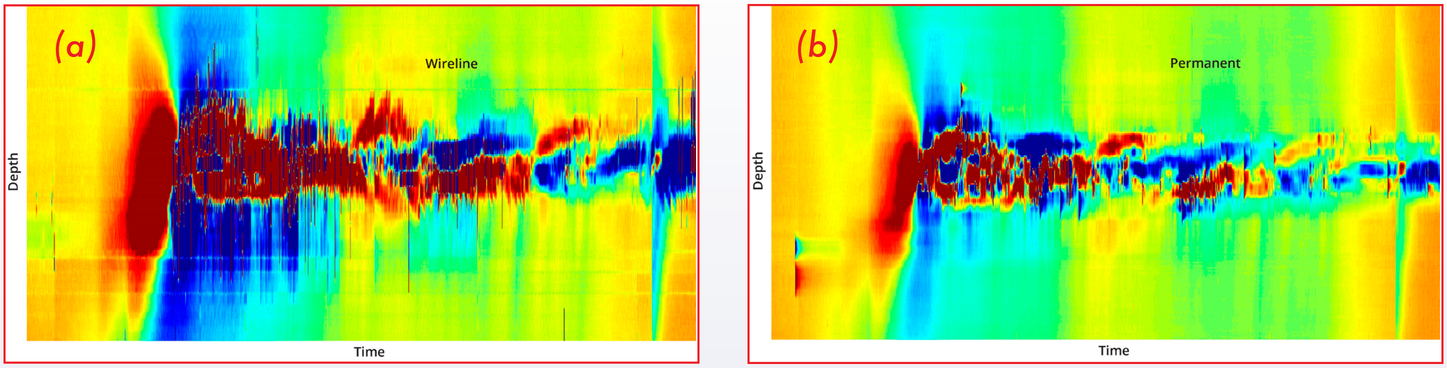


*Figure 4. (a) Low-frequency strain data on the wireline intervention cable compared to (b) the permanently installed cable cemented behind the casing in the same well (300m wide over few hours)*

The results indicate that there is a sufficient frictional coupling between the wireline cable and the inside wall of the casing. In addition, we can see the strain rate (in the order of tens of nano-strain per second) exerted on to the outside of the cable is transferred to the fiber inside the cable in both cases.

Distributed temperature data was also recorded along both cables with a fine resolution down to 0.01oC. The results confirmed that the low-frequency strain data are not affected by any observable temperature changes during this time interval.

Multiple frac hits can be observed following the tensional and compressional strain building up due to the poroelastic effects as the fluid is pumped into the reservoir.

## Frac hits identification

As discussed previously, the engineered fiber deployed on wireline enabled us to acquire high quality distributed data between the wells. As shown in *Figure 5*, by simultaneous recording along three cables, each in a different well, we were able to map the fracture azimuth propagation through

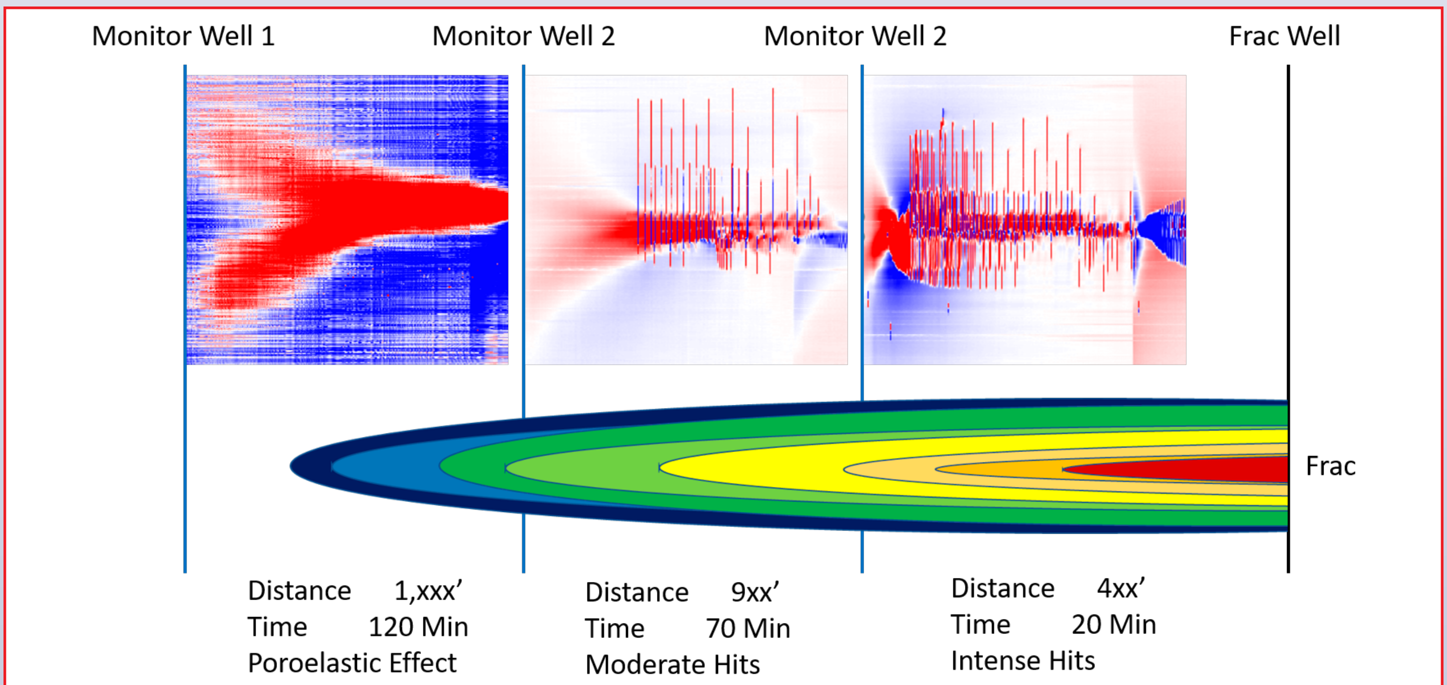


*Figure 5. Monitoring the poroelastic effect and frac hits passing through three fiber locations*

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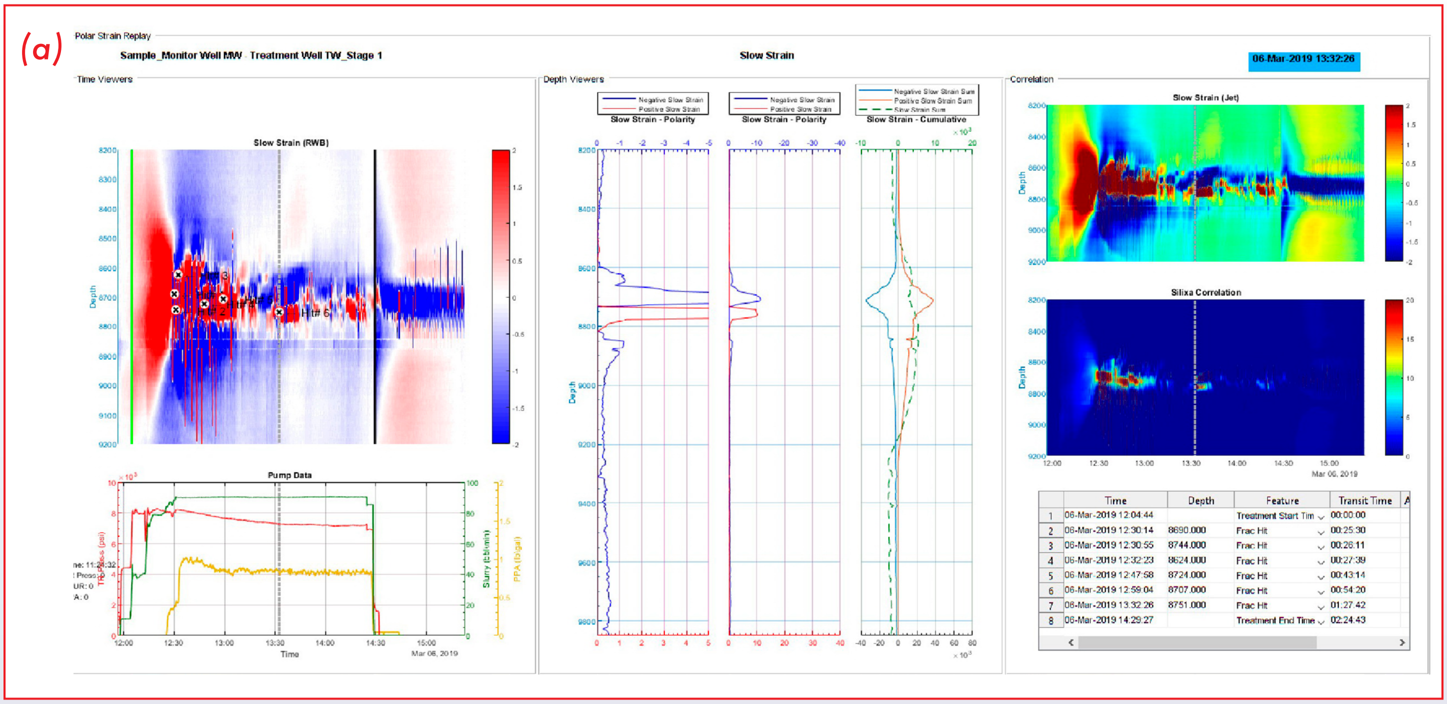
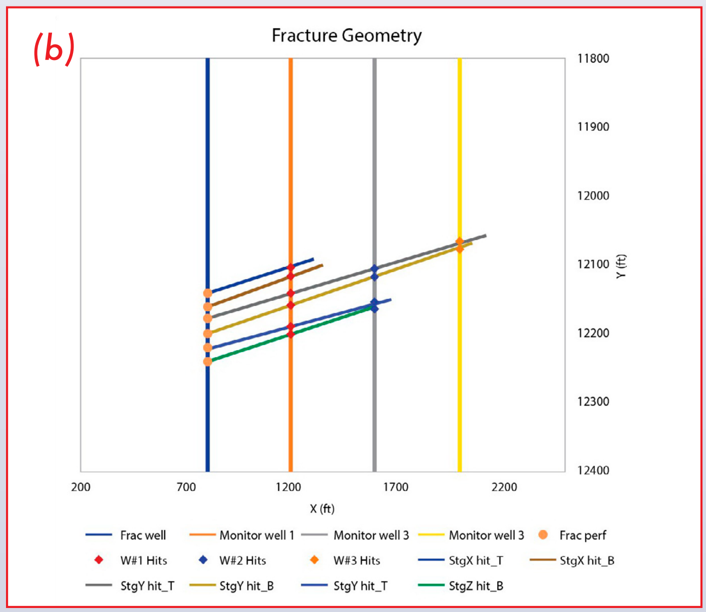



Figure 6. (a) Interactive strain data processing and (b) identifying the frac hits in real time




the formation and as passing through each fiber location. For illustrative purposes, an example of a fracture half-length is also displayed (Viegas G. et al. 2018). We can see that the wells closer to the frac well have a higher intensity of strain events and the farthest well does not actually experience a frac hit.

*Figure 6* shows the strain data was processed and the frac hits were identified in real time at the wellsite, including the direction and the magnitude, and the information was immediately fed back interactively into the completion designs plan.

## Microseismic

The objective in hydraulic fracture monitoring (HFM) is to map the treated volume's height, length, width and azimuth. We assume this volume is closely approximated by a microseismic cloud of event locations or hypocenters. Until recently, only geophones had sufficient signal-to-noise quality to detect and locate a sufficient number of events hypocenters to map the fracture. Due to recent advances in optical fiber engineering a single fiber can collect data comparable to over 5000 Z-component geophones.

If only one monitor well is available, only the origin time, measured depth and distance from the fiber can be determined for each event. Plotting event time and measured depth on a strain waterfall shows strong correlation between strain and microseismicity, enhancing support for both. While an array in a single horizontal or vertical monitor well is not able to fully locate micro seismic events, two or more such arrays certainly can. Colocation finds the hypocenter which best fits arrival times at all monitor wells simultaneously. Therefore, colocation by two or more monitor wells is highly recommended.

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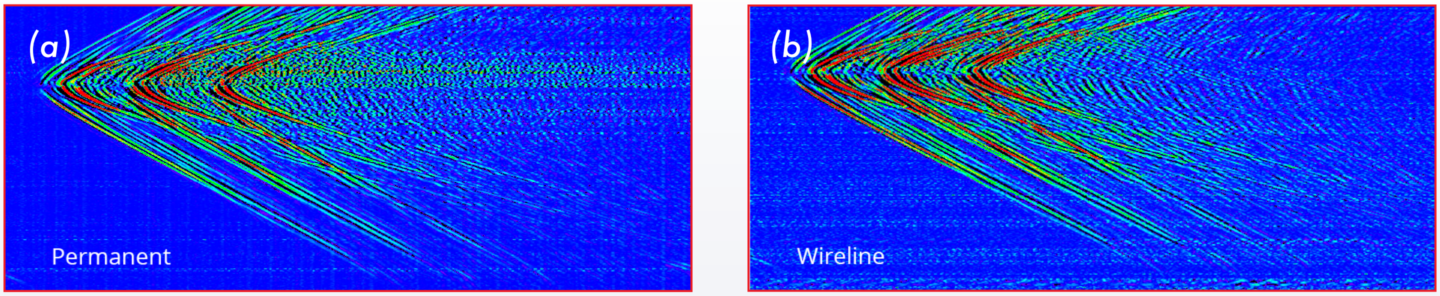


*Figure 7. Comparison of the field microseismic event detection on (a) the permanent and (b) wireline engineered fiber*

Downhole geophones are three-component instruments, measuring ground motion in X, Y and Z directions. This polarization helps constrain the source direction but is more difficult to measure and predict than simple arrival times. Refraction at stratigraphic boundaries and SH and SV shear wave interference complicate this problem. A fiber optic array in two or more wells requires only arrival times for hypocenter determination, negating the need for polarization modelling and measurements.

The initial impetus for live hydraulic fracture mapping was to enable modification of the treatment on the fly. For example, stopping a stage that is growing into a water bearing zone or continuing a frac that had not achieved desired length. Such incidents have indeed happened, but more commonly the value of live HFM is simply quality control. The operator can be assured that good valid fracture diagnostics are being recorded for each stage. Today critical fracture parameters such as clusters per stage and cluster and stage spacing can be tested and optimized for later stages of the same job.

Experience with geophones shows that data quality is dependent on the degree of coupling between the phones and the surrounding rock. Magnets, bow springs, and even strong locking arms do not provide ideal coupling because of the high mass of the recording tool and the very limited area of contact with the casing, typically only three points.

An engineered fiber laying inside a typical horizontal well contacts the casing over 5 km or more and is much lighter per meter of well than a downhole geophone recording tool. Direct comparisons have shown that this coupling enables data quality as good as or better than fiber permanently installed in the cement outside the casing.

Both P and S arrivals from a microsesimic event can be seen over the entire cable length as shown in *Figure 7*. With the sensitivity of the measurement, we can see events in the vertical section as well as the horizontal, allowing for better location by taking in to account the wellbore trajectory.

It is worth noting that fiber optic HFM has:

No moving parts to wear out,

No downhole electronics to fail (particularly in high temperatures),

It can be pumped down thanks to the low weight, and

No polarization processing required.

### Time-lapse Vertical Seismic Profiling (VSP)

An important aspect of time-lapse VSP is the effort to characterize the changes in the reservoir. In this case we recorded changes during frac activities, with VSP data acquired after each frac stage during the course of the project. Using this technology, the effectiveness of the frac design and ultimately the return on investment for the pad, can be continuously improved.

The recent improvements in DAS measurements utilizing the engineered fiber means that we now can collect high quality VSP data in between stages without interfering with the

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overall operations. *Figure 8* shows a comparison of same stage measured with permanent cable vs. intervention wireline cable. In addition, high quality microseismic events can be correlated with 4D-VSP effects to help understand fracture complexity.

By having the improved sensitivity and broader bandwidth of the new engineered DAS system, we can now easily measure the changes at the reservoir before and after stages on the neighboring wells to understand fracture half lengths and frac hits on a well (Byerley G. et al. 2018). This is achieved with a large antenna that could cover the entire well with few vibroseis sweeps. in addition, we can measure accurately time-depth pairs and velocities along the borehole and changes in velocity due to fracking activity. The ability of having multiple cables on a project allows for better understanding of dynamic changes in the reservoir.

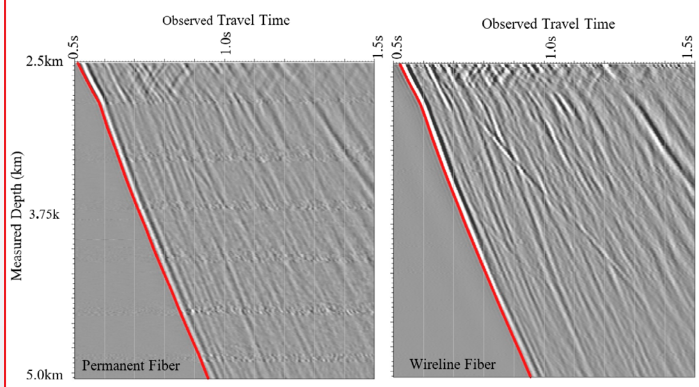


*Figure 8. Permanent installed fiber (left) vs Wireline Intervention cable fiber (right) VSP acquired during the same stage with same source location.*

## Conclusion

The next generation of DAS system utilizing the engineered fiber offers 100x improvement in sensitivity compared to standard fiber and provides unprecedent data quality both on permanent and wireline intervention cables.

The intervention wireline cable can be economically deployed to provide additional accessible measurement axes for crosswell strain identification on frac hits, microseismic monitoring, and time-lapse Vertical Seismic Profiling (VSP) acquisition. The wireline data can be combined with the permanently installed fibers to provide a wide volume coverage for fracture monitoring and completion diagnostics in near real-time.

## Acknowledgements

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