

Distributed Acoustic Sensing for Cross-well Frac Monitoring

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Summary

In this paper we examine diagnostic tools for hydraulic fracture stimulation (HFS) that can help determine the geometry, reach, and effectiveness of the created fracture(s). In particular we focus on using the combination of micro-seismic and Distributed Acoustic Sensing (DAS) technology to gain a more complete understanding of the resulting stimulation treatment and identify further optimization opportunities.

DAS has many applications, and this paper will consider two particular cases in combination with micro-seismic data acquired by geophones in an observation well:

1. When DAS is recorded in a treatment well, it can be used to determine and quantify which stages and perforations take fluid. When this is combined with micro-seismic data we can establish a relationship between the micro-seismic events and the fracture fluid itself. This can help determine the overall effectiveness of the fracture design and resulting treatment.
2. When DAS is recorded in an offset well (developed in the same pad as the treatment well), it can be used to determine when hydraulic fracture fluid (initiated from the neighboring treatment well in the same pad) intersects that well. We can then establish how the micro-seismic events relate to actual fluid placement and interference from neighboring wells. It can also provide an exact location and timing where fractures intercept offset wells and are linking up, and are a direct measurement of a conductive fracture.

In both cases micro-seismic combined with DAS data provides an opportunity for further completion optimization, well spacing optimization, and/or pad design and/or well spacing.

Introduction: Integrated Hydraulic Fracture Stimulation Diagnostics

To determine the geometry, reach and effectiveness of hydraulically created fractures, micro-seismic data is often recorded at wells or well pads where hydraulic fracture stimulation (HFS) is to take place. Frequently geophones are deployed in a dedicated vertical observation well with the possibility of deploying more geophones in horizontal offset wells to help reduce the uncertainty in location and magnitude of the micro-seismic events.

Distributed Acoustic Sensing (DAS) is an acoustic detection technology that has recently been applied in production (Molenaar et al. 2011) and geophysical settings (Mestayer et. al, 2012). Downhole DAS is a fiber-optic distributed sensing technology that can provide key diagnostic insights during hydraulic fracturing operations. During the course of 2009 through 2012, a number of DAS and Distributed Temperature Sensing (DTS) deployments have been carried out in North America's tight sand and shale gas fields to monitor (in real-time) hydraulic fracturing operations. Recordings were made in different fields and different reservoir formations for different well configurations and completions.

Fiber-optic cables can be installed in vertical and horizontal wells, which can be treatment wells, injector wells or observation wells. Within the cable there are often both single mode fibers (for DAS) and multi-mode fibers (for DTS). Multiple fibers within one cable can offer redundancy and the ability to interrogate with different instrumentation simultaneously.

DAS data differs from Geophone data in a few ways. First, fibers can be deployed down treatment wells, allowing the recording of acoustic records in environments that would be prohibitive for geophones. Second, DAS is primarily sensitive along its axis, making it analogous to a single component geophone oriented along the wellbore (which itself could be deviated and changing orientation). Lastly, at low frequencies DAS can be sensitive to temperature variations as well as acoustic sources.

DAS data can be recorded for a variety of purposes. In this paper we examine the two aforementioned cases:

1. Recording DAS data in a HF treatment well. This enables determination of which stages and perforations preferentially take HF fluid in a quantitative manner.
2. Recording DAS data in an offset well. In a multi-well completion schedule, this can simply be any fibered nearby well that is not currently being treated. In this case we can detect when the HF fluid intersects the fibered offset well. We can determine the intensity of the intersection along with the time taken for the intersection to occur.

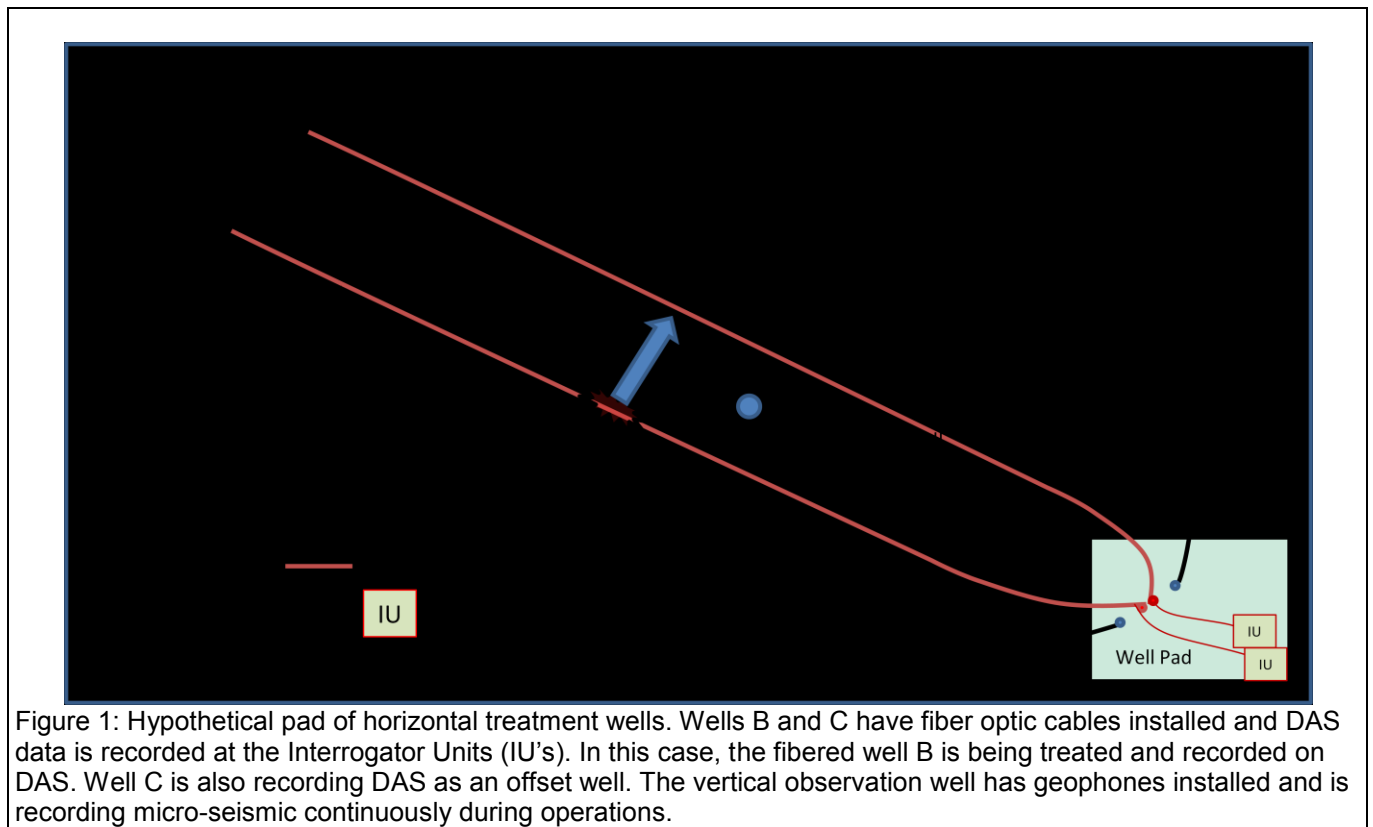
In both cases the addition of information provided by micro-seismic enables us to obtain a more complete understanding of the HF behavior.

Data Gathering Method(s)

Figure 1 shows a hypothetical pad of horizontal wells in plan view with each well scheduled to be hydraulically fractured in turn. There is a vertical observation well in which geophones are deployed for the duration of operations. Optionally geophones could also be deployed in one of the horizontal wells in order to refine the location and magnitude estimate of the micro-seismic events recorded.

Two wells have single mode optic fibers installed and these can be interrogated for DAS data either when they are being treated or when they are an offset well and a neighboring well is being treated.

A single mode optic fiber in a cable is attached to a well bore and interrogated with laser pulses. An Interrogator Unit on the surface generates the laser pulses which in turn are back-scattered by impurities within the silica lattice structure. This Rayleigh back-scattered light is collected back at the surface using the Interrogator Unit and recombined with the input signal to determine an amplitude and phase associated with the depth from which the signal came. Thus, the fiber can effectively be segregated into many acoustic channels of a chosen length along the whole length of the fiber, limited by the speed of the switch generating the laser pulse. The resulting signal has a bandwidth of 20 kHz on a 4km fiber (although it can be much higher on shorter fibers) with channel lengths ranging from 1-10m. The signal is effectively a representation of the instantaneous strain on the fiber, which can be generated by sound (pressure waves and shear waves) and, at low frequencies, changes in temperature.



Examples & Results

Below we detail two examples of combining DAS with micro-seismic. The data are acquired in a shale gas reservoir. The first example will show the recording of DAS in a treatment well during HF stimulation and combining it with micro-seismic observations; and second example will be the recording of DAS in an offset well also in conjunction with micro-seismic data.

Treatment well DAS and Micro-Seismic

Recording DAS data in a treatment well while the HF stimulation is carried out has provided insights as to the stimulation effectiveness and revealed issues with effective zonal isolation when using mechanical isolation that would otherwise not have been possible. This information can generate new learnings, which could lead to improvements in design and execution of in-well activities and hydraulic fracture treatments.

The first example presented here is a fracture treatment in a cemented ‘plug and perf’ completion, using a limited entry diversion design to create an equal fluid and proppant placement in the 4 cluster HF stage. In Figure 2, the upper graph shows the processed DAS measurements; the middle graph shows a color map representation of the DTS data; and the bottom graph shows the surface treating pressure, slurry rate and proppant concentrations.

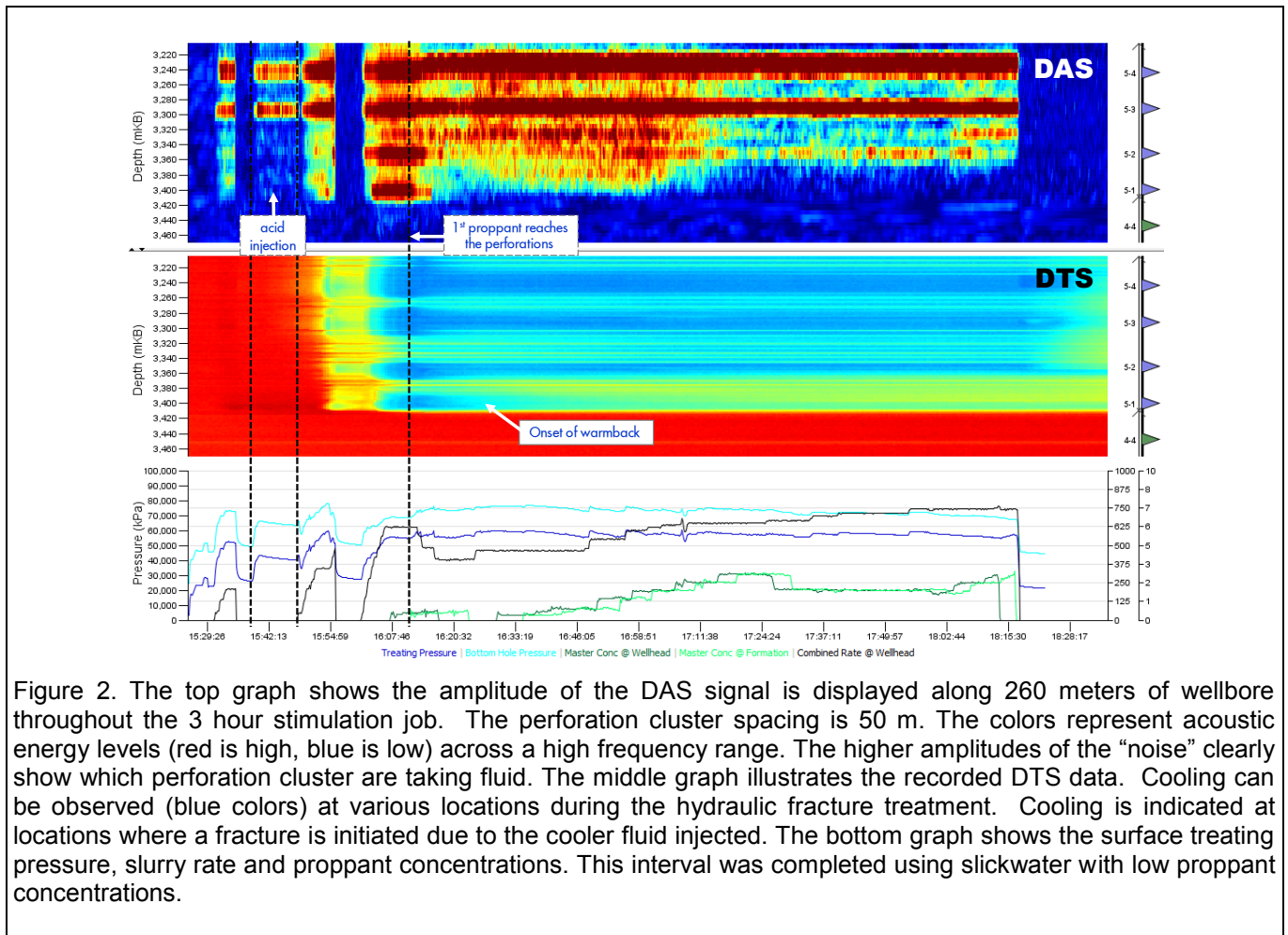
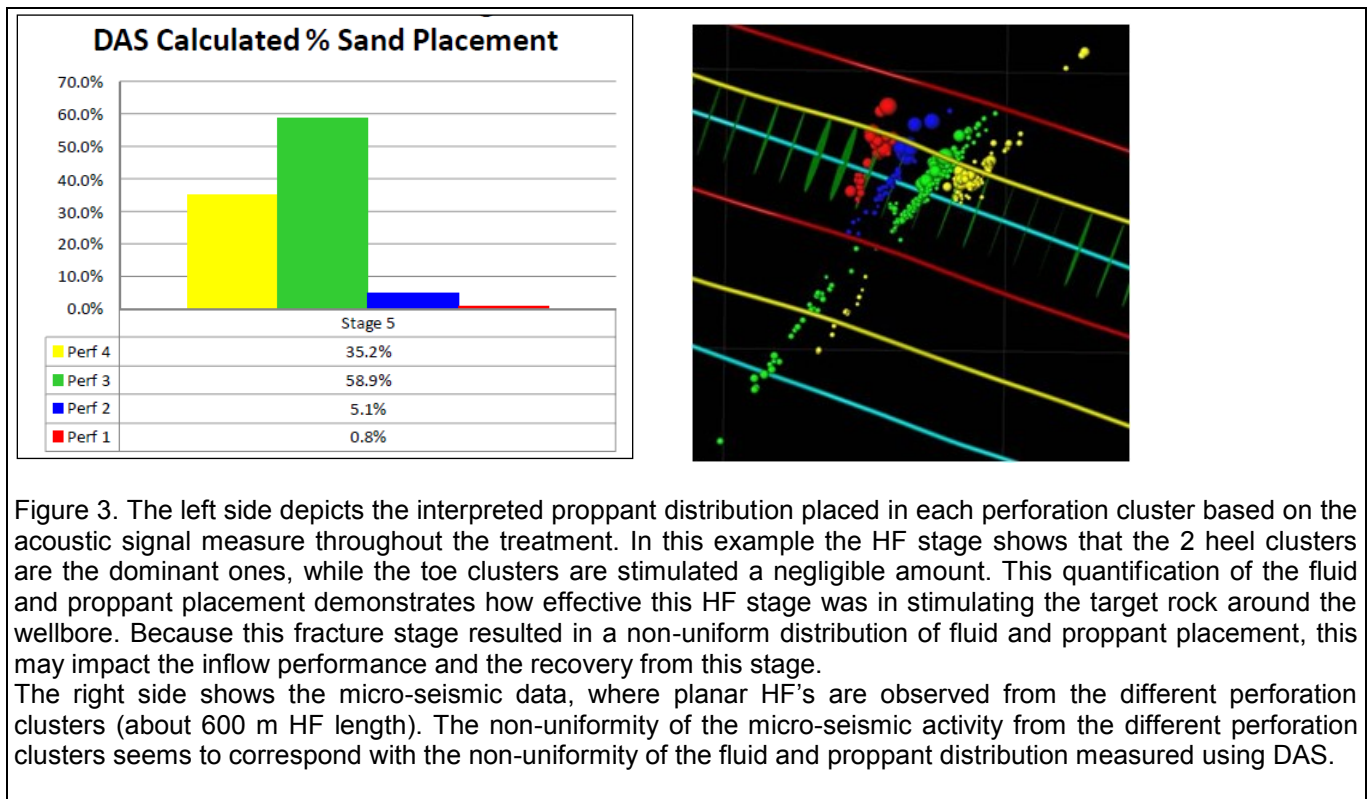


Figure 2. The top graph shows the amplitude of the DAS signal is displayed along 260 meters of wellbore throughout the 3 hour stimulation job. The perforation cluster spacing is 50 m. The colors represent acoustic energy levels (red is high, blue is low) across a high frequency range. The higher amplitudes of the “noise” clearly show which perforation cluster are taking fluid. The middle graph illustrates the recorded DTS data. Cooling can be observed (blue colors) at various locations during the hydraulic fracture treatment. Cooling is indicated at locations where a fracture is initiated due to the cooler fluid injected. The bottom graph shows the surface treating pressure, slurry rate and proppant concentrations. This interval was completed using slickwater with low proppant concentrations.

The DAS technology is specifically of interest as the measurements are capable of capturing the dynamic changes throughout the treatment exceptionally well and enable discrimination between perforation clusters which are active during the acid injection stage and which ones are taking most of the fluid and proppant throughout the

job. Using a proprietary workflow the quantitative injection rates per perforation cluster can be derived from the amplitude of the 'noise' levels measured using DAS.

In this example the relation between the treatment well DAS data and the micro-seismic data will be investigated. During the treatment, first the fluid and proppant injection generates 'noise' at the perforations observed by the DAS fiber, and next, when the fluid and proppant travel into the formation, they generate noise by fracturing the reservoir matrix, which is observed by the micro-seismic. For this field case, micro-seismic data was collected in conjunction with DTS/DAS data. Figure 3 shows DAS calculated proppant placement per perforation cluster compared to micro-seismic data showing planar fractures created from the perforations. The non-uniformity of the micro-seismic activity from the different perforation clusters seems to correspond with the non-uniformity of the fluid and proppant distribution measured using the DAS. Besides, combining the DAS and micro-seismic data enables a more detailed interpretation of the fracture development; the fractures can be interpreted at a perforation level, and the potential interaction between the perforations can be resolved (Molenaar and Cox 2013).



In this example, the DAS and micro-seismic data both indicate that an even distribution of the fluid using limited entry hydraulic fracturing stimulation design is in practice not guaranteed. This non-uniform stimulation of the planned fractures can have a negative impact on well performance and may also impact well spacing and recovery. In this case, there is no associated production data available for further analysis, but the ability to better redirect fluid and proppant distribution could be a critical part of optimizing multi-cluster stimulation performance moving forward.

Offset Well DAS and Micro-Seismic

DAS data recorded during HF operations has revealed a number of events detected on DAS in neighboring offset wells. These events have been accompanied by noticeable temperature variations on DTS and also coincide with pressure increases on external well pressure gauges. This supports the concept that the cross-well measured events are evidence of a conductive fracture approaching and intersecting the fiber optic cable in the observer well.

Characteristics of DAS cross-well signatures

It may take hours for a signature from the treatment well fracture to appear at the offset well, depending on the separation of the wells. This tells us they are not an acoustic event, but related to a mechanical disturbance propagating through the subsurface. Temperature variations on DTS and pressure changes via in-well pressure gauges have also been observed associated with DAS signature. In general there are number of characteristics that help define this event:

1. There is a fracture process zone lasting 1-30minutes that is 10-50m (a few channels) wide.
2. This is followed by the main event which starts with a high energy event
3. As time progresses a greater number of channels are detecting noise associated with the event. This typically lasts 1-2 hours and is limited to 50-80m.
4. Most of the energy is within the low frequencies; less than 20 Hz with the majority of that being less than 1Hz.
5. Within the event there are often short duration, small extent events, or “cracks”.
6. Often the initial few channels that are disturbed carry on being disturbed for a long time (many hours) even after the stimulation on the treatment well has stopped.

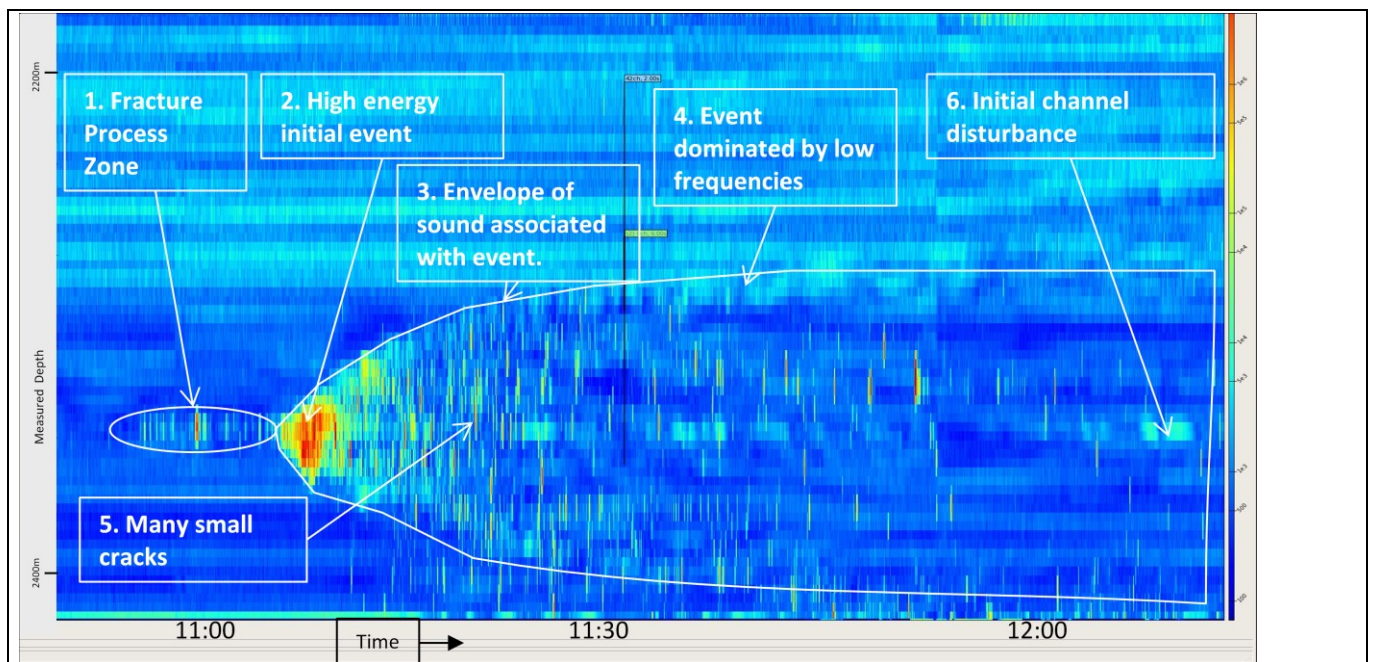
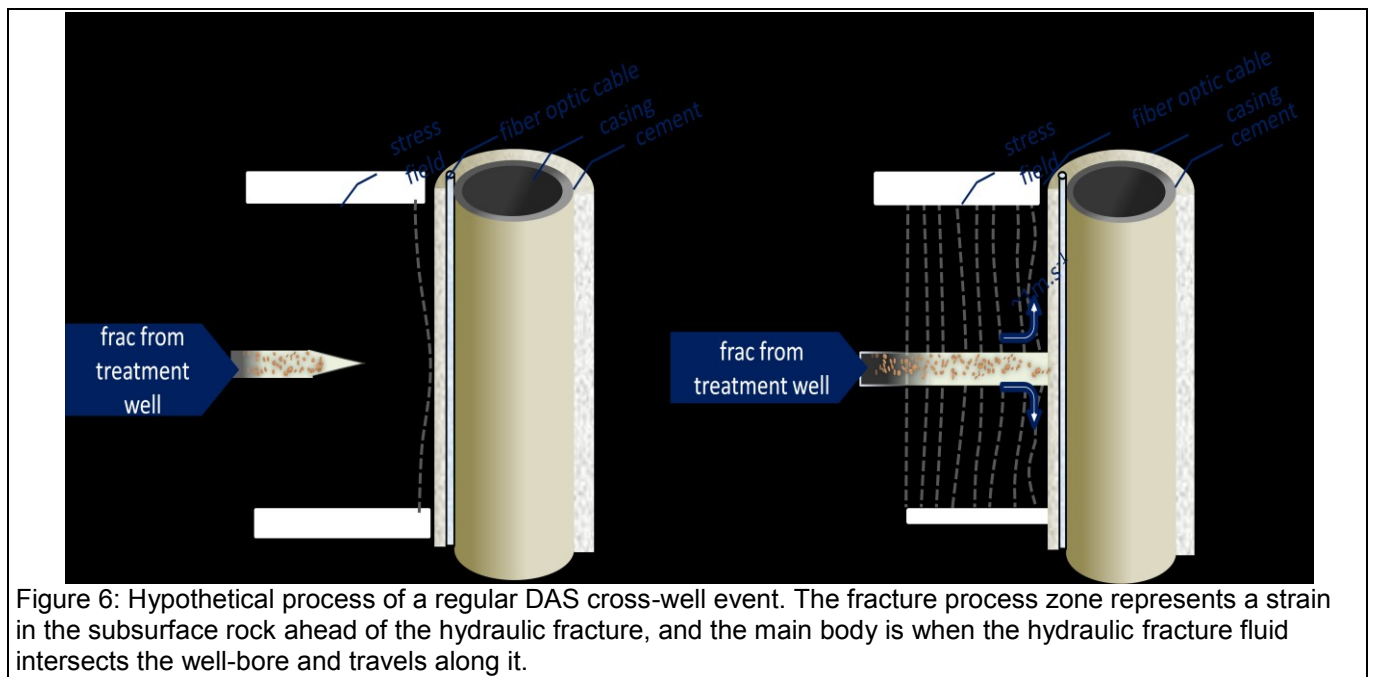


Figure 4: Typical regular DAS cross-well event signature. The y-axis is measured depth along the horizontal well and the x-axis is time. Colours represent the energy of the DAS data. The fracture process zone lasts 1-30 minutes and the main body lasts 1-2 hours.

Hypothetical Processes and Interpretation of DAS events

The hypothetical process is that the intermediate space in front of the fracture tip between the cracked and the uncracked rock is straining the rock. This fracture process zone is detected by the DAS fiber ahead of the physical arrival of the fracture. When the fracture physically arrives at the offset well, it creates a relatively loud sound and the DAS then shows the noise proceeds to migrate around and along the well-bore until it loses the energy to do so or encounters an obstacle (this is the main event). This is suspected to be the pressure and fluid movement along a micro-annulus in the cement. In wells instrumented with external pressure gauges the move-out of the noise corresponds with increases in pressure along the wellbore.



Application of DAS cross-well events

DAS cross-well events can clearly be used to determine to what extent the HF fluid intersects a neighboring/offset well. This can be divided into 3 cases:

1. No intersection – no DAS cross-well events were detected. The fluid took a path away from the offset well or did not reach it.
2. Minimal intersection – only a fracture process zone was observed.
3. Intersection – a “regular” DAS cross-well event was observed. The fluid intersected and possibly went past the offset well.

Knowing the origin of the hydraulic fracture the location the cross-well events can also be used to help determine the height growth and azimuth of the fracture(s). We can also combine them with micro-seismic events (see Figure 8) with respect to time to determine which part of the micro-seismic cloud can be associated with the HF fluid. This can help constrain stimulated rock volume estimates.

Future work could include measuring the speed and size of the DAS cross-well events; this information could then be used to determine rock properties or fracture networks.

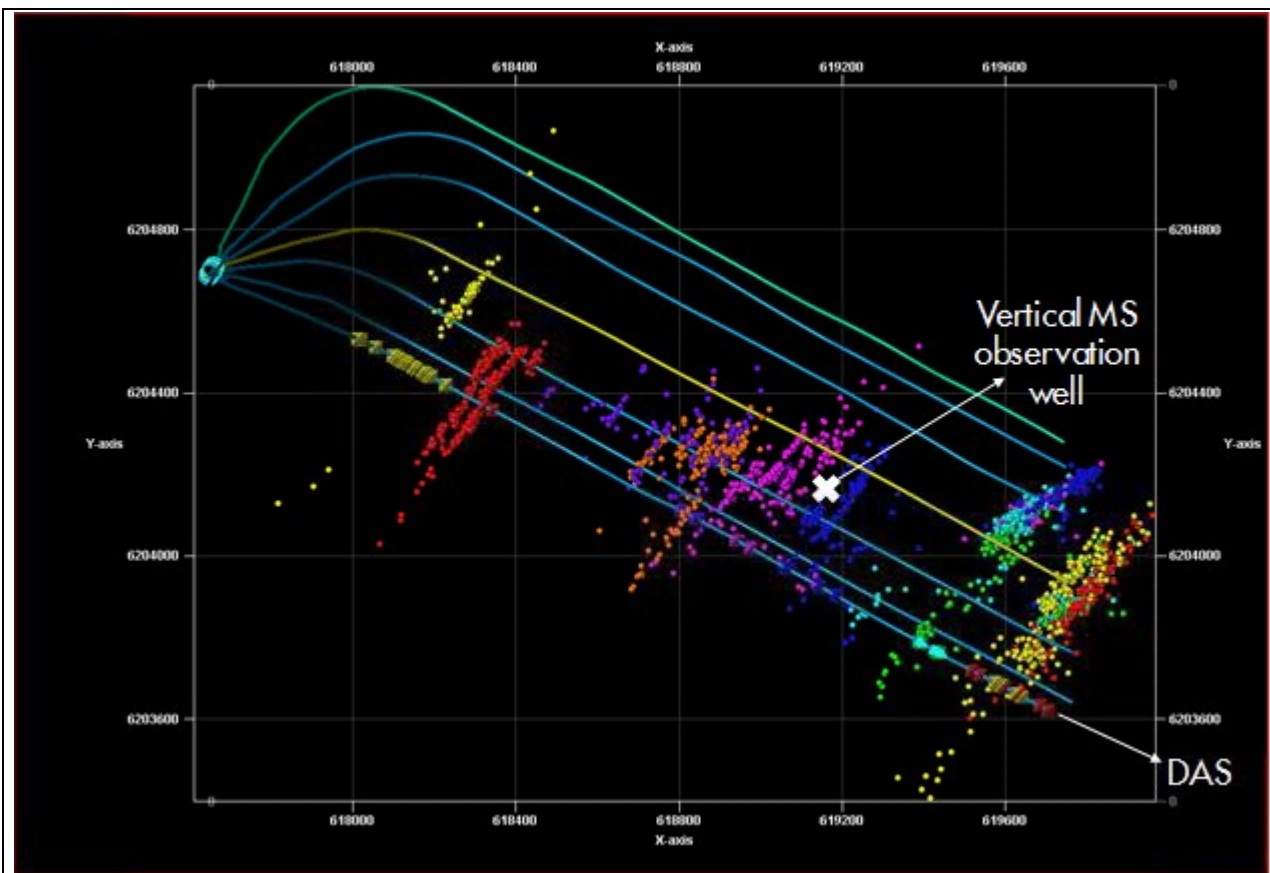


Figure 8: DAS cross-well events (triangles) can be visualized together with micro-seismic events (dots) in 3D visualization software. This could lead to a better understanding of the relationship between micro-seismic and location of fracture fluid.

Conclusions

A fiber optic cable installed in a well can be used for HF diagnostics, as well as to monitor cross-well interference if in a pad/multiple well setting. When combined with micro-seismic acquisition, we can gain a more complete understanding of the hydraulic fracture process. Inferences can be made about which perforations are accepting fluid, how the micro-seismic events relate to actual fluid placement and interference from neighboring wells. It can also provide an exact location and timing where fractures intercept offset wells and are linking up; and are a direct measurement of a conductive fracture.

Installing fiber optic cables in key wells can accelerate learnings and allow for a more rapid optimization of future wells in the same area.

Acknowledgements

Shell Teams: Upstream Americas TE&D team; W. Westwood, Asset team; Fred Mandybura, Operations team; Mark Anderson, Carlos Nieto; Geophysical Technical Services team; Colin Perkins, Jonathan Wall, Jeff Tan, IT Support; Richard Tummers, Colin Wiebe, SIEP; Alexander Droujinine. OptaSense; David Hill, Andrew Lewis & Jim Roy. We thank Shell and OptaSense for permission to publish this paper.

References

Mestayer J., B. Cox, P. Wills, D. Kiyashchenko, J. Lopez, M. Costello, S. Bourne, G. Ugueto, R. Lupton, G. Solano, D. Hill, and A. Lewis, 2011, Field trials of distributed acoustic sensing for geophysical monitoring: 81st Annual International Meeting, SEG, Expanded Abstracts, 4253–4257.

Molenaar, M. et al. 2011, First downhole application of Distributed Acoustic Sensing (DAS) for hydraulic fracture monitoring and diagnostics, Society of Petroleum Engineers 140561.

Molenaar, M.M. and Cox, B.E. 2013. Field Cases of Hydraulic Fracture Stimulation Diagnostics Using Fiber Optic Distributed Acoustic Sensing (DAS) Measurements and Analyses. Paper SPE 164030 presented at the SPE Middle East Unconventional Gas Conference & Exhibition, Muscat, Oman, 28-30 January 2013.