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Measuring Hydraulic Connection in Fractured Bedrock with Periodic Hydraulic Tests and Distributed Acoustic Sensing

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ABSTRACT

Efficient geothermal reservoir exploitation often hinges on creating sufficient fluid circulation between injection and production wells. Tracers are effective for determining flow connections, but are expensive and time consuming. We explore the use of periodic (oscillatory) hydraulic testing for measuring hydraulic connectivity between wells in saturated fractured bedrock. In a periodic test, head/flow is varied periodically in one well and the head response observed in nearby wells. The amplitude attenuation and phase of the observed hydraulic signal is indicative formation permeability. We present a field example of this approach in a low permeability fractured bedrock. One well underwent periodic injection and pumping while five observation wells 30 to 47 m away were monitored. Only one well pair is reported here, however. Tests were repeated for a range of pumping oscillation periods (frequency). We measured hydraulic connection using traditional pressure transducers and very low-frequency fiber optic distributed acoustic sensing (DAS). The DAS observations were conducted in two modes. In the first, fiber optic cable was suspended in the well water column and oscillating longitudinal strain in the cable was measured in response to hydrostatic (lateral) compression. In the second, the fiber optic cable was pressed against the borehole wall using a flexible liner while oscillating strain in the cable was measured in response to dilation/contraction of rock fractures that intersect the borehole. Both modes of operation produced periodic signals using DAS in a well 36 m from the source, but the response to dilation of the rock in response to hydraulic propping produced a much clearer signal. Sensitivity in both cases was improved with larger frequency and amplitude of head oscillation. In hydrostatic mode, DAS was sensitive to heads oscillation with periods as long as 12 minutes and head amplitudes of as small as 15 cm. In dilation mode, DAS was sensitive to heads at periods as long as 18 minutes (at 15 cm head amplitude) and head amplitudes as small as 3 mm (at 2 min periods). Laboratory tests indicate that hydrostatic DAS response is linearly related to pressure when head oscillation has short periods and large amplitudes but non-linear (power law) or poorly correlated at short periods and small amplitudes. To our knowledge, this is the first application, in laboratory or field setting, where DAS has been used to measure fluid pressure. The technology has potential for real-time monitoring of pressure response in geothermal wells. If the fiber optic cable is cemented in the annulus between the casing and formation wall monitoring may be achieved outside of currently perforated intervals. Very low frequency DAS can take advantage of existing installations of fiber optic cable for DAS seismic or acoustic monitoring or even distributed temperature sensing (DTS).

1. INTRODUCTION

Tracers are the "go to" technology for establishing hydraulic connectivity in fractured geothermal reservoirs and have been shown to be an effective tool [Chrysikopoulos, 1993; Rose et al., 2001; Shook, 2001]. However, tracer tests typically last weeks or more and incur expensive personnel and analytic costs. In addition, tracers are typically run only once in the early lifetime of a geothermal well and can only determine connectivity at established extraction and injection intervals. A more useful tool would provide nearly continuous monitoring of hydraulic connectivity as reservoir configurations change and would provide hydraulic pathways even at depths where perforations do not exist. In this article we describe a new technology that provides measurements of hydraulic perturbation along the length of a borehole in response to oscillating pressures at an injection well. Fiber optic distributed acoustic sensing (DAS) is used to sense pressure pulses at mHz (e.g. ~100 min periods), orders of magnitude lower than the frequencies for which DAS is most commonly used. We demonstrate the technology in both laboratory and field experiments. To our knowledge, this is the first time DAS has been employed for the purposes of pressure measurement.

We investigate two modes of measuring hydraulic signals in fractured bedrock (Figure 1). In the first mode, the cable is installed in the wellbore fluid by hanging the cable along an injection or pumping string. The DAS system responds to the longitudinal strain in response to the radial strain due to hydrostatic pressure. Thus, the response of the DAS system to pressure is a function of the Poisson ratio of the fiber glass (usually about 0.25).

In the second mode of measurement, we measure the strain changes in the fiber optic (FO) cable in response to dilation of the fracture as the fluid pressure is propagated through the formation. The dilation of a fracture in response to fluid pressure increase is sometimes referred to as "hydraulic propping." For this application, where pressure oscillation is small (<1-2 m of head), fracture response is expected to be approximately elastic [*Schweisinger et al.*, 2009]. For this measurement mode to work, the cable must be anchored against the formation to force rock strain to be transferred to the cable. In a geothermal well, this is expected to be accomplished by installing the FO cable in cement that bonds the metal casing to the formation wall. In our experiments, we used a removable flexible liner that pressed the FO cable against the formation wall.

The focus of this article is the empirical instrument response to measurements made in these two modes. We do not enter into discussions of the physics behind these measurements. The transfer of hydrostatic pressure to lateral cable strain, for example, is important to understanding the instrument response mode. Likewise, the propagation of strain from dilation of a fracture or fracture zone through cement and to the cable, is important for understanding response in the second mode. This aspect of the project is being addressed through simulations and additional testing and will be reported in future publications.

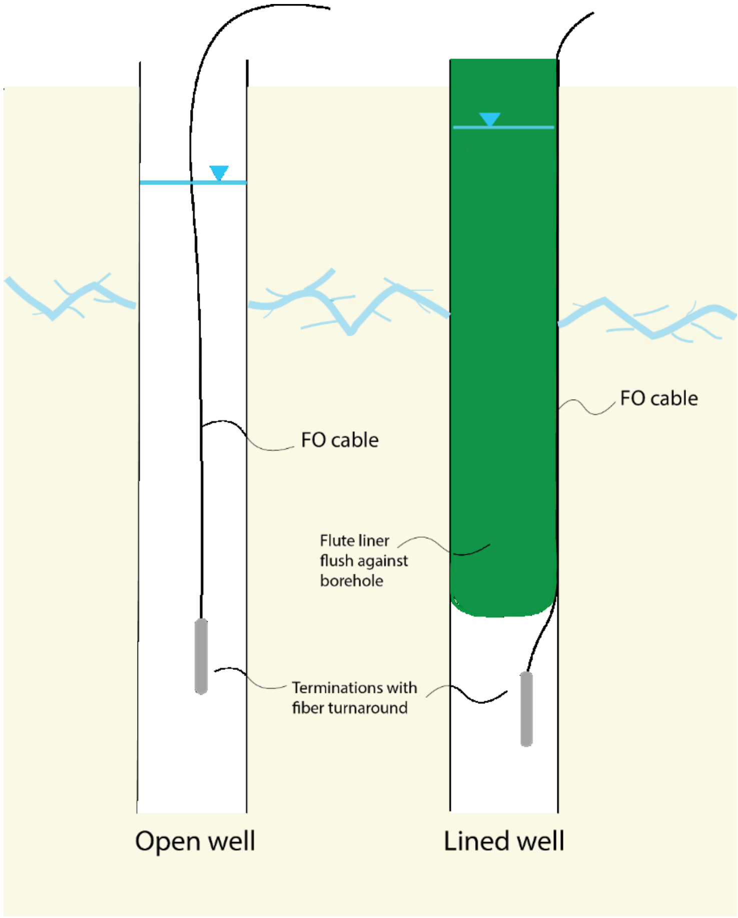


Figure 1: The two modes of measuring hydraulic response to periodic pressure tests. (Left) the well is left open hole and the FO cable is suspended in the borehole (Right) the borehole is fitted with a flexible liner that forces the FO cable against the borehole. In the first mode, hydrostatic pressure is sensed, in the second dilation of the fracture in response to hydrostatic pressure is sensed.

2. METHODS

Tests were conducted in the laboratory to determine sensitivity to hydrostatic pressure. Further tests were conducted at a shallow fractured rock field laboratory to determine sensitivity to hydrostatic pressure in a well setting, and dilation/contraction of fractures along the borehole wall in response to pumping.

Both tests used the Silixa iDAS^{TM} system to measure hydraulic response. Like most DAS systems, iDAS is designed to measure acoustic and seismic signals, often in petroleum wells [*Johannessen et al.*, 2012]. DAS seismic monitoring has been proposed as a particularly useful tool for performing seismic testing for carbon sequestration and geothermal projects because FO cable is able to withstand high temperatures and pressures not tolerated by most quartz-electronic sensors [*Paulsson et al.*, 2014].

The principles of DAS operation and current technology are summarized elsewhere [e.g. *Cannon*, 2013; *Mestayer et al.*, 2011]. For this discussion, it suffices to note that the native measurement of the iDAS system is strain rate along the FO cable. The strain rate is measured over a specified gauge distance along the cable and recorded at the center location along this distance [*Daley et al.*, 2015]. For our experiments, measurement channels were every 0.25 m along the cable and the gauge distance was 10 m. Conversion to strain was accomplished by integration with time for the laboratory tests presented here, but not the field tests. Strain and strain rate should present the same relative oscillation, however, making the results comparable. Our approach to DAS is unique in that we extend acoustic or seismic strain signals at frequencies of Hz or kHz to mHz. At the mHz frequency, it is possible to measure signals with periods of relevance for periodic hydraulic testing.

2.1 Laboratory Tests

Laboratory tests were designed to measure response of the DAS system to sinusoidal pressure fluctuation in anticipation of periodic hydraulic testing in the field. To maximize sensitivity to hydrostatic pressure and simplify relationships between fiber longitudinal and lateral strain in these proof-of-concept experiments we used a 900 micron tight buffered fiber that did not have the typical fiber in metal tube (FIMT) construction of downhole cables. FIMT construction was used in the field experiments, however, as discussed below.

Laboratory tests were conducted by inducing a sinusoidally varying pressure on a tight buffered optical fiber and monitoring the response using the iDAS system. Pressure oscillation was induced by tethering a solid cylinder to a rotating disc and placing that cylinder in a water reservoir. As the disc was rotated by a computer-controlled stepper motor, the cylinder displaced water in the reservoir as a perfect sinusoid. About 200 m of optical fiber was wrapped about a 10 cm (4 in) diameter PVC pipe and submerged in the reservoir. This fiber was connected to the iDAS system. Sinusoid periods varying from 10 to 720 seconds in length were tested. Water levels oscillations corresponding to pressures of 100 Pa (1 cm head) to 1000 Pa (10 cm head) were tested.

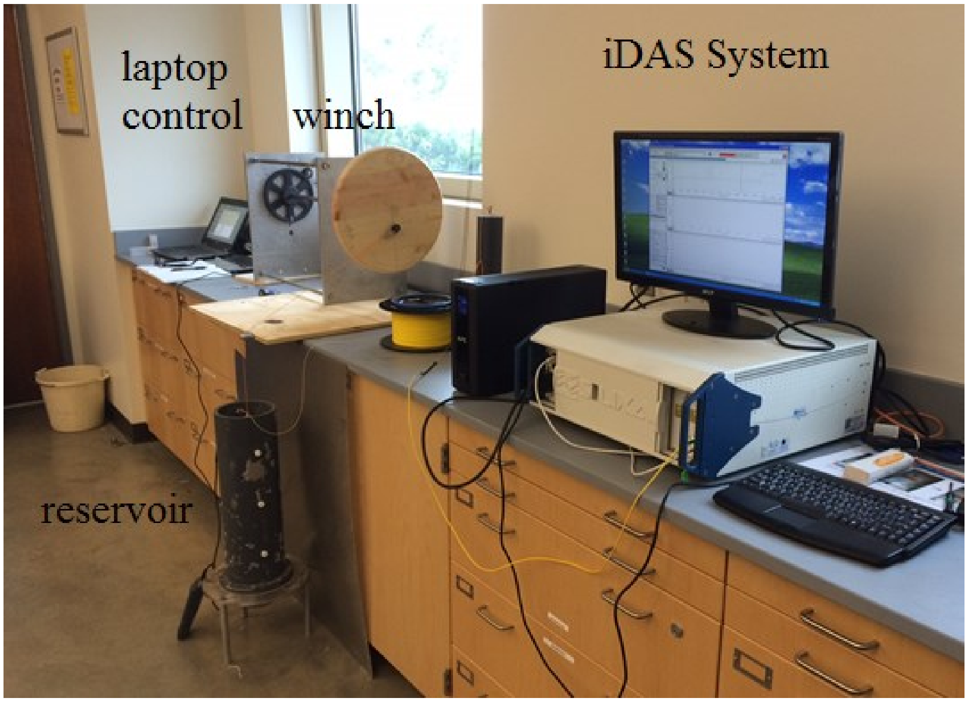


Figure 2: The laboratory experimental setup. From left to right, a laptop for collecting pressure and temperature measurements in the reservoir, a computer controlled winch, reservoir containing water and coiled optical fiber, the iDAS distributed acoustic system. The rotating disc drives a small cylinder up and down in the reservoir to create a sinusoidal pressure signal.

2.2 Field Tests

Field tests were conducted at the Mirror Lake Fractured Rock Hydrology site, within the Hubbard Brook Experimental Forest. The Mirror Lake site was established by the U.S. Geological Survey's Toxic Substances Hydrology program to investigate contamination issues in fractured bedrock. The site itself is free of any contamination and the wells are on U.S. Forest Service property. The many prior investigations conducted in the Forest Service East (FSE) well field provided an important baseline for the hydraulic studies conducted for this work.

Bedrock at the FSE well field is composed primarily of granitoids that have intruded the peletic schist country rock [*Johnson and Dunstan*, 1998]. A combination of tectonic and unloading stresses have resulted in the formation of a complex fracture network throughout the crystalline bedrock to a depth of at least 300 meters. Individual fractures tend to extend less than 10 meters in length, so permeability and transport is along interconnected fractures and fracture zones [*Becker and Shapiro*, 2000; *Becker and Shapiro*, 2003; *Hsieh and Shapiro*, 1994]. The experiments discussed here were conducted between wells FSE 6 and FSE 9 (Figure 3), which have been the subject of many other tracer experiments [*Becker*, 2003; *Becker et al.*, 2004; *Becker et al.*, 2003; *Becker and Shapiro*, 2000; *Becker and Shapiro*, 2003].

To conduct periodic hydraulic tests, FSE 6 was subjected to alternating pumping and injection to create either periodic step or sinusoidal hydraulic signals. This was accomplished using two variable speed pumps (Grundfos RediFlo2) controlled by two programmable variable speed controllers. *Rasmussen et al*. [2003] used a similar setup to conduct periodic hydraulic tests in unconsolidated sediments. A tank located near the wellhead was used to store water for reinjection. Flow meters up hole and down hole were used to assure that the injection and pumping rates were kept equivalent during the tests. For the results discussed here, periodic step tests were used. In the periodic step tests, pumping and injection were alternated at a constant rate of about 15 L/min. In tests not presented here, pumping and injection rates were varied as a sinusoid. Both methods produce approximately sinusoidal head responses at the monitoring wells. Period step tests were conducted with oscillation periods of 2, 4, 8, 12, and 18 minutes, with the first half-period pumping and the second half-period injecting. The difference between maximum and minimum head in FSE 6 ranged from about 2 m for the short period (2 min) tests to about 7 m for the long period (18 min) tests.

During the oscillation of flow in FSE 6, heads were recorded in FSE 6 and the 5 monitoring wells using pressure transducers (Figure 3). In addition, a single fiber optic circuit was routed through all of the monitoring wells such that measurements from distributed temperature (DTS) and distributed acoustic sensors (DAS) could be recorded during the test. A fiber in metal tube (FIMT) cable containing multimode fiber for DTS and single mode fiber for DAS was used. We also deployed a separate cable designed specifically for strain sensing in FSE 9. However, the strain-sensing cable did not perform significantly better in the tests than the standard FIMT cable so the results are not presented here.

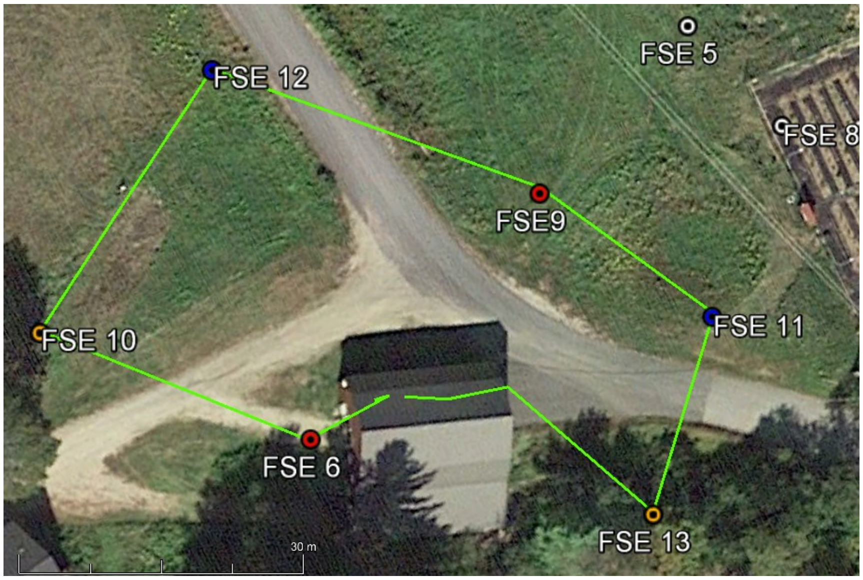


Figure 3: Aerial view of the FSE well field. The pumping well (FSE 6) and the five monitoring wells (FSE 10, FSE 12, FSE 9, FSE 11, and FSE 13) are shown as bullets. The green line shows the routing of FO cable from the iDAS system stored in the barn near FSE 6 to all of the wells.

As noted in the introduction, two types of completions were employed in the wells: packers and liners. In the packer-outfitted wells, inflatable rubber packers were installed in the 15 cm diameter boreholes to isolate the uppermost conductive zone. Packers were inflated just below the conductive fracture zones (30-60 m depth) as located through previous testing and geophysical logging [*Johnson and Dunstan*, 1998]. In FSE 9, the conductive fracture zone is at a depth of 42 m, 35 m below the water surface. The FO cable was suspended above the packer to measure pressure fluctuation in the water column. The objective of this completion was to test the measurement of varying hydrostatic pressure using DAS. Because of the large volume of water in the 15 cm (6 inch) diameter boreholes, it is possible that pressure response was dampened for the shorter period tests.

The liner installation was used to press the FO cable against the borehole wall to measure fracture dilation. Specially designed FLUTe^{TM} liners were used for this purpose. These liners are used widely in fractured rock hydrology to prevent cross contamination in boreholes and monitor and depth discrete locations [*Cherry et al.*, 2007]. They are made from impermeable, tubular, flexible nylon fabric that extends from the top of the well (anchored at the well casing) into the borehole. Installation is accomplished through "eversion" (turning it inside out) as water is pumped in from the top. When installed, about 3 m of overpressure head is maintained to force the liner against the borehole wall. In our installation, FO cable was hung from the surface and the liner was everted to press the FO cable against the borehole wall [*Coleman et al.*, 2015] for several meters past the target fracture depth.

3. RESULTS

3.1 Laboratory Tests

Figure 4 shows some examples of iDAS measured pressure signals for 10, 100, and 500 Pa pressure amplitudes. The results for periods of 10 seconds and 600 seconds are compared. The signal has been subjected to a low pass Butterworth filter that removes frequencies that are more than 20% greater than the oscillation frequency. The signal from 30 measurement channels (7.5 m) farthest from the iDAS instrument are shown for each test. Notice that the clarity of the measured response is best for short periods and high pressure amplitudes. At long oscillation periods the rate of strain is reduced creating a poor signal to noise ratio at the detector. At low pressures, the magnitude of the strain is small, again creating poor signal to noise ratio at the detector.

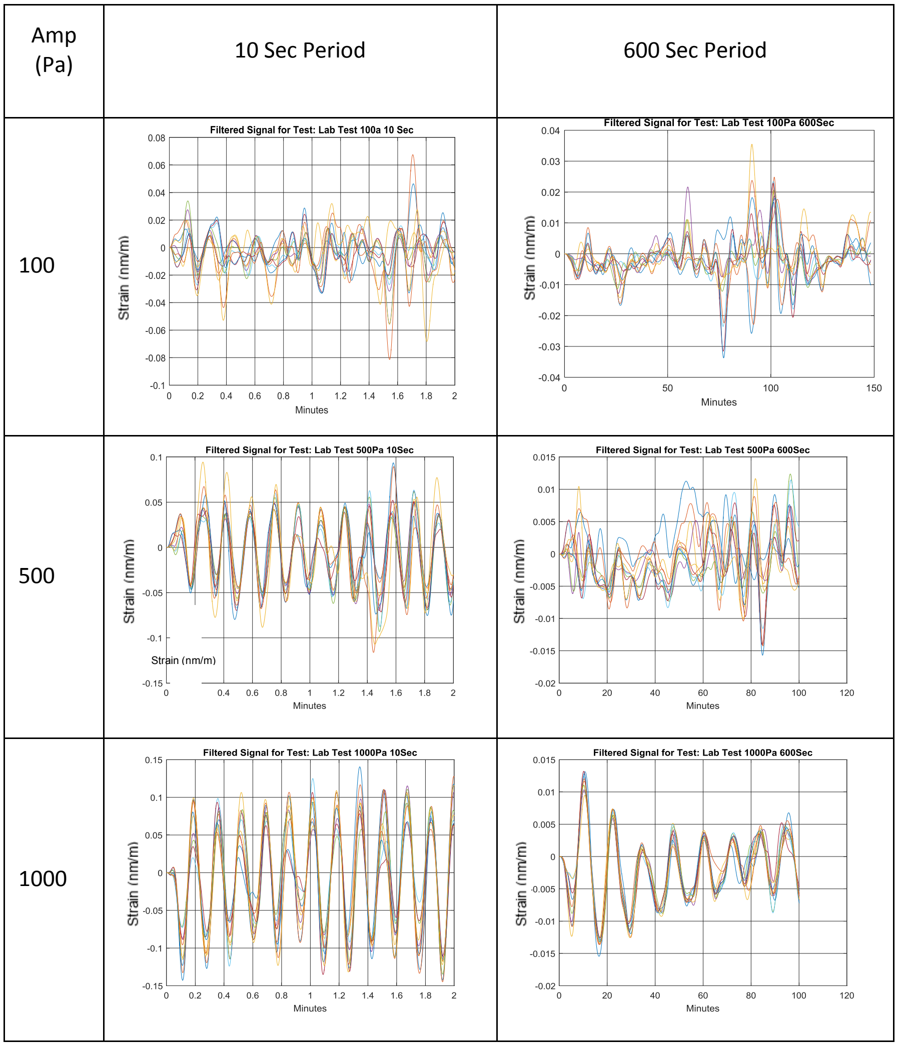


Figure 4: Selected strain responses from laboratory tests of iDAS. Pressure in the reservoir was varied sinusoidally with amplitudes of 100 or 1000 Pa (1 cm or 10 cm water level) and periods of 10 or 600 seconds. Response is better for short periods and high pressure amplitudes.

The relationship between signal period and DAS response illustrates the predicted trade off with pressure sensing in the field. Longer periods of oscillation in the source well will lead to greater pressure signal at an observation well. The amplitude of oscillation is expected to increase with the square root of the period [*Guiltinan and Becker*, 2015]. This is because at longer periods more volume is injected and removed from the oscillation well, resulting in greater hydraulic impact on the formation. However, at longer periods the sensitivity of the DAS is reduced due to a lower strain rate. Thus, to maximize DAS sensitivity to periodic pressure changes one will have to find the optimal source well pressure oscillation period that creates a strong pressure response in the monitoring well and that produces a detectable strain rate.

Stacking of the iDAS channels resulted in a significant improvement of the signal to noise ratio. Figure 5 shows the 100 Pa pressure amplitude with 100 second periods, with no stacking (single channel), stacking 10 channels, and stacking 200 channels. The response has again been filtered with a low pass Butterworth filter with the pass frequency 20% higher than the oscillating frequency. Every channel of response represents 0.25 m of cable coiled in the reservoir. A consistent amplitude of strain rate was acquired only after stacking approximately 80 channels when the pressure oscillation was 100 Pa (10 cm head). Fewer stacked channels were required for larger variations in head.

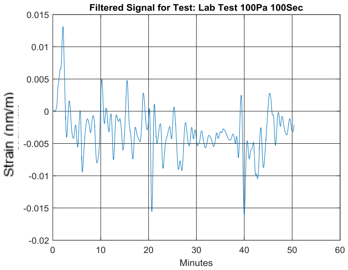
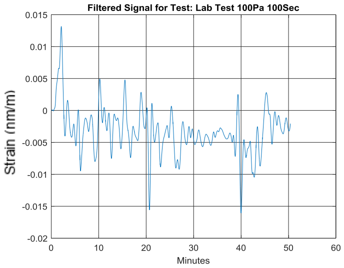
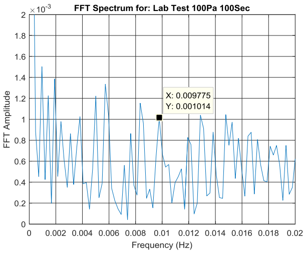
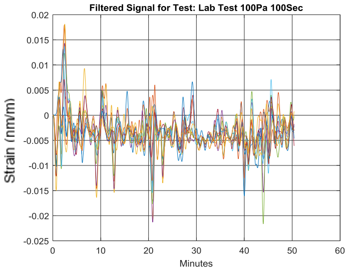
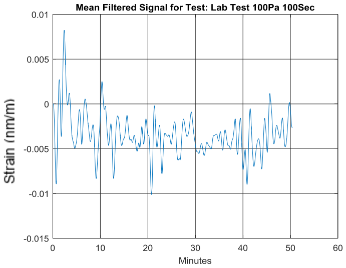
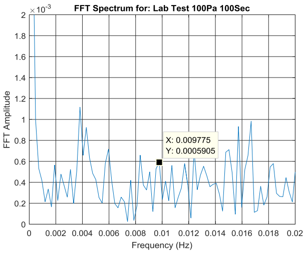
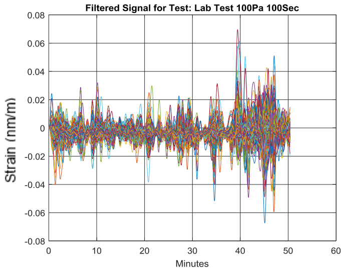
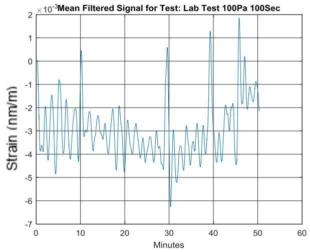
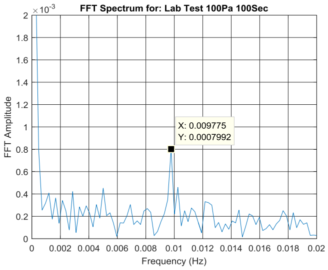
Pressure Amp (Pa)	Filtered Signal (Strain nm/m)	Mean Filtered Signal (Strain nm/m)	FFT Spectrum (Strain nm/m)
Single Channel			
Stack 10 Channels			
Stack 200 Channels			

Figure 5: Selected strain responses from laboratory tests of iDAS showing the effect of channel stacking on amplitude estimation. The left column shows the filtered signal, the center column shows the mean filtered signal, and the right column the FFT spectrum of the stacked filtered response. Head oscillation in these tests had an amplitude of 100 Pa (1 cm water) and a period of 100 seconds.

For each test, the amplitude of strain rate measured by the iDAS was determined by applying a Fast Fourier Transform (FFT) to the strain rate signal from 10 stacked channels. The amplitude of strain rate is plotted versus pressure oscillation for three different periods of oscillation in Figure 6. Power law trend lines display the strength of the correlation between the strain rate amplitude and the pressure amplitude. At short oscillation periods there is a strong linear relationship between strain rate amplitude and pressure amplitude. At moderate periods the relationship becomes non-linear but the correlation remains strong. At the longest periods tested (720 seconds) the relationship is both non-linear and weak.

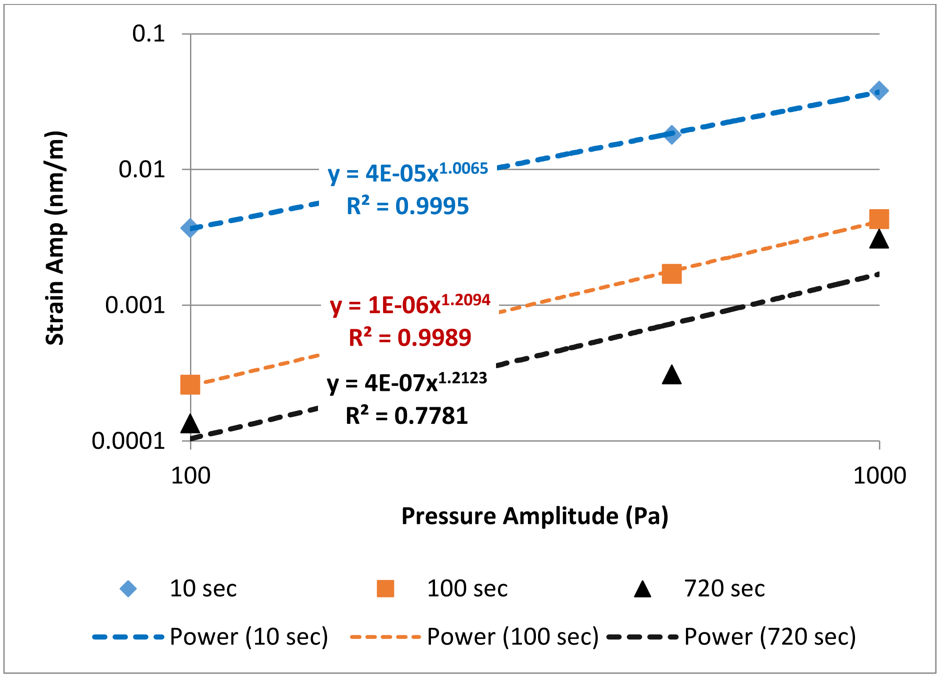


Figure 6: Summary of responses from laboratory tests. The relationship between strain rate and hydrostatic pressure is linear for large short periods but becomes increasingly non-linear and poorly correlated at longer periods. The power-law trend lines are shown as dashed lines.

The relationship between stacking and fidelity in response suggests that it will be difficult to measure hydrostatic pressure responses over short depth intervals in a well. However, if the FO cable is suspended in a well it is likely that hydrostatic head will be applied at 100's of meters of FO cable nearly simultaneously. Stacking should be a practical method for enhancing signal in such deployments. If one wishes to localize the source of the pressure change, say an intersecting fracture zone, then a much higher sampling frequency would be required. At 1 kHz sampling, for example, the acoustic signal from inflowing water may traced to its source by measuring wave acoustic wave propagation from the fracture zone. DAS measurement of propagating of acoustic pressure waves along water in well bores has been demonstrated with the iDAS system [*Xiao et al.*, 2013].

3.2 Field Tests

Example DAS response for selected field tests are shown in Figure 7. For each step test period the filtered stacked response, the FFT of the stacked response and the hydraulic head response are shown. The deepest 30 channels (7.5 m) were stacked to enhance signal to noise. Additional stacking did not produce a markedly better response as was the case for the laboratory tests (Figure 6). The stacked response was processed using a low-pass Butterworth digital filter to remove noise 20% above the imposed frequency. Heads measured in FSE 9 had amplitudes ranging between 0.5 cm (2 min period) and 15 cm (12 min period). Only the 12 min (720 second) and longer periods provided a reliable pressure response in the DAS system.

The DAS response in the lined well was much cleaner at all tested frequencies. Figure 8 shows the same pressure transducer data as shown for the unlined wells (Figure 7), except that the head responses have been high-pass filtered to remove the influence of trends due to prior testing activity. The head data are filtered in the lined response because the fiber is assumed to be responding to the pressure derivative rather than the pressure magnitude in the fracture intersecting the wellbore. Because we plan further processing of the data, responses are left in the native units of strain rate. Because conversion essentially involves integration over several time steps, strain and strain rate should have the same shape and signal to noise.

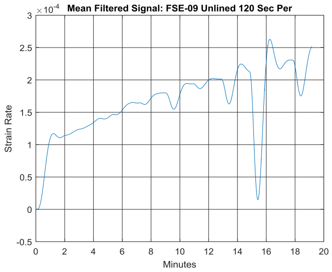
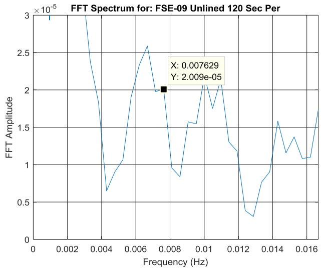
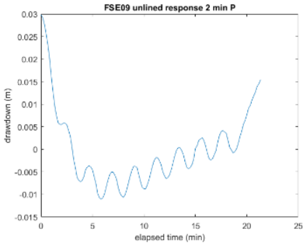
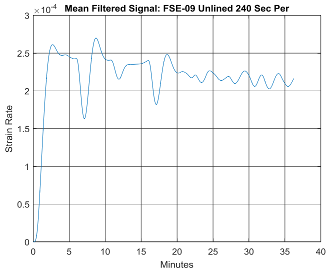
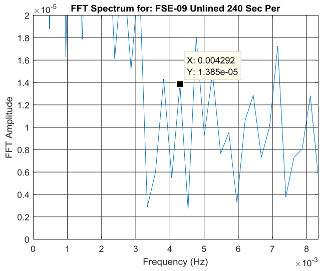
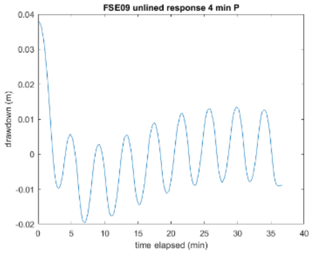
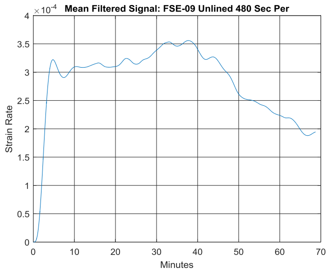
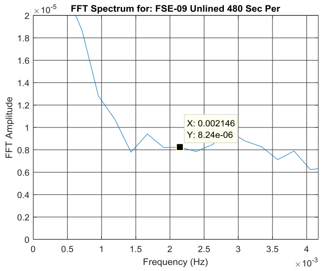
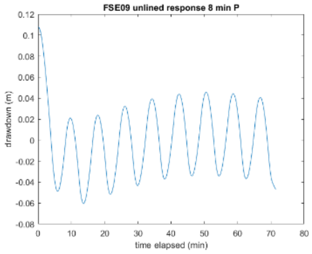
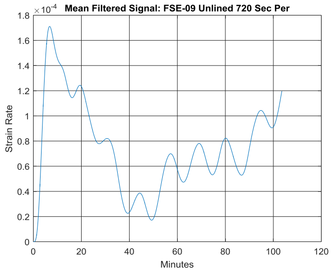
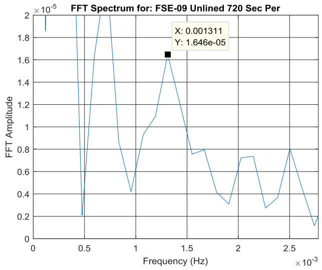
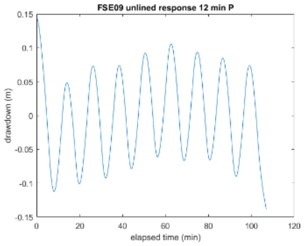
Period (sec)	Filtered/Stacked iDAS Signal	Stacked iDAS Signal FFT	Head Response (m)
120			
240			
480			
720			

Figure 7: Summary of the selected response in unlined FSE 9 well. The bottom 30 channels (30 m) of DAS response are stacked then low-pass filtered to remove high frequency noise. The FFT spectrum is from the unfiltered but stacked DAS response. Head measurements were made using a pressure transducer in the water column of FSE 9.

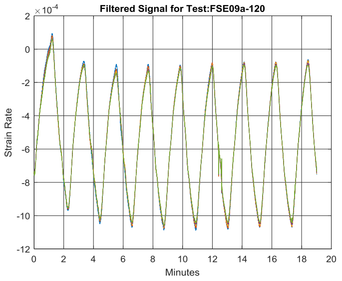
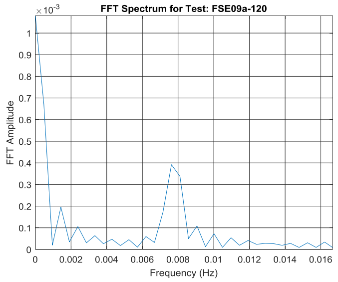
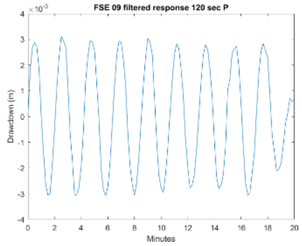
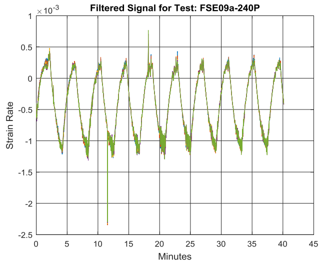
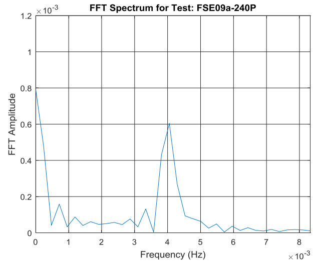
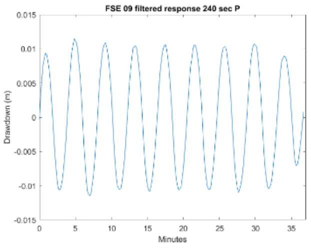
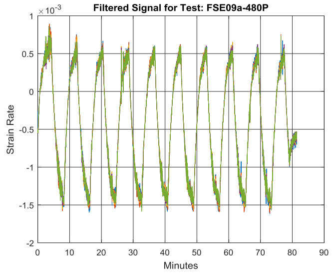
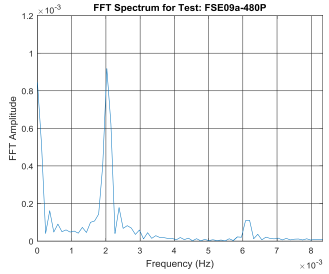
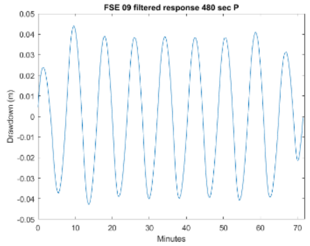
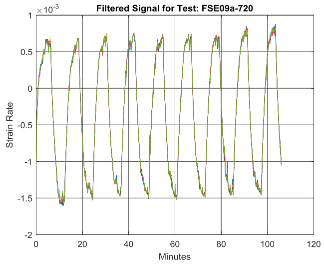
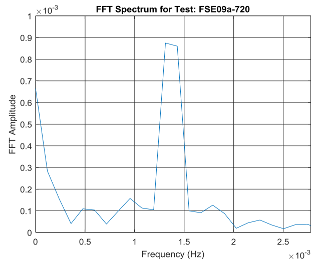
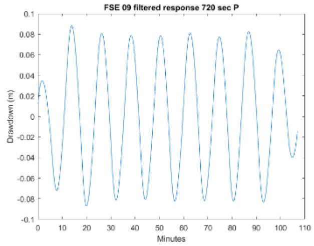
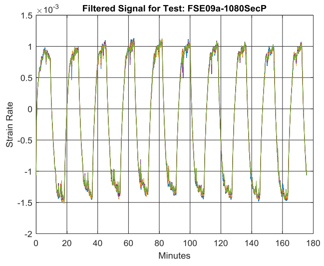
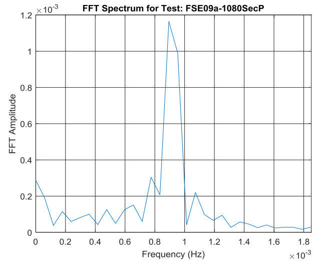
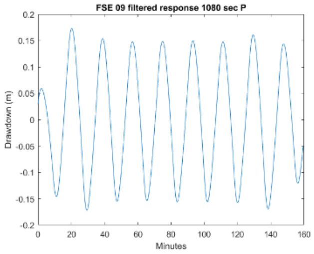
Period (sec)	Filtered/Stacked iDAS Signal	Stacked iDAS Signal FFT	Head Response (m)
120			
240			
480			
720			
1080			

Figure 8: Summary of the selected response in lined FSE 9 well. Responses shown are from FSE 9 in response to oscillation in FSE 6. FSE 9 was fitted with at FLUTe™ liner which pressed the FO cable against the borehole wall. DAS response, therefore, represents strain changes due to dilation and contraction of the fracture zone in response to pressure oscillation. Pressure measurements were measured in identical tests without the liner.

4. DISCUSSION AND CONCLUSIONS

Periodic hydraulic responses were measured using fiber optic distributed acoustic sensing (DAS). The response was observed either as a longitudinal strain resulting from hydrostatic (lateral) pressure on the fiber or as a longitudinal strain resulting from dilation and contraction of a fracture subjected to normal fluid pressure. The first mode of operation was tested in both a laboratory and field setting, while the second mode of operation was tested only in a field setting.

To our knowledge, this is the first time that DAS has been used to measure fluid pressure. In the laboratory, pressure oscillations could be sensed with amplitudes as small as 100 Pa (1 cm water) and periods as short as 100 seconds. At smaller pressure amplitudes or shorter periods, the signal became weak and could not be correlated to pressure measure with a transducer. In the crystalline bedrock field site, an oscillating pressure signal was created by alternately pumping and injecting into a borehole. Pressure was sensed using DAS through a FO cable suspended in the water column of a well located 36 m away. Pressure could be sensed at oscillation magnitudes as small as 1500 Pa (15 cm water) and periods as small as 12 minutes. Longer periods result in greater hydraulic communication between the source well and the observation well. Thus, there is a tradeoff between short periods which are more readily sensed by the DAS system and long periods which create a greater pressure amplitude. The sensitivity of the instrument to oscillation periods is due to the fact that the DAS instrument used (Silixa iDAS™) records strain rate, rather than strain.

Much clearer responses were obtained when the FO cable was pressed against the borehole wall using an over pressured flexible liner. When the fiber optic cable was bonded to the borehole wall, fracture dilation at the monitoring well, in response to periodic pressure in the source well, resulted in a measurable strain in the FO cable. Observation of oscillating fracture dilation and contraction could be observed at periods as small as 2 minutes (the smallest imposed) and pressure magnitudes as small as 60 Pa (6 mm water) could be sensed. There is some uncertainty with respect to the magnitude of head oscillation, however, because head was sensed using the same experimental parameters but when the well was unlined. We are currently processing data from another well in which strain and pressure were measured concurrently in a lined well.

Both modes of measuring hydraulic response are relevant to geothermal installations. Hydrostatic pressure could be measured by strapping FO cable along tool lines or pump strings. Fracture dilation/contraction could be measured by cementing cable outside of a well casing. In this way, hydraulic responses could be measured even where no perforations exist, allowing new perforations to be selected or new wells to be drilled in zones of hydraulic communication between injection and pumping wells. Existing installations for acoustic/seismic DAS or even DTS could be utilized to measure hydraulic response.

Work continues to understand the physics behind the empirical observations reported here. In hydrostatic mode, we are evaluating the longitudinal strain expected in response to lateral (radial) compression according to the Poisson ratio of glass (about 0.25) and as affected by cable construction. In dilation mode, we are evaluating how strain imposed by hydraulic propping of a fracture is translated through well cement/grout and to a fiber. It is clear that the strain must be transferred to the cable if it is bonded to the cement and the cement bonded to the formation, but the relationship between fracture dilation and fracture strain is not necessarily straightforward. Both of these issues are being investigated using geomechanical simulations.

Because of the small incremental cost of including DAS hydraulic sensing over other FO installations, and considering the utility of other FO installations such as DTS and seismic/acoustic DAS in geothermal wells, the technology demonstrated in this article should be tested in operating geothermal wells at the earliest opportunity. In addition, this technology has potential use for leak detection for geologic carbon sequestration [*Sun et al.*, 2015] as well as petroleum operations [*Hollaender et al.*, 2002]. In all cases, a period hydraulic signal must be induced in the reservoir, but this is readily accomplished by varying injection or pumping rates in existing wells. These signals can be superimposed on injection or pumping drawup or drawdowns; it is not necessary to alternate injection and pumping as was done for these field experiments. Consequently, hydraulic monitoring can be accomplished in real time over long periods without interruption of normal field operations. Thus an adaptive approach can be taken to well completion and field operation to optimize efficiency of heat extraction.

REFERENCES

Becker, M. W. (2003), The effect of tracer buoyancy on tracer experiments conducted in fractured crystalline bedrock, *Geophys. Res. Lett.*, *30*(3), 1116, doi:1110.1029/2002GL016480.

Becker, M. W., S. A. Collins, D. W. Metge, R. W. Harvey, and A. M. Shapiro (2004), Effect of cell physicochemical characteristics and motility on bacterial transport in groundwater, *Journal of Contaminant Hydrology*, *69*(3-4), 195-213.

Becker, M. W., D. W. Metge, S. A. Collins, A. M. Shapiro, and R. W. Harvey (2003), Bacterial transport experiments in fractured crystalline bedrock, *Ground Water*, *41*(5), 682-689.

Becker, M. W., and A. M. Shapiro (2000), Tracer transport in fractured crystalline rock; evidence of nondiffusive breakthrough tailing, *Water Resources Research*, *36*(7), 1677-1686.

Becker, M. W., and A. M. Shapiro (2003), Interpreting tracer breakthrough tailing from different forced-gradient tracer experiment configurations in fractured bedrock, *Water Resources Research*, *39*(1).

Cannon, R. T. (2013), Distributed Acoustic Sensing: State of the Art, edited, Society of Petroleum Engineers, doi:10.2118/163688-ms.

Cherry, J. A., B. L. Parker, and C. Keller (2007), A New Depth-Discrete Multilevel Monitoring Approach for Fractured Rock, *Ground Water Monitoring & Remediation*, *27*(2), 57-70.

Coleman, T. I., B. L. Parker, C. H. Maldaner, and M. J. Mondanos (2015), Groundwater flow characterization in a fractured bedrock aquifer using active DTS tests in sealed boreholes, *Journal of Hydrology*, *528*, 449-462, doi:10.1016/j.jhydrol.2015.06.061.

Daley, T. M., D. E. Miller, K. Dodds, P. Cook, and B. M. Freifeld (2015), Field testing of modular borehole monitoring with simultaneous distributed acoustic sensing and geophone vertical seismic profiles at Citronelle, Alabama, *Geophysical Prospecting*, n/a-n/a, doi:10.1111/1365-2478.12324.

Guiltinan, E., and M. W. Becker (2015), Measuring well hydraulic connectivity in fractured bedrock using periodic slug tests, *Journal of Hydrology*, *521*, 100-107, doi:http://dx.doi.org/10.1016/j.jhydrol.2014.11.066.

Hollaender, F., P. S. Hammond, and A. C. Gringarten (2002), Harmonic Testing for Continuous Well and Reservoir Monitoring (77692-MS), paper presented at SPE Annual Technical Conference and Exhibition, 29 September-2 October 2002, San Antonio, Texas, Society of Petroleum Engineers Inc.

Hsieh, P. A., and A. M. Shapiro (1994), Analyzing cross-hole hydraulic tests in fractured crystalline rock; an example from the Mirror Lake site, New Hampshire, *American Geophysical Union, 1994 spring meeting*, *75*(16, Suppl.), 153.

Johannessen, K., B. K. Drakeley, and M. Farhadiroushan (2012), Distributed Acoustic Sensing - A New Way of Listening to Your Well/Reservoir, edited, Society of Petroleum Engineers, doi:10.2118/149602-ms.

Johnson, C. D., and A. H. Dunstan (1998), Lithology and fracture characterization from drilling investigations in the Mirror Lake area, Grafton County, New Hampshire, USGS Water-Resources Investigations Report Number 98-4183, *Report Rep. 98-4183*.

Mestayer, J., et al. (2011), Field Trials of Distributed Acoustic Sensing For Geophysical Monitoring, edited, Society of Exploration Geophysicists.

Paulsson, B. N. P., J. L. Toko, J. A. Thornburg, F. Slopko, and R. He (2014), Development and Test of a 300°C Fiber Optic Borehole Seismic System; PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, SGP-TR-202, edited.

Rasmussen, T. C., K. G. Haborak, and M. H. Young (2003), Estimating aquifer hydraulic properties using sinusoidal pumping at the Savannah River site, South Carolina, USA, *Hydrogeology Journal*, *11*(4), 466-482.

Schweisinger, T., E. J. Svenson, and L. C. Murdoch (2009), Introduction to Hydromechanical Well Tests in Fractured Rock Aquifers, *Ground Water*, *47*(1), 69-79, doi:10.1111/j.1745-6584.2008.00501.x.

Sun, A. Y., J. M. Lu, and S. Hovorka (2015), A harmonic pulse testing method for leakage detection in deep subsurface storage formations, *Water Resources Research*, *51*(6), 4263-4281, doi:10.1002/2014wr016567.

Xiao, J., M. Farhadiroushan, A. Clarke, Q. Khalifa, A. Mulhem, H. Forero Reyes, T. R. Parker, J. Shawash, and H. C. Milne (2013), Inflow Monitoring in Intelligent Wells using Distributed Acoustic Sensor, edited, Society of Petroleum Engineers, doi:10.2118/167447-MS.