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Authors
Willis, Mark
Ajo-Franklin, Jonathan
Roy, Baishali

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Introduction to this special section: Geophysical applications of fiber-optic distributed sensing

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Mark Willis[1], Jonathan Ajo-Franklin[2] and Baishali Roy[3]

1 Halliburton.

2 Lawrence Berkeley National Laboratory.

3 ConocoPhillips.

Abstract

This special section is dedicated to geophysical distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) applications. Since the introduction of commercial DTS units in the 1980s and more recent deployment of DAS in this decade, distributed sensing is quietly revolutionizing sectors of geophysics, particularly those requiring permanent downhole measurements. The common component of distributed sensing technologies is the use of laser scattering measurements on fiber-optic cables (tens of kilometers long) to estimate the physical state of each fiber segment with measurands including temperature (DTS), static strain (DSS), and, most recently, dynamic strain and seismic waves (DAS) recorded either continuously or on an as-needed basis. The high spatial coverage, accuracy, and resolution of this technology make it a truly groundbreaking addition to our subsurface sensing toolbox.

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With the relentless progress being made in fiber-optic interrogator technology, fiber-optic cables and completions, and creative ways to utilize these systems, there is a critical need to keep abreast of this rapidly evolving field. While pioneered in the borehole community, DTS and DAS are now finding application in a broad range of contexts, including fracture characterization, vertical seismic profiling (VSP), time-lapse imaging, near-surface studies, ambient-noise recording, pressure sensing, geothermal monitoring, and earthquake seismology. Due to the broad range of application domains, this special section cannot cover all relevant distributed sensing applications; we focus on DAS in particular with the exception of recent geothermal DTS applications described in the paper by Patterson et al. This special section contains 10 papers; eight are presented here in the print edition and two can be found in TLE's expanded Digital Edition (http://www.tleonline.org) and in the SEG Digital Library (https://library.seg.org/toc/leedff/36/12).

One domain in which DAS is finding increased application is for monitoring stimulations in unconventional oil and gas environments, in particular to determine the effectiveness of individual hydraulic-fracturing stages. Jin et al. use low-frequency (<0.05 Hz) DAS strain data collected during a hydraulic-fracture treatment to constrain induced fracture geometry. Their DAS data set provides a unique view of events associated with fracture opening and closing, stress shadow creation and relaxation, ball seat, and plug isolation. Using crosswell DAS observations, they are able to successfully measure far-field fracture geometry parameters such as length, height, width, and density.

While DAS has been utilized in VSP acquisition for several years, few studies have provided comparisons of differences between DAS vendors and their associated interrogator technologies. Olofsson and Martinez compare the quality of DAS VSP data acquired by three different vendors at the Acquistore site (Canada) with corresponding geophone data for ground truth. They show a reassuring result that the DAS records from the three vendors, when carefully processed, can be converted from strain (or strain rate) to be extremely similar to the geophone data.

Many studies using DAS VSP P-wave data have been shown in the literature, but not much discussion has been given to S-wave DAS data. Wu et al. show a convincing comparison of DAS VSP shot records and processed images from P- and S-wave sources with the corresponding results using geophones. The theoretical angular response of the fiber to P- and S-waves is shown for a single point on a fiber and for an entire well. This study opens the way for more advanced elastic wavefield acquisition using DAS as the detector.

Fiber-optic cables can be constructed in many ways, for example in the number and type of fiber-optic strands in the cable but also in the way the strands are coupled to the cable itself. In the first of two papers from this special section that are published in the TLE Digital Edition, Correa et al. explore the response characteristics of two different fiber-optic cables to seismic waves in the context of VSP surveys acquired at the Otway CO2CRC site in Victoria, Australia. They find that a proprietary fiber was able to capture higher signal-to-noise data than the conventional fiber. They also provide a comparison of the angle of incidence response of the fiber as well as improved workflows for strain-rate/velocity conversion.

Time-lapse studies are key to understanding the movement of reservoir fluids over the life of the field. Mateeva et al. demonstrate that the amplitudes of DAS VSP data collected offshore are reliable, which enables monitoring of reservoirs for time-lapse effects from production and injection. Even reducing the amount of source effort to provide cost savings does not significantly diminish the quality of the result to accurately provide time-lapse analyses. They also conduct an economic analysis and demonstrate the business case for time-lapse DAS acquisition using the value-to-investment ratio formalism.

Areas with severe near-surface velocity variations pose significant challenges for surface seismic imaging. Bakulin et al. propose a new methodology to use a network of many shallow wells instrumented with fiber optics using a continuous fiber-optic cable. A DAS seismic recording is made while the vibe truck traverses over this network of shallow wells. These mini-VSPs provide densely sampled overburden velocity information as well as the ability to image the subsurface directly with the shallow well data. Their results show that the shallow well coverage improves the image quality much faster than trying to add additional surface seismic effort.

James et al. study the effectiveness of a novel fracturing method in a shallow well using passive DAS. The induced fractures are characterized through time-lapse changes in the seismic velocity before and after stimulation. This is detected using high-frequency ambient noise recorded by fiber-optic cables installed in four wells that surround the stimulated well. Application of 3D Bayesian tomography provides detailed images of the fractured zone.

Pressure communication between wells can be used to characterize the permeability structure of geothermal, carbon sequestration, and petroleum reservoirs. Becker et al. perform an elegant laboratory investigation into the possibility of using pressure measurements from DAS strain rate to detect low-frequency pressure oscillations. They find a good response for short oscillation periods (10 s) but a decreased sensitivity at longer periods (100 and 720 s) for which larger pressure oscillations (~1000 Pa) are required for detection. While the observed long-period response was weaker than expected, the development of such a response function is useful beyond pressure monitoring and informs domains such as earthquake seismology and geodesy, which target frequency bands below typical exploration seismic measurements.

Geothermal plant operators need to constantly monitor the thermal profile of the reservoir to track, for example, the steam-water interface. In the second of this issue's Digital Edition features, Patterson et al. describe a successful application of DTS to monitor eight days of production. They show images that locate the steam-water interface and visualize the changes in the borehole temperature profile following an injection of a cold-water slug, and allow for the inversion of rock thermal properties near the wellbore. These spatiotemporal dynamics are not able to be captured by conventional pressure-temperature surveys.

Conventional telecommunication systems have expansive underground networks of buried optical fiber. Martin et al. explore the use of the existing fiber-optic cable infrastructure on the Stanford University campus to measure seismic signals. Both active and passive seismic data have been collected and analyzed. They show that the kinematics of P- and S-waves from earthquakes can be measured reliably on these DAS recordings. In addition, dispersion analyses can be made from surface waves. This leaves open the possibility of utilizing conventional telecom infrastructure to create large networks to monitor earthquakes.

We hope you find this special section to be a useful update on recent advances in DAS!