# Transforming Safety and Sustainability in Oil & Gas with Fiber Optic Sensing

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## Abstract

Distributed Fiber Optic Sensing (DFOS), including Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS), is transforming monitoring in the oil and gas industry by delivering real-time, high-resolution insights into upstream and midstream applications, such as well integrity and well equipment monitoring, production optimization, and various aspects of pipeline monitoring. Field deployments in downhole installations demonstrate its effectiveness in detecting leaks, identifying production anomalies, and enabling timely interventions. In midstream operations, DFOS enhances leak detection and anomaly monitoring, especially when integrated with machine learning for predictive analytics. Initially developed for the oil and gas sector, DFOS is now proving highly effective in geothermal and carbon capture and storage (CCS) projects. This study presents case studies showcasing DFOS applications across these domains, emphasizing its role as a reliable, non-intrusive solution for enhancing safety, reducing risks, and optimizing operations.

## Introduction

Distributed Fiber Optic Sensing (DFOS) has emerged as a powerful technology for real-time monitoring in various industries, particularly in the oil and gas sector. Using standard fiber optic cables as continuous sensors, DFOS provides high-resolution spatial and temporal data across extensive infrastructure. The DFOS unit sends laser pulses along the fiber and analyses the backscatter (Figure 1, adapted from AP Sensing). By examining components like Raman and Rayleigh scattering, DFOS can capture a range of data, including temperature variations and strain or vibration-induced changes, which are vital for monitoring and intervention.

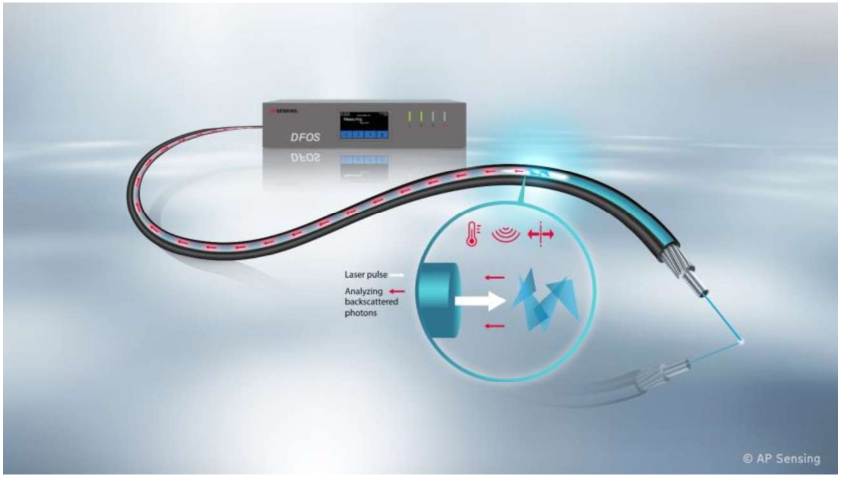


**Figure 1.** Schematic representation of a DFOS unit connected to a fiber optic cable. The zoomed-in area of the fiber optic cable illustrates the directions of the laser pulse and the backscattered signal.

Two key DFOS techniques, Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS), enable advanced monitoring capabilities based on different physical principles. DTS utilizes Raman backscattering to measure temperature variations along the fiber, while DAS uses Rayleigh backscattering to detect strain or vibration-induced changes, enabling acoustic monitoring (Figure 2, adapted from AP Sensing). Notably, the low-frequency component of the DAS signal is highly sensitive to both subtle strain and temperature variations, enhancing its effectiveness in specific applications, which will be discussed further.

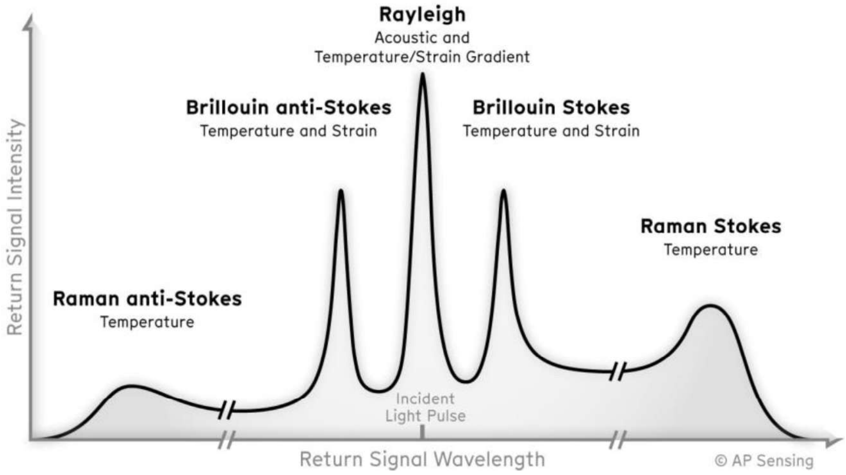


**Figure 2.** Spectrum of the backscattered signal. The DTS unit analyzes the Raman Stokes and anti-Stokes components, while DAS measurements rely on the Rayleigh scattering component of the backscattered light.

These technologies support critical applications such as leak detection, flow characterization, seismic monitoring, and well integrity assessment, among others. By leveraging the sensitivity and extensive coverage of fiber optic sensing, DFOS enhances operational efficiency, strengthens safety measures, and enables proactive decision-making across downhole, midstream, and cross-sector applications, including geothermal and CCS.

## DFOS Utilization in the Oil and Gas Sector

The integration of DFOS into upstream and midstream assets in the oil and gas sector offers several key advantages. DFOS provides simultaneous spatial and temporal measurements, delivering continuous, real-time data that enhances operational efficiency by enabling proactive decision-making and timely interventions.

Moreover, DFOS is well-suited for operation in harsh environmental conditions, making it a reliable solution for monitoring remote or challenging installations. The fiber optic cable serves as a continuous sensor, providing high-resolution data across vast infrastructure.

In addition to improving operational efficiency, the real-time data provided by DFOS also contributes to minimizing the sector's carbon footprint. By enabling precise monitoring and optimization of production processes, DFOS helps minimize energy waste and supports more sustainable practices in various operations.

## Case studies of DFOS Applications in Oil and Gas Upstream

To further illustrate the impact of DFOS in the oil and gas industry, several case studies have been documented across various applications in downhole installations.

One key application of DFOS is the analysis of distributed sensing data in production wells, providing valuable insights into well performance, especially when conventional logging tools encounter operational challenges.

A study by Urmantseva et al. (2023) highlights the benefits of DFOS for post-perforation production profiling in the horizontal well. It demonstrates that DAS data can help identify potential production zones that might be missed by DTS analysis alone. Additionally, the study shows how integrating DTS and DAS data to optimize well temperature models can significantly enhance production optimization efforts. The DFOS data in the horizontal reservoir section and final production profile are shown in Figure 3.

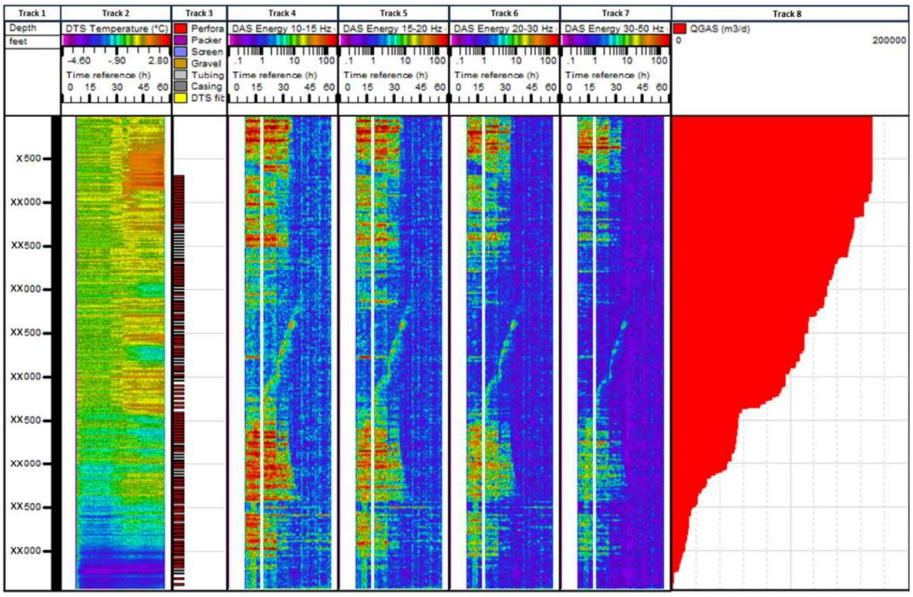


**Figure 3.** Representationm of DTS (track 2) and DAS data (track 4-7) within the reservoir's horizontal section throughout the entire acquisition period, along with the final production profile (track 8).

DFOS also provides critical downhole data not only on reservoir conditions, but also wellbore integrity, and equipment performance. Webster et al. (2023) discuss the use of fiber optic slickline for well integrity issue localization (Figure 4). By applying DTS and DAS technologies, the study identified specific issues in under 8 hours, reducing operating hours and saving on personnel, wireline equipment, and bleed-off costs. The major advantage of DFOS over conventional wireline measurements is its ability to monitor the entire well throughout the survey, enabling real-time observation of well responses to surface changes.

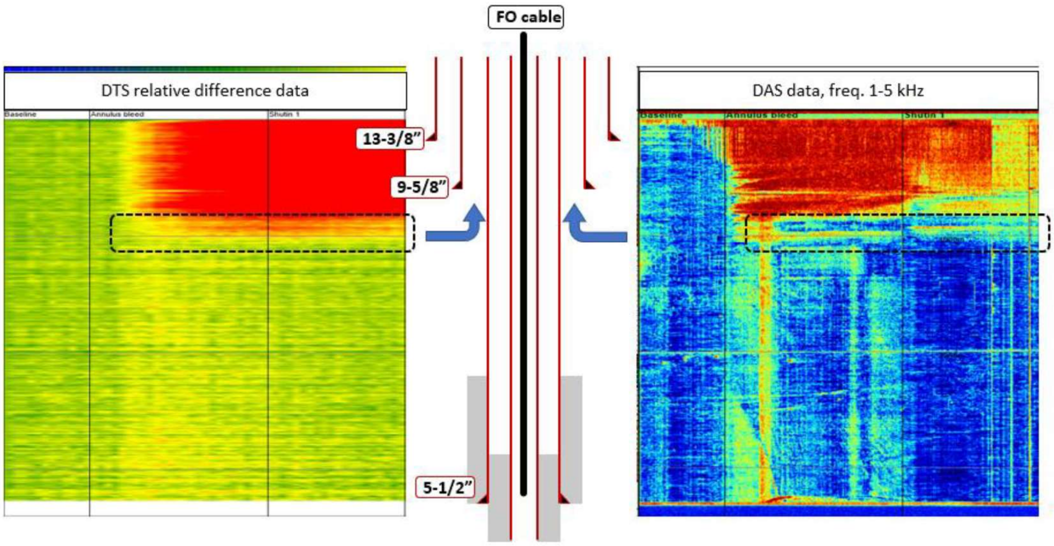


**Figure 4.** Well schematic illustrating various casing sections and their respective sizes. The DFOS-enabled slickline was deployed to the 5-1/2" casing shoe, as shown in the schematic. DTS and DAS were used to identify and locate the sustained casing pressure (SCP) interval, which is marked with blue arrows (adopted from Webster et al., 2023).

A unique feature of DAS is its sensitivity to both strong acoustic events and subtle, slow changes in strain and temperature, as explored by Lauber and Lees (2021). Low-frequency DAS data enhances downhole measurements, revealing previously undetected features. For example, Webster et al. (2024) demonstrated how low-frequency DAS analysis helped identify issues with gas lift valves that could have otherwise been missed.

In this study (Webster et al., 2024), both DTS and DAS data were acquired along the entire length of gas-lifted offshore well. Low-frequency DAS data (Figure 5) captured temperature-related events not clearly visible with Raman DTS, providing valuable operational insights. As a result, a faulty side pocket mandrel (SPM) was isolated, leading to increased oil production from the well.

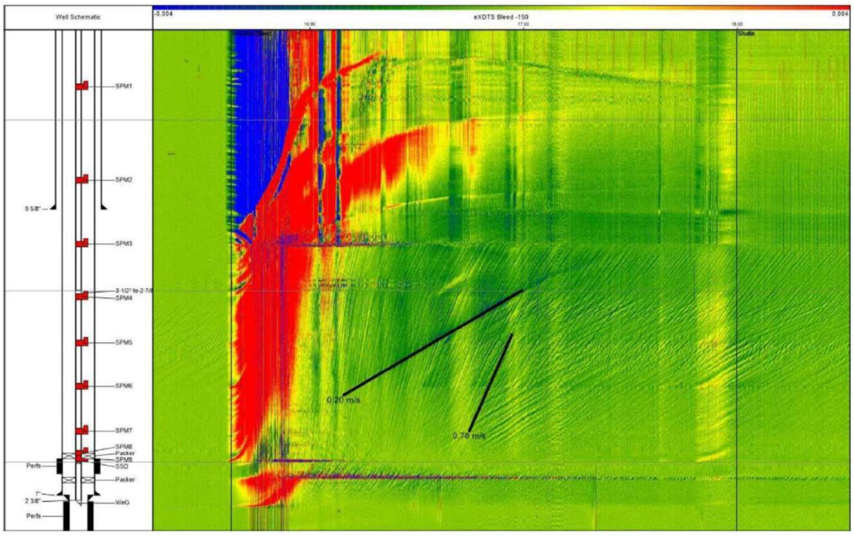


**Figure 5.** Well schematic showing the positions of SPMs on the left and low-frequency DAS data on the right. The effects of flow are visible below SPM3, indicated by two distinct apparent velocity gradients (marked with black lines).

## DFOS Utilization in the Cross-Sector Applications

Originally developed for oil and gas, Distributed Fiber Optic Sensing (DFOS) is now being successfully deployed in cross-sector energy applications, such as carbon capture and storage (CCS) and geothermal energy projects. The versatility of DFOS technology in diverse environments highlights its value in the broader energy sector, providing enhanced monitoring, improved operational efficiency, and increased safety in these evolving fields.

In geothermal energy applications, understanding and monitoring thermal processes in the subsurface is essential for optimizing system efficiency. Bertermann and Suft (2024) explored the use of DFOS for analysing borehole heat exchangers (BHEs), a critical component of geothermal systems. Their study focused on a field with 54 BHEs reaching depths of up to 120 meters, where in several boreholes fiber optic cables were used to perform distributed temperature sensing (DTS). The results demonstrated that DTS is a reliable method for assessing ground temperature dynamics, independent of the construction progress of the BHE field. This continuous thermal monitoring provides valuable insights for optimizing geothermal system performance and efficiency.

A case study by Schölderle et al. (2023) successfully demonstrated the feasibility of installing a permanent fiber optic cable along a sucker rod for continuous monitoring in a deep, deviated geothermal production well in the Southern German Molasse Basin (Figure 6). A permanently installed fiber optic system enabled continuous temperature monitoring, overcoming limitations of traditional spinner flow meter logs, which are typically conducted during injection, rather than production. By applying an inverse modeling approach using DTS data, a more detailed inflow profile was derived, revealing that a small karstified zone at the top of the reservoir dominates production flow. While qualitatively consistent with prior flow meter interpretations, DTS-based profiling provided higher resolution and identified additional minor inflow zones deeper in the reservoir. This highlights the potential of DTS for improved geothermal reservoir characterization, offering a continuous and production-phase alternative to conventional profiling methods.

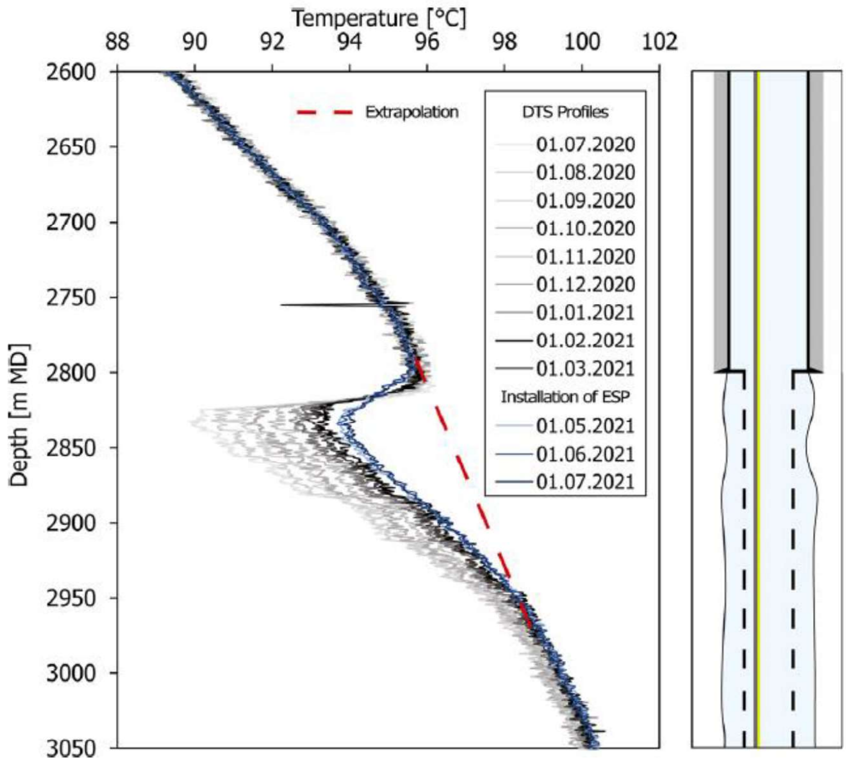


**Figure 6.** Well schematic and DTS profiles in deep geothermal well, Southern German Molasse Basin (adopted from Schölderle et al., 2023).

DFOS has also proven valuable in CCS projects. Its ability to provide continuous, real-time monitoring extends beyond downhole conditions to critical surface infrastructure, such as $CO_2$ pipelines. In CCS operations, early detection of leaks is essential, as $CO_2$ pipeline failures can lead to hazardous ductile fractures with rapid crack propagation. The high sensitivity of DFOS allows for early identification of strain anomalies, temperature changes, and acoustic signatures associated with potential leaks, enhancing the safety and reliability of CCS transport and storage systems.

Beyond surface infrastructure, DFOS techniques, particularly DTS, play a crucial role in downhole monitoring of $CO_2$ injection wells. The study (Shawcross et al., 2024) explores the use of DTS in monitoring $CO_2$ injection wells at the Gorgon CCS Project. DTS warmback surveys were conducted in four wells to assess the $CO_2$ injection profile and verify containment. The surveys relied on a disposable fiber optic system, which enabled rigless intervention while minimizing risks. The method used temperature changes post-injection to infer $CO_2$ distribution, with warmer zones indicating lower $CO_2$ influx. $CO_2$ containment was confirmed, and DTS data, complemented by DAS, provided valuable insights. The findings underscore DTS's potential for $CO_2$ storage monitoring.

## Conclusions

Distributed Fiber Optic Sensing (DFOS) is revolutionizing monitoring in the oil and gas, geothermal, and carbon capture and storage (CCS) sectors. By providing real-time, high-resolution data, DFOS enhances well integrity assessments, optimizes production processes, and improves leak detection across both upstream and midstream operations. The case studies demonstrate its effectiveness in detecting anomalies, supporting predictive analytics, and reducing operational risks. As DFOS continues to expand beyond traditional oil and gas applications, its non-intrusive and scalable nature proves invaluable for enhancing safety, efficiency, and decision-making in the evolving energy sector.

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