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Real-Time and Cloud-Based Fiber Optic Well Monitoring, Part 4: Laying the Groundwork for Downhole Multiphase Fluid Ratio Differentiation

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Summary

Multiphase production plays a critical role in controlling unwanted fluid phases while enabling efficient production of the desired phase. In producer wells, operators typically pursue either full-joint workovers to block unwanted water production or selective interventions targeting specific intervals. Even when comprehensive workovers are performed, post-intervention performance is often evaluated blindly once the well is returned to production.

Accurate identification of fluid entry zones becomes increasingly critical when selective workovers are considered. Given the high operational costs and risks associated with well interventions, the development of fast, reliable, and cost-effective diagnostic technologies is essential for enabling informed decision-making and reducing unnecessary expenditures.

This paper presents a Distributed Acoustic Sensing (DAS)–based framework for multiphase fluid ratio differentiation, enabling quantitative assessment of oil, water, and gas production at individual joints along lateral sections. As most wells in Western Canada are already equipped with multi-mode fiber-optic infrastructure, DAS-based monitoring represents a scalable and economically attractive solution when combined with advanced analytics.

A major challenge lies in extracting meaningful physical information from massive DAS datasets. At typical acquisition rates of approximately 20 kHz, DAS systems generate hundreds of megabytes of data per second over kilometer-scale intervals, corresponding to tens of millions of data points per acquisition window. Efficient interpretation of such data volumes remains a fundamental bottleneck. While gas-related signatures are often identifiable, robust oil–water differentiation has remained largely unresolved.

This work addresses a fundamental question: can the conventional interpretation of DAS frequency content; low frequencies associated with liquids and high frequencies associated with gas; be reliably extended to complex challenges such as oil–water differentiation and flow fingerprint recognition?

We demonstrate that reliable multiphase discrimination requires analysis of the full spatiotemporal dataset rather than selected frequency bands or localized segments. Furthermore, we introduce a novel interpretation paradigm based on acoustic reconstruction and audio-inspired signal processing. Using our intelligent, real-time, cloud-based monitoring platform, we show that DAS data can be used to reconstruct audible sound signals generated near the fiber, including music and speech played through an external speaker. Reconstructed audio files are provided as supplementary material.

The successful and high-quality reconstruction of external acoustic signals confirms that DAS measurements preserve detailed waveform-level fingerprints associated with physical excitations along the fiber. This result indicates that characteristic flow-induced signatures are reliably captured within the recorded data stream. Consequently, if external sound sources can be reconstructed with high fidelity, the corresponding acoustic fingerprints of water and oil production must also be present and extractable. This finding provides direct physical validation of the feasibility of reliable oil–water differentiation using broadband DAS analytics.

Building on this insight, we plan to develop an integrated workflow combining full-band DAS analysis, audio-style feature extraction, and deep learning to enable robust, automated multiphase fluid differentiation.

Theory / Method / Workflow

The development of optical fiber sensing dates to the 1970s, when early studies demonstrated the potential of fiber technology for detecting acoustic-induced point strain [1]. During the same period, advances in geodesy incorporated long-baseline optical interferometry using evacuated tubes [2]. The subsequent adoption of optical fibers as the light transmission path for long-baseline strain measurements significantly simplified interferometer design while improving measurement precision and operational practicality [3].

By the 1990s, optical fiber sensing had expanded beyond its initial experimental applications to enable reliable pressure and temperature monitoring. Conventional single-point sensors were progressively replaced by more advanced fiber-optic systems, which gained widespread acceptance in the oil and gas industry. These systems are commonly categorized into three groups: Point Sensors (PS), which measure pressure and temperature at the fiber termination; Quasi-Distributed Sensors (QDS), which incorporate multiple sensing locations along the fiber for strain and temperature measurements; and Distributed Sensors (DS), which employ the entire fiber length as a continuous sensing element. The ability of a single optical fiber to substitute for numerous conventional sensors enables more efficient and comprehensive monitoring of pressure, temperature, strain, and acoustic phenomena [4].

Fundamental to fiber-optic sensing is the principle of optical backscattering, whereby incident light interacts with the internal structure of the fiber. Three primary scattering mechanisms, Rayleigh, Brillouin, and Raman, form the basis of most distributed sensing technologies [5], as illustrated in Fig. 1. These interactions are classified as either elastic or inelastic scattering processes. Rayleigh scattering is an elastic phenomenon arising from microscopic refractive-index variations within the fiber, redirecting light without changing its frequency. In contrast, Brillouin and Raman scattering are inelastic processes in which the backscattered light experiences frequency shifts, generating Stokes (downshifted) and anti-Stokes (upshifted) components [6].

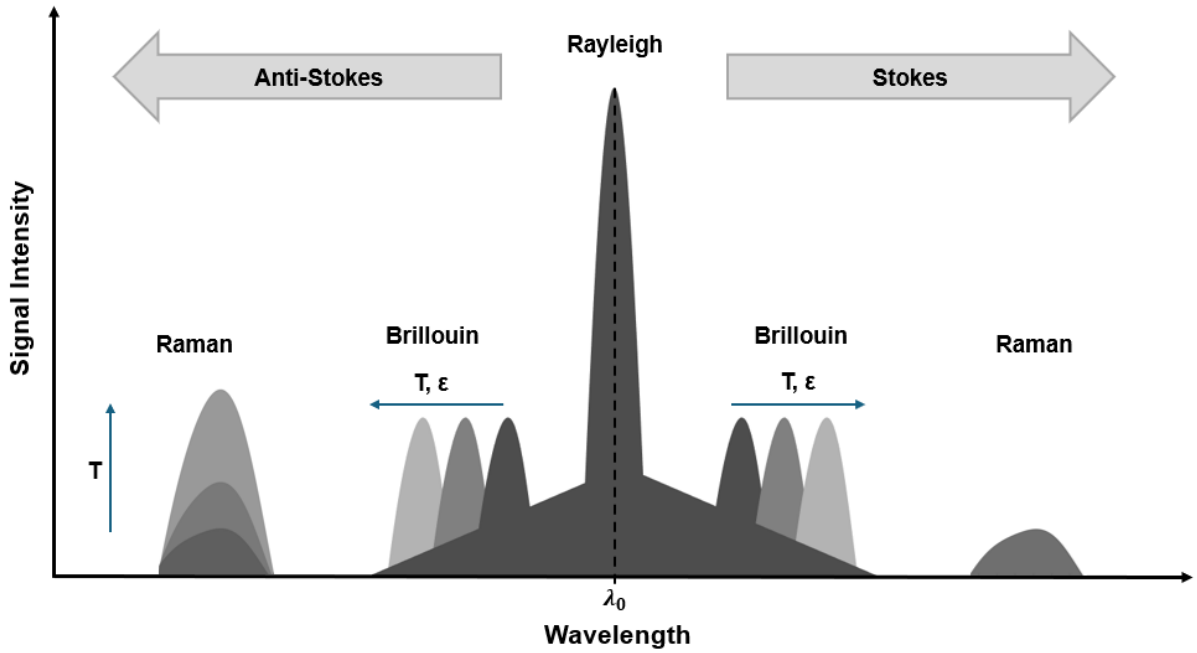


Figure 1 - Three types of scattering in fiber optic cables (redrawn and adapted from [6]).

Among the three primary backscattering mechanisms, Rayleigh scattering generates the strongest signal intensity, followed by Brillouin and Raman scattering. These scattering phenomena form the foundation of distributed fiber-optic sensing technologies, which enable three principal applications: Distributed Temperature Sensing (DTS), Distributed Strain Sensing (DSS), and Distributed Acoustic Sensing (DAS).

In this study, DAS is employed to record acoustic signals generated by a sound source positioned near the optical fiber. The recorded DAS data are subsequently used to reconstruct the original audio signal. The mathematical framework underlying this reconstruction method is protected under a pending patent application; however, the experimental results and performance outcomes are presented and discussed in this paper.

In phase-sensitive DAS, short coherent laser pulses at wavelength λ are launched into a standard single-mode fiber. Microscopic index inhomogeneities along the core Rayleigh-scatter a tiny fraction of light back toward the interrogator. By mixing the returned field with a local oscillator (heterodyne detection) we recover the phase of the backscatter as a function of distance. The interrogator forms many “virtual channels” by differencing the complex backscatter from two points separated by the gauge length L_g (typically meters). A change in axial strain $\varepsilon(z,t)$ and/or temperature $\Delta T(z,t)$ within that interval alters both the fiber length and its refractive index, producing a differential phase shift.

$$\Delta\phi(z,t) \approx \frac{4\pi}{\lambda}\left[nL_g\varepsilon(z,t) + L_g\frac{\partial n}{\partial T}\Delta T(z,t)\right]$$

where n is the fiber index.

Using the phase data, we developed signal-processing blocks (spectrograms, whitening, band selection, and simple source-separation filters) that make the DAS content “audible” in the sense of being interpretable, either by ear for demonstrations or, more importantly, by algorithms that operate on the same time, frequency features used in audio analysis.

Results, Observations, Conclusions

The successful reconstruction of external acoustic signals demonstrates that DAS measurements retain high-fidelity, waveform-level fingerprints associated with physical excitations along the fiber. The exceptional quality of the reconstructed audio further confirms that the proposed intelligent framework can reliably isolate and extract physically meaningful signatures from background noise and complex interference environments. These results indicate that characteristic flow-induced responses are consistently preserved within the recorded data stream. Consequently, the ability to reconstruct external sound sources with high fidelity implies that the corresponding acoustic fingerprints of water and oil production are inherently embedded in the DAS measurements and can be robustly recovered. This finding provides direct physical validation for the feasibility of accurate and reliable oil–water differentiation using broadband DAS analytics.

Audio reconstructions of a classical music piece and a GeoConvention 2021 short video, available on YouTube, are presented in Link #1 and Link #2. These examples serve as real-world case studies demonstrating how fingerprint extraction enables high-quality and accurate audio reconstruction.

Novel/Additive Information

First experimental demonstration of high-fidelity, waveform-level acoustic reconstruction from DAS measurements as direct physical validation of multiphase flow fingerprint preservation, establishing a quantitative link between external sound recovery and subsurface fluid discrimination.

Introduction of a full-band, spatiotemporal DAS interpretation framework inspired by advanced audio signal processing, transcending conventional narrowband frequency analysis to enable robust and scalable oil–water–gas differentiation.

Development of a real-time, cloud-enabled, and scalable DAS analytics platform for joint-level multiphase quantification in horizontal wells, providing a reliable, cost-effective alternative to conventional production logging and post-intervention blind assessment.

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