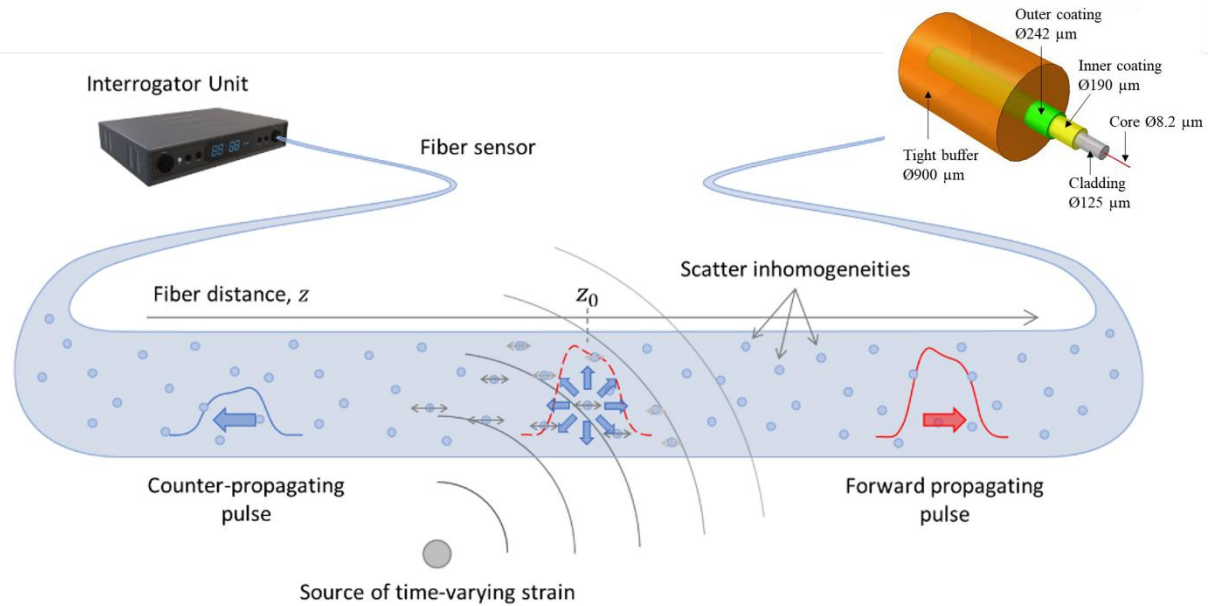




Final report from 12 June 2025

DFOS overview

Distributed Fiber Optic Sensing overview report



Source: SEAFOM. Measurement specification working group.



ETH zürich

Publisher:

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Berne
www.energy-research.ch

Co-financing:

Swiss Federal Office of Energy
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:

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SFOE contract number: SI/502823-01

The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Summary

This report provides a concise overview of Distributed Fiber Optic Sensing (DFOS), with a focus on Distributed Acoustic Sensing (DAS) as a transformative tool for subsurface monitoring in geenergy applications. It explains the physical principles of Raman, Brillouin, and Rayleigh scattering, and how they underpin DTS, DSS, and DAS technologies. A key emphasis is placed on DAS, which leverages Rayleigh scattering to convert telecom-grade optical fibers into dense seismic arrays. The document discusses DAS system architecture, including interrogator unit design, optical noise challenges, and gauge length effects. It compares DAS to conventional technologies, highlighting advantages in cost per channel, deployment in harsh environments, and long-term monitoring capabilities, especially when pre-installed or dark fiber is available. Detailed sections cover active and passive seismic applications. Numerous published case studies demonstrate DAS's ability to deliver high-resolution data for VSPs, microseismicity monitoring, and time-lapse surveys. Swiss initiatives are presented. The report concludes that DAS, as part of the broader DFOS suite, is becoming a cornerstone technology for real-time, large-scale geophysical monitoring supporting Switzerland's energy transition.

Zusammenfassung

Dieser Bericht bietet einen prägnanten Überblick über die verteilte Glasfaser Sensorik (Distributed Fiber Optic Sensing, DFOS) mit Schwerpunkt auf der verteilten akustischen Sensorik (Distributed Acoustic Sensing, DAS) als revolutionäres Werkzeug zur Überwachung des Untergrunds in Geoenergieanwendungen. Es werden die physikalischen Prinzipien der Raman-, Brillouin- und Rayleigh-Streuung erläutert, welche den DTS-, DSS- und DAS-Technologien zugrunde liegen. Ein besonderer Schwerpunkt liegt auf DAS, das Rayleigh-Streuung nutzt um Telekommunikations-Glasfaser in dichte seismische Arrays umzuwandeln. Das Dokument behandelt die DAS-Systemarchitektur, einschliesslich des Designs der Abfrageeinheit, der Herausforderungen des optischen Rauschens und der Auswirkungen der Messlänge. Es vergleicht DAS mit konventionellen Technologien und hebt die Vorteile bei den Kosten pro Kanal, dem Einsatz in widrigen Umgebungen, und den langfristigen Überwachungsmöglichkeiten hervor, insbesondere wenn bereits installierte oder ungenutzte Glasfaser vorhanden ist. Detaillierte Abschnitte behandeln aktive und passive seismische Anwendungen. Zahlreiche veröffentlichte Fallstudien demonstrieren die Fähigkeit von DAS, hochauflösende Daten für VSPs, die Überwachung von Mikroseismizität, und Zeitrasteruntersuchungen zu liefern. Schweizer Initiativen werden vorgestellt. Der Bericht kommt zu dem Schluss, dass DAS, als Teil der breiteren DFOS-Suite, sich zu einer Schlüsseltechnologie für die geophysikalische Echtzeit-Überwachung im grossem Masssstadium entwickelt, und somit die Energiewende in der Schweiz unterstützen wird.

Résumé

Ce rapport donne un aperçu concis de la détection distribuée par fibre optique (DFOS), en mettant l'accent sur la détection acoustique distribuée (DAS) en tant qu'outil de transformation pour la surveillance de la subsurface dans les applications géo-énergétiques. Il explique les principes physiques de la diffusion Raman, Brillouin et Rayleigh, et la manière dont ils permettent les technologies DTS, DSS et DAS. L'accent est mis sur le DAS, qui exploite la diffusion de Rayleigh pour convertir des fibres optiques en réseaux sismiques denses. Le document traite de l'architecture des systèmes DAS, notamment de la conception des unités d'interrogation, des problèmes de bruit optique et des effets de la longueur de la jauge. Il compare les DAS aux technologies conventionnelles, en soulignant les avantages en termes de coût par canal, de déploiement dans des environnements difficiles et de capacités de surveillance à long terme, en particulier lorsque des fibres préinstallées ou des fibres noires sont



disponibles. Des sections couvrent les applications sismiques actives et passives. De nombreuses études publiques démontrent la capacité de DAS à fournir des données à haute résolution pour les PSV, la surveillance de la microsismicité et les études répétées à intervalles réguliers. Des initiatives suisses sont présentées. Le rapport conclut que DAS, en tant qu'élément de la suite DFOS, est en passe de devenir une technologie de base pour la surveillance géophysique en temps réel et à grande échelle dans le cadre de la transition énergétique de la Suisse.

Main findings («Take-Home Messages»)

- Distributed Acoustic Sensing (DAS) enables dense, large-scale, and long-term seismic monitoring using existing or deployable fiber optic infrastructure, providing a cost-effective solution for subsurface imaging and surveillance.
- DAS technologies have been successfully integrated into Swiss geoenery projects (e.g., BedrettoLab, CITru, GeoCogen), demonstrating their practical relevance and scalability for geothermal and carbone storage monitoring.
- By repurposing telecom-grade fibers, including dark fiber networks, DAS supports sustainable use of infrastructure while enabling real-time, remote monitoring crucial for safe energy operations.
- The project strengthens Switzerland's capacity to monitor and manage geoenery systems, aligning with national energy transition goals by enhancing safety, transparency, and long-term subsurface data availability.



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1 Introduction

Distributed Fiber Optic Sensing (DFOS) utilizes optical fibers as continuous sensors to measure environmental parameters along their length. Among the various DFOS techniques, Distributed Acoustic Sensing (DAS) has emerged as a rapidly evolving technology that transforms conventional fiber-optic cables (Figure 1) into high-resolution seismic sensor arrays. DAS enables real-time subsurface monitoring over vast spatial scales, providing a cost-effective and scalable alternative to traditional geophysical sensing methods. This report presents a comprehensive overview of DAS, detailing its fundamental principles, recent technical advancements, and diverse applications, with a particular focus on its role in monitoring geothermal energy projects (including EGS) and Carbon Capture and Storage (CCS). It highlights the distinct perspectives of both operators and regulators in the deployment of DAS within these critical geoenergy sectors.

Section 2 introduces the broad DFOS framework, which encompasses multiple sensing techniques based on light scattering in optical fibers. It explains the fundamental scattering mechanisms enabling Distributed Temperature Sensing (DTS), Distributed Strain Sensing (DSS), and DAS, respectively. This section also discusses fiber-optic cable designs, and their influence on sensing performance. Section 3 delves into the fundamental principles of DAS, detailing how Rayleigh scattering enables the detection of dynamic strain variations along fiber-optic cables. It explains the core technology behind DAS—phase-sensitive Optical Time-Domain Reflectometry (Φ -OTDR)—which facilitates high-resolution strain measurements. Section 3 also discussed DAS Interrogator Units (IU), their key components, and operational principles. Section 4 addresses the practical aspects of DAS data acquisition, discussing critical technology limitations that must be considered to optimize performance and ensure application-specific implementation. This section provides insights into the challenges associated with coupling, directional sensitivity, and data processing, all of which influence the accuracy and reliability of DAS-based measurements. Section 5 reviews the diverse applications of DAS in geophysics, emphasizing its potential for passive and active seismic monitoring. In particular, it highlights the transformative impact of DAS in geoenergy applications, where continuous and spatially extensive seismic monitoring is crucial for operational efficiency and environmental safety. Section 6 outlines ongoing DFOS initiatives in Switzerland, showcasing key industry and academic collaborations focused on geoenergy projects. This section provides an overview of national efforts to integrate DFOS into subsurface monitoring programs, reinforcing Switzerland's role as a hub for research and development. Section 7 explores emerging trends in DAS research and application, emphasizing the integration of DAS in operational seismic monitoring systems as a groundbreaking opportunity for large-scale, cost-effective surveillance. This section highlights the potential of leveraging pre-existing telecommunication networks to reduce deployment costs while enhancing seismic observation capabilities.

By synthesizing the latest advancements and practical applications of DAS, this report aims to provide valuable insights into its evolving role in subsurface monitoring. It underscores the opportunities and challenges associated with adopting DAS for geoenergy applications, offering perspectives relevant to both industry operators and regulatory bodies.



2 General background

Distributed Fiber Optic Sensing leverages optical fibers as distributed sensors to measure environmental parameters along their length (Figure 1).

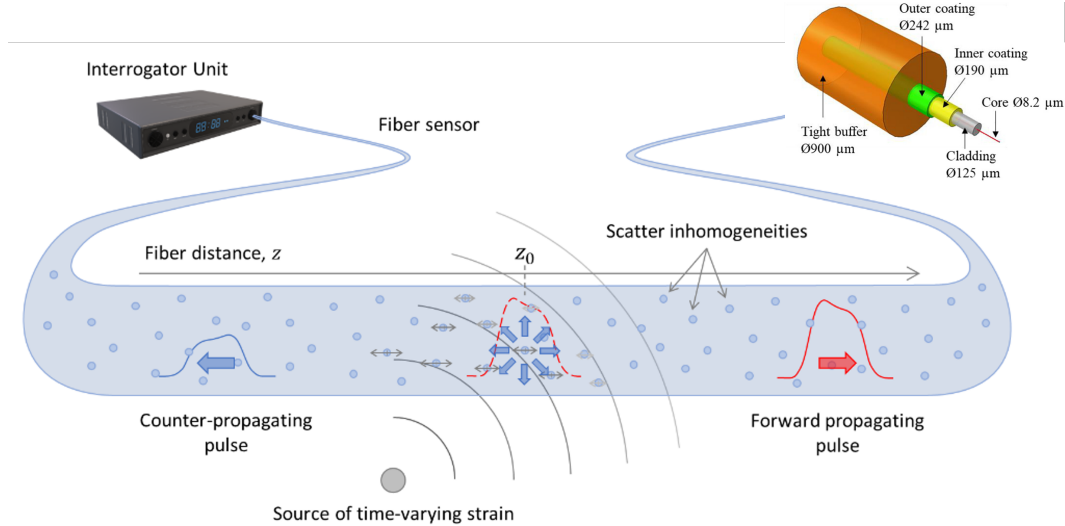


Figure 1: DAS sensing illustration, with core components: IU, FO cable containing FO core(s). Source [123].

2.1 Scattering in fiber

For telecommunication purposes, scattering caused by inhomogeneities in the fiber is a constrain, as it leads to signal attenuation and limits transmission efficiency. Those heterogeneities result from fiber optic manufacturing processes, when the fiber is drawn and its material is softened at a very high temperature, which produces fluctuations in the density of the material over distances of the order of 100 nm ([49]), causing scattering. At a larger scale (e.g. 10s of cm), those scatterers can be assumed uniformly distributed. Distributed Fiber Optic Sensing (DFOS) leverages those scatterers within the fiber to detect environmental changes. When an optical pulse is injected into the fiber, it interacts with the medium, generating scattered light. This backscattered signal carries valuable information about the physical conditions along the fiber's length. By analyzing the characteristics of this scattered light such as phase shifts, frequency shifts or intensity variations, distributed sensing systems can provide real-time measurements of various environmental parameters ([49, 101]). The three primary forms of scattering utilized in DxS systems are depicted in Figure 2 and briefly described below.

2.1.1 Raman scattering - Distributed Temperature Sensing DTS

Raman scattering is a type of inelastic scattering and occurs when pumped photons excite electronic vibrational states of an atom or molecule, resulting in the re-emission of scattered photons at a different frequency [89]). Raman backscattering consists of two components: the Stokes signal (lower frequency, higher wavelength) and the anti-Stokes signal (higher frequency, lower wavelength). The intensity of the anti-Stokes component is strongly temperature-dependent, while the Stokes component remains relatively stable. Raman scattering is therefore used for Distributed Temperature Sensing (DTS). The temperature T at a given location is determined using the ratio of these intensities, giving an absolute measurement, i.e. the true temperature (not relative, at least under ideal conditions). DTS systems are widely used for monitoring temperature along power cables, oil wells and reservoirs, as



well as for structural health applications and environmental sensing. DTS plays an important role in geothermal reservoir characterization, heat extraction optimization, and system efficiency monitoring. By detecting temperature anomalies, DTS helps assess whether injected water is effectively circulating through the geothermal reservoir. DTS can detect abnormal temperature fluctuations caused by CO_2 migration, alerting potential integrity issues before significant leakage occurs.

2.1.2 Brillouin scattering- Distributed Strain Sensing DSS

Brillouin scattering is another type of inelastic scattering which involves a transfer of energy between the incident and scattered photons. When the light pulse propagates through the fiber, it interacts with acoustic phonons ([89]), generating backscattered light shifted in frequency, known as the Brillouin frequency shift (ν_B):

$$\nu_B = \nu_{B0} + C_\varepsilon \cdot \varepsilon + C_T \cdot \Delta T, \quad (1)$$

where ν_{B0} is the unstrained reference Brillouin frequency, C_ε and C_T are calibration coefficients for strain (ε) and temperature (T), respectively.

Distributed Strain Sensing is based on Brillouin scattering to detect slow (quasi static) strain fluctuations relative to a baseline. By isolating strain effects from temperature influences (for example using collocated DTS, or hybrid cable having both tight buffer and loose tube fiber, see section 2.3), DSS provides a continuous mechanical strain profile along the fiber. This technology is used, among others, for monitoring structural health of the fiber, geotechnical applications, and pipeline integrity assessment. DSS also plays a crucial role in EGS and CCS by tracking high-resolution geomechanical fluctuations, for example micro-deformations that could indicate reservoir compaction, stress along borehole, potential caprock failure or leakage pathway, therefore ensuring structural integrity, optimizing operational efficiency and safety compliance.

2.1.3 Rayleigh scattering - Distributed Acoustic Sensing DAS

Rayleigh-scattering mechanism is an elastic scattering process meaning that the frequency of the incident light and the scattered light is the same. It arises when a source of light interacts with an inhomogeneous medium that contains spatial variations of its refractive index of length scales much shorter than the wavelengths of the light source. The Rayleigh type is the most impacting form of scattering, accounting for approximately 96% of the attenuation in optical fiber. It is the scattering mechanism used by DAS technology, discussed in more detailed in section 3

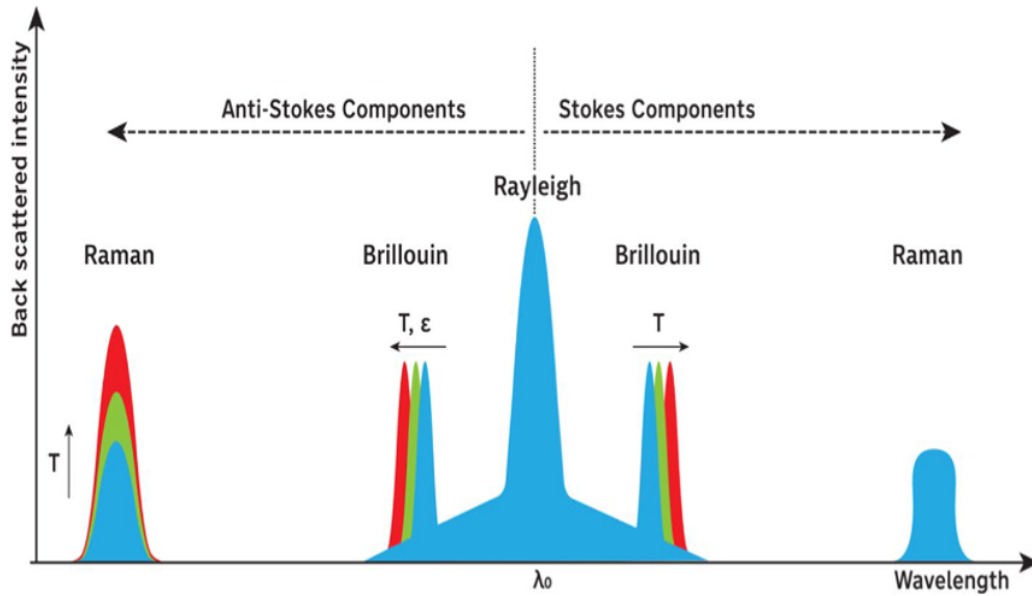


Figure 2: Sensing principle (back scattering form) for DTS (Raman, see section 2.1.1), DSS (Brillouin, see section 2.1.2) and DAS (Rayleigh, see section 2.1.3 and 3).

2.2 Optical Reflectometry

Determining where along the fiber the scattering occurred is typically made through Optical Reflectometry, most often in the time domain. It is very commonly used to monitor the operational health of telecom optical fibers. The technique involves the emission of a laser pulse into an optical fiber and considers the travel time for the backscattered signal to return, from which the distance along the fiber can be calculated using the formula $x = \frac{c}{2n_c} \cdot t$ where t is the backscattered detection time (also called fast time, the vertical axis in Figure 3), c is the speed of light, n_c is the refractive index of the core, and the factor of 2 accounts for forward and backward propagation. In its simplest form, a high-coherence short light pulse width is employed, for example with a laser diode driven by an electrical pulse generator like an electro-optic modulator (EOM). The backscattered light is detected in a photodiode (PD) via a circulator or splitter. The detected signal is converted into digital format and analyzed in a data acquisition device (DAQ). The DAQ is synchronized to the optical pulse source so that the propagation time of backscattered signals can be calculated precisely, thus accurately locating backscattering events along the fiber (see table 1). This is the basic approach for most DxS technologies.

In the specific case of Brillouin scattering, note that two distinct DSS interrogation modes have been developed: **BOTDR** is a passive, single-ended technique that relies on spontaneous Brillouin scattering. A single probe pulse is launched into the fiber, and the backscattered signal is analyzed to determine the Brillouin frequency shift. Since no counter-propagating signal is required, BOTDR does not require a loop configuration. However, it suffers from a lower signal-to-noise ratio (SNR), resulting in lower spatial resolution (typically meters) and limited strain sensitivity (e.g. ten microstrain). **BOTDA** is an active, stimulated Brillouin scattering technique requiring a dual-ended fiber configuration. A continuous pump wave is injected at one end, while probe pulses are sent from the opposite end. The interaction between the pump and probe enhances the Brillouin gain, significantly improving SNR and spatial resolution (down to centimeters). BOTDA achieves higher strain accuracy (e.g. microstrain) but requires bidirectional access and therefore u-turn of the fiber at the bottom of wells. Implementing such a configuration presents significant operational



challenges due to spatial constraints, environmental conditions, and cost considerations. One approach is to U-turn the entire optical cable, which typically includes protective buffering and armoring. This requires a large bending radius to avoid physical damage or signal degradation, making it difficult to implement within the limited space at the bottom of a well. Additionally, this method effectively doubles the required cable length and introduces significant installation complexity, increasing both material and labor costs. An efficient alternative is to use a cable that contains two optical fibers and implement the U-turn with a compact loop of bare fiber inside a specially designed (potentially high-pressure and high-temperature resistant) module. This "mini-loop" configuration allows bidirectional access without duplicating the entire fiber length and simplifies installation effort. However, it requires careful engineering to ensure the bare fiber is properly protected from mechanical stress and thermal effects. In general, the mini-loop approach offers a more practical and cost-effective solution for BOTDA deployment in space-constrained and harsh downhole environments.

Note also that Optical Frequency Domain Reflectometry **OFDR** techniques can be proposed, providing substantial higher spatial resolution (e.g. mm) but generally at the cost of significantly lower interrogation range.

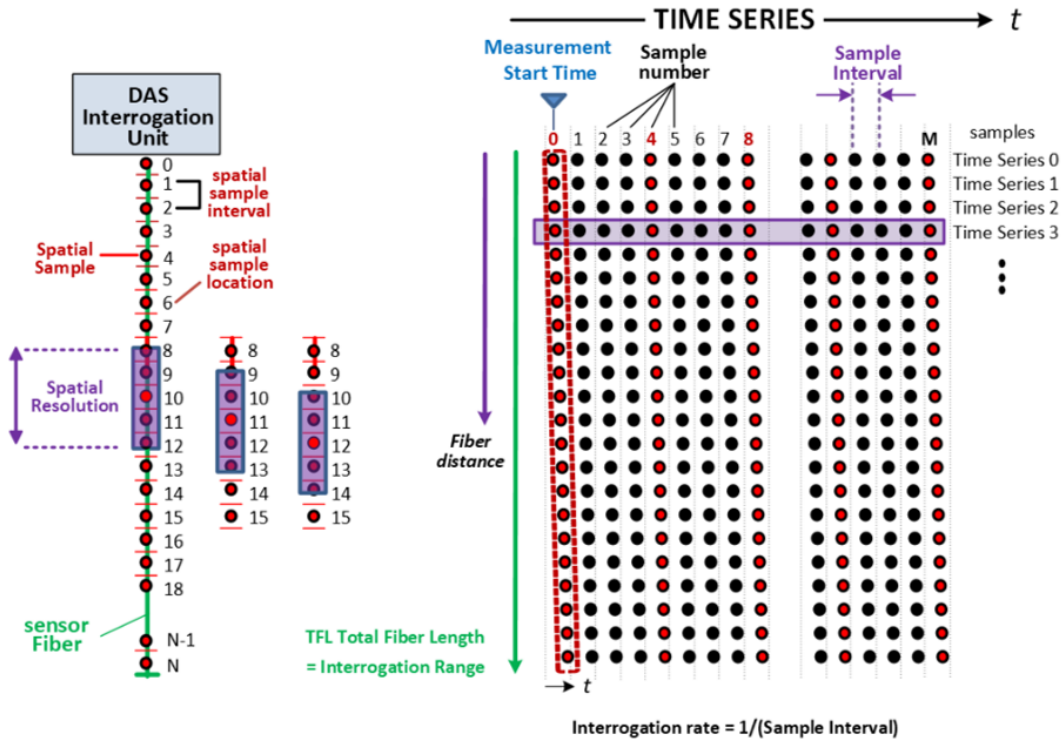


Figure 3: DAS sensing illustration of the spatial sampling, spatial resolution. Vertical direction (e.g. green arrow) corresponds to the fast axis, while the horizontal direction corresponds to slow time axis (i.e. recorded time-series). Source: [123]

2.3 FO cable type and structure

The fiber optic cable serves as both the medium for transmitting the light pulses and as the sensor itself. Changes in the environment, such as temperature fluctuations, strain, or vibrations, affect the light that travels through the fiber. These fibers can be laid across large distances, making DxS a particularly powerful tool for monitoring vast areas without the need for numerous individual sensors. The structure of the fiber optic cable (Figure 4)



significantly influences its sensing capabilities. This section describes key components.

The optical guide: The fundamental and central part of an optical fiber aims at propagating the light, the optical guide. It consists of two main elements: the core and the cladding (Figure 1). The core, made of high-purity glass, is primarily engineered for efficient transmission with minimal loss/attenuation. Surrounding it, the cladding is composed of glass with a lower refractive index, ensuring the light remains confined within the core through total internal reflection (i.e. reflection at an angle greater than the critical angle; if the medium beyond has a lower refractive index, the light is entirely reflected back into the core, preventing leakage). Optical fibers leverage this principle to effectively "trap" and guide light along their length. Together with the scattering, that is the property that make fiber optic cables an attractive medium for both data transmission and sensing.

Fiber type: SM vs MM: There are two types of optical fiber: single-mode (SM) and multi-mode (MM). SM fibers have a smaller core diameter, typically about 8-10 microns, and a cladding diameter of about 125 microns. SM allows for only one mode of light propagation, minimizing dispersion and enabling long-distance range ([105]). MM fibers, on the other hand, have a larger core diameter, typically about 50-100 microns, with a cladding diameter of about 125 microns. This larger core allows for multiple modes, or paths, of light that cause modal dispersion ([5]). MM fibers are generally used for sensing applications such as distributed temperature sensing (DTS). Most DAS and DSS applications use single-mode fibers because they can provide long-range. SM fiber may sometimes exhibit limited sensitivity in certain sensing techniques owing to their smaller core size.

Coating: A fiber is then protected by the buffer coating. It is the first protective layer surrounding the optical waveguide (Figure 1), typically made of materials like acrylate or polyimide. Its primary role is to safeguard the fragile bare fiber (core plus cladding) by minimizing the risk of damage from bending, twisting, or external stresses. Beyond mechanical protection, it also shields the fiber from environmental factors such as moisture, chemicals, and abrasion, preserving its optical performance and longevity.

TB vs LT: There are two main manners of embedding a fiber in its jacket: Loose-Tube (LT) and Tight-Buffer (TB), see Figure 4. LT type is a design where the optical guide(s) are housed in a protective tube (e.g. plastic, metallic) that is loosely filled with a gel or dry water-blocking material. It provides further protection against environmental factors like moisture, temperature fluctuations, and mechanical stress. LT cables offer good protection against microbending losses, which can significantly degrade sensing performance, although they may be more susceptible to temperature variations, making them suitable for DTS. TB fiber optic cable is another type of construction where each optical fiber is individually coated with a protective layer. In contrast to LT, TB cables ensure that the jacket and the optical guide are coupled, therefore better transferring the strain fluctuation from outside to inside the fiber. TB type of cable is required for DSS sensing. TB cables can be made more compact and easier to install but are more prone to microbending.

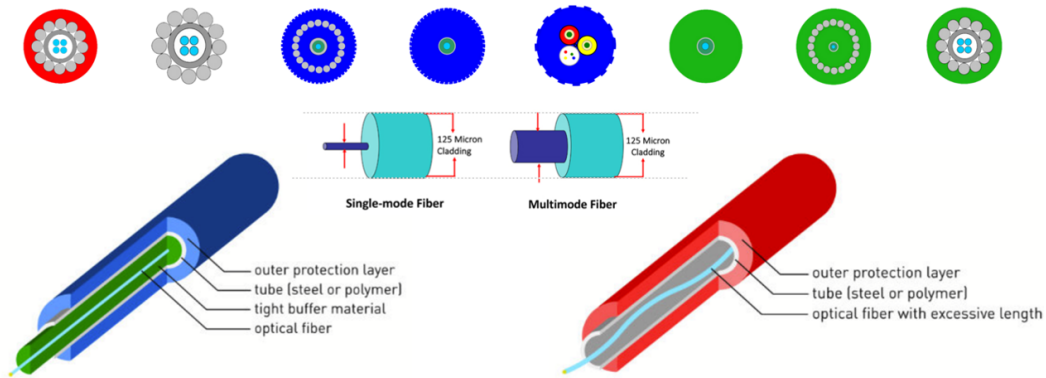


Figure 4: Tight buffer TB (left) and Loose tube LT (right) type of buffer. Note that cables can contain multiple fibers (SM or MM) in different buffer types, providing the opportunity to sense multiple parameters (e.g. DTS, DASS and DAS) with an unique cable, as illustrated in the cross-sections. Source: Fibristerre (<https://www.fibristerre.de/>) and Solifos (<https://solifos.com/en/sensing/>)

FO cable Designs: Note that a single loose tube can contain multiple fibers. Moreover, cables can contain a number of loose tube and/or tight buffer fibers. Telecom cables may contain hundreds of fibers, usually strongly reinforced to protect them and ensure longevity. Sensing dedicated cables typically contains less fibers, but a wide range of designs exist, with possibility of combining LT and/or TB types of SM and MM fibers, all encapsulated in various strength members and a final outside jacket material that should provide adequate protection against environmental factors while minimizing the impact on signal transmission/propagation. Various cable type structures are illustrated in the top of Figure 4. Strength members, often high-strength materials like Kevlar or steel wires, can drastically enhance the cable's mechanical robustness. Water-blocking materials are typically included to prevent water ingress, which can degrade fiber performance. Optimizing cable structure for sensing applications requires careful consideration of several factors. Minimizing microbending losses is crucial, which can be achieved through appropriate cable design, installation practices, and the use of suitable buffer materials. The choice of strength members can also impact sensing performance. Metal strength members, while providing high strength, can attenuate high-frequency signals, potentially limiting the spatial resolution of some sensing techniques. They may also introduce electromagnetic interference (EMI) in certain cases. Aramid fibers offer a good balance of strength and low signal attenuation. In brief, selecting fiber types that balance sensitivity, attenuation, and dispersion characteristics for the specific sensing application is essential. The overall cable design must be carefully considered. Finally, ensuring adequate environmental protection with a suitable jacket material is vital. By carefully selecting and designing fiber optic cables, it is possible to achieve high-performance sensing systems with enhanced sensitivity, spatial resolution, and long-term stability. The specific requirements for cable structure will vary significantly depending on the specific sensing application (e.g., DAS for earthquake monitoring vs. DTS for pipeline monitoring). The sensitivity of optical fiber cables to acoustic vibrations ($> 20Hz$) is discussed in [35]. A simplified overview of the requirements for operating the DxS family is presented in Table 1, demonstrating that a single cable containing at least one loose-tube multimode (LT-MM) fiber and two tight-buffered single-mode (TB-SM) fibers is sufficient to support all three sensing types simultaneously. However, note the significant difference in measurement duration, with DTS and DSS being quasi-static compared to the dynamic nature of DAS.



Characteristic	DTS	DSS	DAS
Scattering	Raman	Brillouin	Rayleigh
Sensitivity	temperature	slow strain / deformation	dynamic strainrate / vibrations
Fiber Type	MM	SM	SM
Cable Type	LT	TB	LT or TB
Measurement Duration	minutes	minutes	millisec
Accuracy	$\pm 0.1C$	$\pm 2\mu\epsilon$	$\pm 5p\epsilon$
Spatial Resolution	> 0.5 m	> 0.5 m	> 2 m
Max Range	100 km	80 km	40 km

Table 1: Summary of typical characteristics of DxS

3 DAS principle

The process described here as DAS is also known in the geophysics community as Distributed Vibration sensing (DVS) or Distributed Dynamic Strain Sensing (DDSS). It converts optical fibers into dynamic strain sensors, leveraging **Rayleigh scattering**, when the frequency of the scattered photons is the same as that of the incident photons (elastic scattering). Light pulses are sent thousands of times per second, guided and scattered in the fiber. The forward Rayleigh scattered light continues its journey along with the incident light, while the Rayleigh backscattered light returns to the interrogator unit (IU) and is captured by a photodetector, providing the "optical" raw data to be analysed in real-time, usually using phase-sensitive OTDR (Φ -OTDR).

3.1 Φ -OTDR

The Φ -OTDR is comparable to the traditional OTDR but typically uses a narrow linewidth laser and stable frequency source usually of 1550 nm wavelength. A Φ -OTDR system is designed to use coherent peaks resulting from interference between Rayleigh backscattered light from different scattering centers within the pulse width, which are sensitive to external disturbances ([89]). The intensity of the detected signal is related to the relative phase of the light coming from different scattering centers within the corresponding spatial distance of the pulse width. Since the scattering centers are randomly distributed along the fiber, the Φ -OTDR traces typically show random oscillatory features. This pattern will remain the same over time if the scattering centers do not change. If there is a disturbance at a particular location, the relative phases of the backscattered light will change and the Φ -OTDR traces will vary at that disturbance location. In brief, the Φ -OTDR technique dynamically measures the changes in the phase of light $\Delta\Phi$, which is proportional to the local strain $\epsilon_{zz} = \frac{z+\delta z}{z}$ ([83]):

$$\Delta\Phi(t, z_i) = \frac{4\pi n L_g \xi}{\lambda} \left(\frac{z + \delta z}{z} \right), \quad (2)$$

where n is the refractive index of the fiber material, L_g is the gauge length (the segment over which strain is measured), ξ is a scalar factor accounting for refractive index changes due to stress, and λ is the source wavelength. The value of ξ varies from 0.79 for pure silica [122] to 0.735 for GeO₂-doped fibers [10]. A typical value for n is 1.45 at a wavelength λ of 1550 nm. Note that in practice, the majority of DAS systems extract the temporal change of the phase, ie $\partial_t(\Delta\Phi)$, in which case the output is strain rate $\dot{\epsilon}_{zz}$ instead of strain ϵ_{zz} :

$$\partial_t(\epsilon_{zz}) = \dot{\epsilon}_{zz} = \frac{\lambda}{4\pi n L_g \xi} (\partial_t(\Delta\Phi)), \quad (3)$$



Several methods are proposed to retrieve $\Delta\Phi$, or its time-derivative, including interferometric approaches using a single pulse, e.g. [114, 92], a dual-pulse approach [31], and a heterodyne approach [48]. More recent advances in DAS include the use of a chirp pulse as a source to boost the optical budget and allow long-range interrogation/measurements exceeding 170 km [141]. Note that the measured phase change is constrained within the range $-\pi$ to π therefore phase unwrapping techniques must be applied before strain retrieval using Equation (3). This step can impact the dynamic range of the system.

3.2 DAS Interrogator Unit (IU)

Together with the FO cable, the Interrogator Unit (IU) is a crucial component in fiber optic sensing. The IU does not only send and receive scattered light, it is the brain of the system by interpreting the changes in the backscattered light and converting them into measurable parameters. While interrogation methods and devices vary, the principle remains the same: to enable high-resolution, real-time monitoring of large areas using fiber optic cables. A key element in an IU is of course the laser (or Electro-Optic Modulator EOM) that generates high-precision optical signals that are injected into the fiber. The laser must be a stable light source, often in the near-infrared spectrum, while the EOM modulates the light to achieve the required signal characteristics, such as frequency or amplitude modulation, depending on the sensing technique. The photon-detector is another key component, which aims at capturing the scattered light that returns from the fiber. This light is typically weak and can be scattered over long distances, so high sensitivity and low noise characteristics are crucial in selecting the detector. Then the light phase changes have to be measured (see section phase-OTDR). In many sensing systems, an interferometer (e.g. Michelson, or Mach-Zehnder) is used. In addition to these core components, the IU typically includes electronics for signal processing, a data acquisition system to record and analyze the measurements, and a user interface for controlling the system and displaying the data. The performance of the IU directly impacts the resolution, accuracy, and sensitivity of the fiber optic sensing system.

The current main **DAS IU providers** are (in alphabetic order) Alcatel Submarine Network (ANS), APsensing, Febus, Fosina, Neubrex, Omnisense, Optasense, Silixa, Sintela, and Terra15. The market is very dynamic and choosing an IU can be challenging not only because different applications may require different specifications/performances, but also because understanding those specifications is not straightforward. This lack of standardization presented a challenge for users seeking to assess and compare DAS solutions.

As data output, most manufacturers opted for a standard file structure: HDF5 (Hierarchical Data Format version 5), a format designed to efficiently store large amounts of data. Some manufacturers also propose PRODML (based on HDF5), a standard providing a framework for handling complex data types, therefore ensuring efficient data management between service providers and operating companies (mainly oil and gas). It offers a way to share standardized datasets. SEG-Y may also be proposed. At this stage however a standard for seismology purposes (typically SEED based) is not yet in place but is in development at a number of institutions, and in particular at ETHZ/SED.

As the DAS technology becomes more widely adopted for geophysical applications, understanding the instrumental response of these systems is important. However, in contrast to seismometers manufacturers routinely providing detailed calibration response since decades, DAS system manufacturers adhered to a "unified" standard only recently, via the SEAFOM protocols [123]. SEAFOM proposes test procedures and requirements to measure key specifications of IUs, with the categories listed in Table 2. This list highlights some important properties related to DAS instrument response that will aid in better understanding and interpreting the data provided by these technologies. In light of the democratization of DAS solutions, defining and understanding those became crucial for maximizing their potential



in geophysical monitoring. Of course each IU offer different performance and distinct user experiences, but the SEAFOM procedure aims at standardizing key performance metrics and therefore help users to fairly evaluate and compare the specifications of different DAS systems.

Categories	SEAFOM Description
Dynamic Range	The maximum level of uniform strain stimulation that can be applied at a given frequency such that the measured DAS response is not corrupted as compared to the input stimulus.
Frequency Response	The response of the DAS system over the full required or specified frequency range. Measurements are made to determine the magnitude “transfer function” of the system.
Fidelity	Refers to the accuracy and ‘purity’ of the DAS response compared to the original stimulus, which is determined by checking the level of distortion of the signal caused by the presence of harmonics.
Self-Noise	The DAS response in a quiet environment (i.e., free from external acoustic or vibrational stimulus). The self-noise test considers noise measurements in various ways, such as broadband “spot” noise and noise densities in predetermined frequency bands.
Spatial Resolution	The shortest fiber range distance within which the DAS system can spatially resolve localized acoustic or vibrational stimuli in the same frequency band. If two or more sources of strain activity occupy different frequency bands, they might still be resolved spectrally even if they are spatially indistinguishable. This is different from—but in properly working systems, approximately equal in value to—the gauge length (see Section 3.1).
Crosstalk	The presence of unintended residual signals that appear in locations other than the location of the original stimulus.
Loss Budget	An estimation of the performance impact of loss in a fiber due to components over the fiber distance. DAS performance is evaluated as calibrated point losses are inserted into the standard sensor.
Reflection Sensitivity	Refers to the impact on DAS performance of unplanned partial reflections (‘dead zones’) in the sensor fiber, which may cause signal saturation.
Fading	Probability distribution of the occurrence of spatial sample locations where the measured optical phase noise floor is significantly higher than the median level for the full range of the fiber under test. Fading leads to localized instances of elevated acoustic noise compared to the wider self-noise level.

Table 2: SEAFOM categories for assessing DAS system performances. Source [123].

3.3 IU optical noises

IUs, as any opto-electronic system, are prone to electronic and self noises. Multiple authors have identified local noise in DAS data, often referred to as optical noise ([6, 37, 2]). This type of instrumental noise can arise from various known sources.

Assessed in the SEAFOM procedure is optical **fading**, common issue in phase-sensitive OTDR measurements ([43, 85]). This phenomenon arises from destructive interference, which occurs when the random scattering within the fiber result overall in a very small magnitude. The significance of these effects is influenced by photonic factors such as laser frequency, gauge length, and pulse width, making them challenging to distinguish from sen-



sensor coupling ([9, 145, 2]). A strategy to mitigate fading using multiple laser frequencies has been suggested by [154] and next-generation DAS technology will continue to address this issue in the future.

Another classical IU related noise is so-called **common noise modes**, generated by the laser being disturbed by sound and vibrations, and resulting in unwanted constant signal across all data channels simultaneously. This noise is characterized by an infinitely fast apparent velocity. Minimizing the creation common mode noise can be done using a vibration isolation table. Post-acquisition, applying a median filter in time generally provides significant attenuation [6].

The Interrogator Unit (IU) is responsible for converting light into meaningful measurement data. Intuitively, one might assume that increasing the laser intensity would always improve the measurement by maximizing the number of returning photons. However, in practice, laser intensity must be carefully optimized to meet the photodetector’s specifications while avoiding nonlinear photonic effects that can degrade measurement quality. Once the laser intensity is appropriately configured, a common approach to enhancing the signal-to-noise ratio (SNR) is temporal oversampling and averaging, achieved by using the highest feasible Pulse Repetition Frequency (PRF)—the rate at which individual laser pulses are emitted. However, the interval between consecutive pulses must be set to ensure that the light has sufficient time to travel to the end of the fiber and return as backscattered energy to the photodetector before the next pulse is introduced. As a result, the longer the sensing fiber, the lower the maximum PRF to prevent overlapping pulse interference. Given the speed of light in optical fibers, the maximum allowable PRF is approximately 50 kHz for a 2 km fiber and 10 kHz for a 10 km fiber. Despite this reduction in PRF for longer fibers, these sampling rates remain exceptionally high compared to conventional seismic sensors, such as geophones or seismometers, before any temporal averaging is applied.

4 DAS acquisition

Despite being still an emergent technology, DAS already offers great performance and allows for precise real-time strain measurements by turning an optical fiber into a very large number of sensors, therefore providing a cost-effective monitoring solution with **unrivalled spatial resolution** (potentially sub-meter spatial sampling with tens of km long fibers). This makes DAS a very attractive solution compared to conventional point sensors, in particular when traditional sensors are difficult to deploy (e.g. downhole) and when existing fiber network can be leveraged (e.g. telecom fiber originally deployed for telecommunication purposes but not in used, i.e. so-called dark fibers). The compactness, durability, low maintenance, safety and immunity to electromagnetic interference of FO cables are another important aspect making the DAS technology particularly relevant downhole. Another fundamental advantage is the **unrivalled frequency bandwidth** covering mHz to tens of kHz ([109, 84]), something that no other seismic technology can achieve. In brief, DAS offers unprecedented possibilities for real-time remote monitoring over long distances and/or difficult to access terrains. Despite those remarkable benefits, DAS technology also comes with important limitations that are discussed in the present section. Understanding these limitations is crucial for optimizing performance and ensuring the technology meets the specific requirements of an application.

4.1 Gauge Length effect

In contrast to point sensor arrays taking discrete measurements at specific locations, it is important to keep in mind that DAS provide continuous digital measurements along a fiber, with each sampled point representing a weighted average over a specific user-defined distance, called the Gauge Length (GL or L_g in equation 3). This GL governs the spatial resolution (see Figure 3). The GL concept can be compared to the well-know analog group



technique in seismic, when using multiple hard-wired geophones (often referred as string) which are spatially distributed but output a single averaged measurement. This concept has two main advantages:

- firstly, a long group or gauge length, or equivalently a long moving averaging window, can significantly reduce self noise levels (by \sqrt{N} with N being the number of pseudo-sensor within the analog group). This averaging effect can also be beneficial to make the measurement less sensitive to very local "issues" like poor cable-medium mechanical coupling in part of the GL aperture. A clear advantage of DAS versus analog strings, in addition to the cost-effectiveness, is that the gauge length can potentially (IU dependent) be adjusted/changed during the survey, in contrast to analog group type of surveys involving massive field effort to change the geometry in the field.
- Secondly, an analog group length, as well as the DAS GL, results in a spatial filtering, meaning that undesirable type of waves can theoretically be canceled out directly while recording. The GL concept and associated weighted averaging produces notches in the wavenumber spectrum that can potentially be advantageously used if some wavelengths are known to be undesirable, as could be surface waves for example. Note however that whereas such spatial filtering may be crucial with geophone analog strings prone to spatial aliasing (when the group interval is larger than half the minimum wavelength of the wavefield), DAS data are usually so finely sampled in space that it is very unlikely to suffer from any spatial aliasing, therefore enabling noise attenuation during post-processing (e.g. frequency-wavenumber filtering).

The above discusses the potential GL benefit, but it should be noted that ideally any measurement should be made as local as possible, if technically achievable. The fact is that the GL severely impacts the background noise level (generally, longer the GL, better the SNR) and, in practice, its choice/setup is a tradeoff between the magnitude of the targeted signal and its wavelength. Most favorable condition is obviously when targeting long wavelength (e.g. earthquakes), permitting long GL and therefore improved SNR. Note that not all DAS IUs allow to choose the GL, which may be fixed (e.g. to 10 m). In contrast, some IUs enable to collect multiple GLs simultaneously, which can be attractive for comprehensive monitoring of both tiny and long wavelengths, possibly with different frequency rates and at different locations along the FO cable. Note that there is little to gain with very fine spatial sampling with comparatively long GL ([33]) and we globally recommend a spatial sampling of about half the GL, with the latter being set small enough to not attenuate the signal of interest. While coarse resolution means that fine details may be lost, note that point sensors capture precise local values but also miss local variation between these points. DAS measurements remain highly sensitive to local heterogeneities ([142, 88]). Studies such as [125] and ([21]) have shown theoretically and numerically that ground motion gradients such as strain measured by DAS are more affected by small-scale heterogeneities than the ground motions themselves measured by classical seismic sensors.

4.2 Directional strain

It is important to keep in mind that DAS does not provide conventional type of ground motion (displacement, velocity or acceleration), like seismometers or geophones. Instead, DAS outputs strain (m/m or strain rate m/m/s), indicating how the FO cable locally stretches and/or contracts in response to the seismic wavefield. The measured quantity is more closely related to divergence and pressure than true motion/displacement. This leads to challenges for estimating event magnitudes ([83, 131]) for instance.

DAS also provides a single component per location and therefore does not capture the full ground motion vector, unlike conventional multi-component sensors such as seismometers and geophones, which can measure motion in multiple orthogonal directions (e.g., vertical,



north-south, and east-west). The 1C nature of DAS prevents multi-component approaches that can help differentiating wave types based on their polarization, a capability that could be crucial in applications like seismic monitoring, where distinguishing between different wave types (e.g., P-waves, S-waves) and accurately determining wave propagation direction are essential.

In addition, DAS rely on fiber optic cables to capture the dynamic perturbations along their longitudinal axis. This means that DAS is highly sensitive to motion parallel to the fiber but significantly less responsive to perpendicular or transverse motions ([69]). Therefore, the directionality of the DAS response depends on the fiber configuration. The directional response of DAS with respect to the angle of incidence Γ can be found by transforming the strain tensor components using geometric considerations. For a longitudinal (P) apparent wave, the DAS azimuthal response is given by $\cos^2\Gamma$, and for a transverse (S) wave by $\sin\Gamma\cos\Gamma$ (see Figure 5). Detailed analysis for surface waves such as Rayleigh and Love waves can be found in [91].

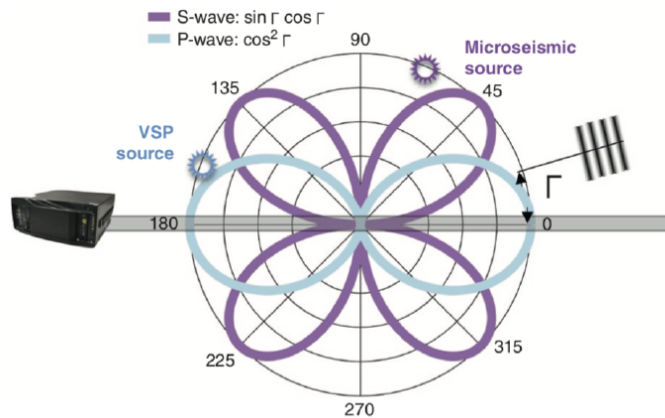


Figure 5: DAS directionality, resulting in high P-wave sensitivity propagating along the cable and S-wave propagating at 45 deg. Source [78].

This directionality issue poses challenges in applications where omnidirectional sensitivity is required. For instance, in seismic monitoring, DAS may struggle to detect certain types of seismic waves depending on the fiber's orientation relative to the wavefront. This is the case for vertically incident P-waves recorded with a FO cable at the surface. For reflection imaging from the surface, the relatively poor ability to detect off-axis (broadside) vibrations may be a strong limitation. [7] proposed mitigating the problem by drilling multiple shallow upholes, a quite costly approach. As a consequence, the implementations of DAS in surface seismic have mainly focused on the estimation of near-surface shear-wave velocities from surface-wave signals with either active or passive sources. Examples of the use of DAS with passive sources utilizing interferometry techniques for shear-wave velocity inversion are shown in [37], [2] and [133], whereas active-source implementations include, e.g., [126] and [26]. Research efforts to address the above mentioned issues are discussed in section 7.

4.3 Ground-to-Fiber Coupling

In DAS studies, it is commonly assumed that fiber optic cables are uniformly and rigidly coupled to the ground. However, this assumption does not always hold, which can significantly influence the quality of DAS data ([95, 69, 2]). The issue of ground-to-fiber strain transfer in DAS was first explored in vertical seismic profiling experiments, where variations in data quality were observed depending on whether the fiber was free-hanging, clamped, or



grouted within oil and gas wells ([99, 97, 100, 87]). The best practice seems to be cementing fiber behind casing for permanent monitoring (see section 4.4).

Horizontally trenched direct-buried fiber, including telecom (or dark) fiber, presents challenges at least as complex as those found in vertical installations ([37]). Several factors contribute to coupling variability, such as cable packing configuration, deployment method (conduit versus direct burial), conduit material, fiber-to-conduit contact, conduit occupancy, and trench depth ([83]). For surface deployments, coupling conditions can be further affected by environmental factors, including vegetation, uneven topography, and variations in soil composition. Consequently, coupling in such installations is often non-uniform and generally sub-optimum, even using sensing dedicated FO cable. [47] discusses inadequate coupling and the associated degradation on data quality. Assessing the coupling between the cable and the surrounding medium is not trivial but can be essential as it directly influences the fidelity and sensitivity of the measurements. Poor coupling can lead to signal attenuation, distortion, or loss of high-frequency content, which in turn reduces the DAS effectiveness for detecting and characterizing events. One approach to assess coupling quality is through analysis of the recorded signal amplitude and frequency content. Well-coupled fiber sections typically exhibit higher amplitude responses and broader frequency spectra, while poorly coupled segments show diminished signals, particularly at higher frequencies. Additionally, examining the spatial coherence or correlation of signals between adjacent fiber channels can reveal inconsistencies; abrupt changes or loss of coherence may indicate zones where the fiber is not in good contact with the medium, such as slack or free-hanging sections. The analysis of a distant earthquake can be considered as the long wavelength pseudo-vertically incident plane wave illuminates the whole fiber quasi instantaneously. Coupling may also be assessed by comparing DAS measurements with data from colocated reference sensors such as geophones or accelerometers. Discrepancies in amplitude, phase, or arrival time between these systems may point to coupling issues. Active-source tests, such as surface vibroseis or perforation shots, provide another potential approach as they introduce controlled energy into the formation. A well-coupled fiber should detect these signals clearly and consistently along its length, while poorly coupled sections will exhibit reduced or incoherent responses. Furthermore, variations in the DAS noise floor and background signal characteristics can indicate coupling quality, as poorly coupled sections often show elevated or irregular noise levels. In brief, evaluating the quality of fiber-to-medium coupling is challenging but can be undertaken by combining signal analysis with installation information and calibration tests. Globally, and as discussed in Section 7, further research is needed to fully evaluate the impact of coupling conditions on DAS data integrity/fidelity.

4.4 Practical considerations

Existing infrastructure: Utilizing dark fibers, when available, is highly convenient and remains the most cost-effective option. However, since these cables were originally deployed for telecommunications rather than sensing applications, their performance may be suboptimal, particularly in terms of coupling efficiency. Despite these limitations, numerous studies have demonstrated the feasibility of extracting valuable data from such fibers, for example in urban areas (e.g. [37, 2]). It is important to note that accurately determining the cable geometry, usually through tap tests, is typically essential to establish the precise mapping of DAS channels.

Surface deployment: In general, it is recommended to use a trenching machine to excavate a shallow trench, followed by backfilling and compacting after cable installation. [103] presents DAS data acquired at varying depths and concludes that deep trenching is unnecessary. A depth of a few centimeters appears sufficient to ensure good coupling while preventing external factors such as wind to impact the data. However, a depth of few tens of centimeters is likely preferable to reduce the risk of potential damage caused by external



activities.

Downhole installation: In boreholes, the deployment of fiber-optic cables has a crucial role. A common practice involves embedding the cables within casing strings and securing them through cementing. This approach not only reinforces the structural stability of the installation but also enhances the reliability of DxS data by improving coupling and reducing noise and potential degradation [102]. Encasing the cables in cement behind the casing serves as a protective shield, safeguarding them from corrosive fluids, abrasive materials, and external environmental stresses that could otherwise impact the performance and longevity of the monitoring system [72]. To further protect fiber-optic cables, oriented perforation techniques may be utilized during well-completion processes. Advanced tools, such as ultrasonic downhole systems can help precisely align perforations, minimizing the risk of damage to the embedded cables. This approach mitigates potential issues related to mechanical stress, fluid flow dynamics, and external interferences, helping to preserve cable integrity throughout the well's operational lifespan [11]. Temporary installation can be considered with cable(s) strapped to wirelines. The integration of these techniques creates a robust and durable framework for obtaining precise and continuous data on essential subsurface parameters, such as temperature, pressure, and strain, through the DxS technology. Figure 6 illustrates the high spatial density of DAS compared to conventional point sensor arrays.

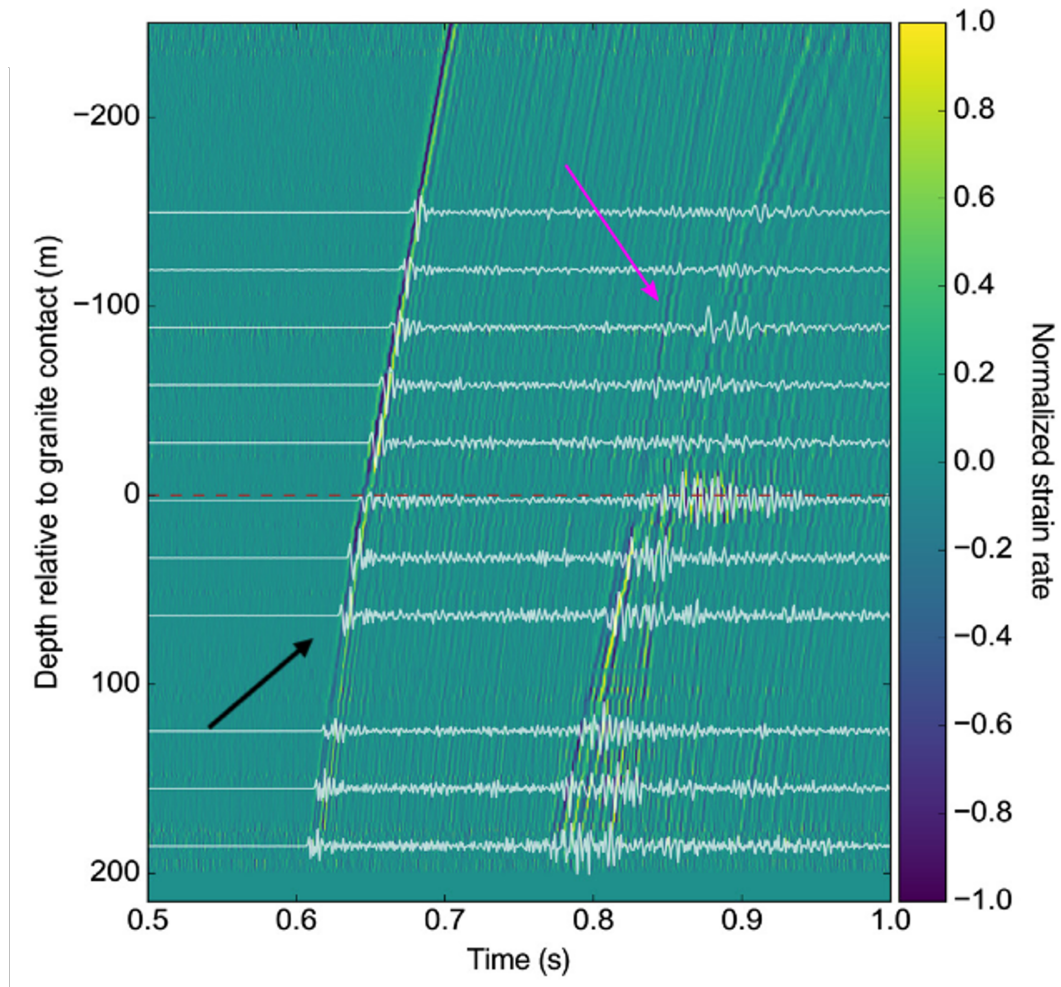


Figure 6: Comparison of DAS data with a geophone array, showing convincing correlation of the microseismic event, both P (black arrow) and S phases (pink arrow) recorded at FORGE (Utah). DAS provides $\approx 100\times$ higher spatial resolution. Source: [75].

5 Applications of Distributed Acoustic Sensing (DAS)

Seismic acquisition and processing using DAS have undergone significant advancements in the past decade. DAS has increasingly become a cost-effective and widely adopted tool for subsurface monitoring, playing a critical role across a wide range of applications ranging from urban seismology [37, 127, 128, 150] to glacial studies [15, 16, 17, 41, 54], volcanology [30, 63, 67, 108], and regional and local earthquake monitoring [13, 14, 64, 65, 80, 86], among many other fields. Here we mainly focus on key energy related applications, geothermal and Carbon Capture and Storage projects, both critical for mitigating climate change.

5.1 Active Seismic

DAS has found widespread use in active seismic applications, especially in borehole seismic surveys for VSPs [99, 8, 32, 95, 42]. VSPs are particularly well-suited for DAS surveys, as the seismic wave angle of incidence is often aligned with the optical fiber, especially in zero-offset VSPs [34]. Vertical fiber-optic cables can be used effectively for these surveys,



enabling repeated measurements with permanent installation. These installations can be placed on production tubing [97], cemented behind casing [32], or potentially installed using temporary cables such as those strapped to wirelines. DAS has also proven successful in subsea VSP applications, where it has demonstrated the ability to provide enhanced seismic illumination and higher-frequency data.

DAS now demonstrated great promises in the CCS context, to monitor the eventual CO_2 plume migration and ensure safe storage. Assessing the integrity of caprocks, which serve as the sealing layers above CO_2 storage sites, is crucial to prevent leaks. While clays and shales are typically considered ideal caprock materials due to their low permeability and self-sealing properties [19, 44], tectonic faults or reactivated fractures may still pose risks, potentially inducing microseismicity (e.g. [1, 132]). Monitoring subsurface changes and fault behavior is essential, and seismic techniques such as crosswell surveys or VSPs have proven to be invaluable tools for imaging subsurface velocity structures (e.g. [44, 132]).

The DAS integration into crosswell seismic acquisition has demonstrated significant potential for enhancing subsurface imaging. Recently, [102] has shown that DAS can provide superior spatial resolution and repeatability compared to traditional seismic methods. This is particularly beneficial for applications requiring high-resolution subsurface delineation, such as CO_2 sequestration, hydraulic stimulation surveillance, and geomechanical studies. One of the main advantages of DAS is its ability to improve the coverage and efficiency of surveys, with the potential to reduce the need for additional monitoring boreholes ([68]), leveraging the high density data through the fibers cemented outside the casing.

The successful implementation of DAS in both VSP and crosswell seismic surveys paves the way for more precise monitoring of subsurface properties, enhancing our understanding of fault behavior, reservoir dynamics, and induced seismicity, particularly in the context of CO_2 injection and other subsurface operations [102].

Note that fluid injection does not always lead to seismicity. Some deformation may occur aseismically [44], therefore underlining the potential of the DSS or Low-Frequency LF-DAS technology to monitor those deformations, track fault behavior and therefore assess the integrity of storage sites (e.g. [38, 18, 110]).

Another advantage is that DAS can also be applied to monitor production and injection wells in real time. By attaching fiber-optic cables to the production tubing, DAS provides valuable insights into **well integrity**. These measurements can be used to detect leaks, monitor valve performance, and assess liquid levels in the annulus [46]. LF-DAS measurements have proven particularly useful for understanding the dynamics of pressure and flow within wells. However, because pressure effects are often coupled with temperature changes, quantitative data analysis remains challenging, hence the need for a comprehensive DFOS solution to also monitor absolute temperature, via DTS.

In brief, what started as a testing phase a decade ago [96, 151] has now transitioned into large-scale deployment for multiple purposes. This shift has been driven by the oil and gas sector [40, 50, 4], the growing need to monitor geothermal sites [75], as well as CO_2 sequestration projects [28, 51]. Leveraging the robustness of FO cables and their permanent installation, DAS proved its capability to track sub-surface changes over time, providing valuable time-lapse (4D) data with high repeatability (e.g. [27, 157, 140]), which is fundamental in geoenery applications.



5.2 Passive Seismic

The typical goal of passive acquisition is to extract accurate event locations, magnitudes, and source mechanisms from continuous wavefield recordings. Knowledge of such parameters is key for surveillance and diagnostic characterization of induced seismicity both in the context of the development of the reservoir connectivity (e.g., reconstruction of spatiotemporal fracture development) and for safety protocols and risk governance ([23, 45, 39, 139]). DAS application during hydraulic stimulation is discussed in, e.g., [6], [65], [9].

Microseismicity monitoring using DAS has emerged as a transformative technology, particularly in geothermal systems induced seismicity detection. The high spatial resolution and dense coverage offered by DAS provide unique advantages over traditional geophone-based systems. While traditional continuous monitoring relies on permanent surface networks and borehole geophone arrays, DAS presents a cost-effective alternative that enhances spatial coverage and detection capabilities [70]. Downhole, a significant advantage compared to conventional seismic sensors for **microseismic monitoring** in geothermal reservoirs lies in the FO ability to operate in high-temperature environments where standard electronic equipment fails. The FO cables not only resist to corrosion [115], they can also withstand reservoir conditions up to 300–400°C (depending on the fiber coating materials, [98]).

DAS-installed seismic cables at reservoir depths therefore provide ideal conditions for subsurface investigations during stimulation and utilization, offering reduced source-receiver distances, thus maximizing detection capabilities. While early implementations in borehole settings underperformed compared to geophones (leading to fewer detections and greater location errors ([55, 143]), the improved technology and deployment practices now allow for the recording of more microseismic events than traditional sparse geophone arrays ([75, 74, 130]). Downhole DAS deployments have proven effective in monitoring microseismicity during hydraulic stimulation operations in the proximity of the well being stimulated, potentially outperforming a surface-based regional seismic network by an order of magnitude ([77]).

A potential limitation for event location estimation is the cylindrical symmetry of the measurements which results in azimuthal ambiguity ([66]) but this can be mitigated with multiple boreholes and/or sensing at the surface. In the latter case, dark fiber can be very convenient, potentially offering a vast and dense network to measure induced seismicity and potentially trigger warnings. Using dark fiber at the surface, [58] recently reported the detection of magnitude down 0.4 with limited number of false alarms, despite the high anthropogenic activities along the fibre optic path.

New processing techniques have been proposed across several different fields of application. For example, the PoroTomo DAS array at Brady Hot Springs geothermal field in Nevada has provided a rich DAS dataset and testbed for template matching techniques ([81]), evaluation of beamforming potential in DAS data ([138]), as well as subsurface mapping and seismic event monitoring ([111]). Template matching and beamforming have also been used for earthquake aftershock detection ([80]) and small earthquake detection at regional distances ([104]). Recently, a fast semblance-based seismic event detection method was proposed, leveraging waveform coherence to overcome high self-noise in DAS data [113].

LF-DAS has enabled detecting hydraulic stimulation induced strain fluctuations that originate from the treatment well and reach the monitoring fiber well ([62, 118, 136, 59, 156]). These so-called frac-hits help characterizing the fractures extend. Additionally, LF-DAS data may provide insights into fracture behavior, indicating when fractures open (extension at fractures with surrounding compression) and when they close (extension zones around fractures) due to fluid leak-off after injection. Instead of connecting located events, another technique to map induced fractures could be reflection imaging, using microseismic events as sources of energy ([46, 117, 82]). Such imaging is not common, probably because it is diffi-



cult to see reflected waves in the microseismic data acquired by sparse and distant geophone arrays. It is therefore an area where DAS could have a strong impact. Recent advancements in machine learning (ML) have enabled improved event detection [57, 56], classification [29], and seismic arrival-time picking. [155] for example proposed a semi-supervised deep-neural-network-based model tailored 2D spatio-temporal DAS data for enhanced phase picking accuracy (PhaseNet-DAS, an extension of PhaseNet).

Distributed Acoustic Sensing (DAS) data typically exhibit a lower signal-to-noise ratio (SNR) compared to conventional geophones [55]. Various sources contribute to this noise, including imperfect coupling, even in wellbore applications. Since DAS technology generates massive datasets, employing efficient denoising strategies is crucial to enhance the detectability of small seismic events. **Traditional seismic denoising methods** have been employed to suppress unwanted signals while preserving the integrity of seismic data. Standard preprocessing techniques, such as bandpass filtering, can be applied if the noise does not overlap with the signal of interest. Given that DAS are inherently spatially unaliased, denoising methods can extend into two-dimensional frequency-wavenumber (FK) filtering, allowing for the selective attenuation of certain propagation velocity ranges. However, FK filtering assumes a linear fiber geometry, making it less effective for curved installations. Alternative domains, such as wavelet [3] and curvelet [20] transforms, have been employed to enhance seismic data by applying thresholding functions to remove undesired noise components. Some of these methods have been adapted specifically for DAS data. For instance, [76] applied median and low-pass filters to improve SNR, while [12] utilized a dip filter to suppress vertical and horizontal noise. [149] leveraged sparse transformation techniques to mitigate coupling noise introduced by instrumentation. Additionally, combining bandpass FK filters with structure-oriented median filtering [24] has proven effective, particularly in handling curved move-outs in non-linear DAS arrays. Despite their success, conventional denoising methods often struggle with DAS data due to their complexity and volume. The enormous size of DAS datasets poses computational challenges, and traditional techniques may result in signal leakage or fail to generalize well across different noise types.

With the increasing computational power available, **machine learning (ML)** has emerged as a promising alternative for DAS denoising. Deep learning models, particularly those leveraging convolutional neural networks (CNNs) and self-attention mechanisms, have shown significant potential in improving the SNR of DAS data ([120]). Supervised learning approaches have been widely explored for denoising. [36] proposed an adversarial denoising network to retrieve weak DAS signals while attenuating noise. Similarly, [25] developed a multiscale recurrent self-attention network for reducing background noise in vertical seismic profile experiments, while [146] introduced a multiscale fusion attention network to enhance DAS data quality. Other CNN-based approaches, such as those by [79] and [148], utilize attention mechanisms and dense residual networks to tackle complex noise types. [152] demonstrated CNN-based strategies for mitigating coupling noise in DAS recordings.

One major drawback of supervised deep learning models is their reliance on large labeled datasets, often requiring synthetic training data, which may lead to generalization issues. To address this, self-supervised and unsupervised learning strategies have gained traction. For example, [138] demonstrated the effectiveness of a self-supervised U-Net [119] for DAS denoising. [71] extended self-supervision by leveraging co-located optic fibers that share seismic signals while exhibiting uncorrelated instrumental noise. Additionally, [15] exploited two-way cables in borehole installations to improve signal reconstruction.

Recent advances in computer vision have further influenced DAS denoising. Inspired by masked image modeling [52], [124] utilized masked autoencoders to achieve impressive noise suppression (see Figure 7). Another innovative self-supervised approach was proposed by [147, 153], incorporating an unsupervised learning framework based on continuous wavelet transform (CWT). This method allows a deep learning network to iteratively refine DAS sig-



nals without requiring labeled training data. By filtering in the wavelet domain, the model adapts its parameters dynamically, balancing noise suppression with signal preservation. Although ML-based denoising techniques demonstrate great promise, they still involve trade-offs between noise reduction and signal fidelity. The rapid progress in ML and signal processing techniques continues to drive innovation, improving the robustness and efficiency of DAS denoising strategies. Integrating DAS into the standard seismic monitoring systems is becoming a reality ([94]), with real-time automated event detection being enabled in standard tools like SeiscomP.

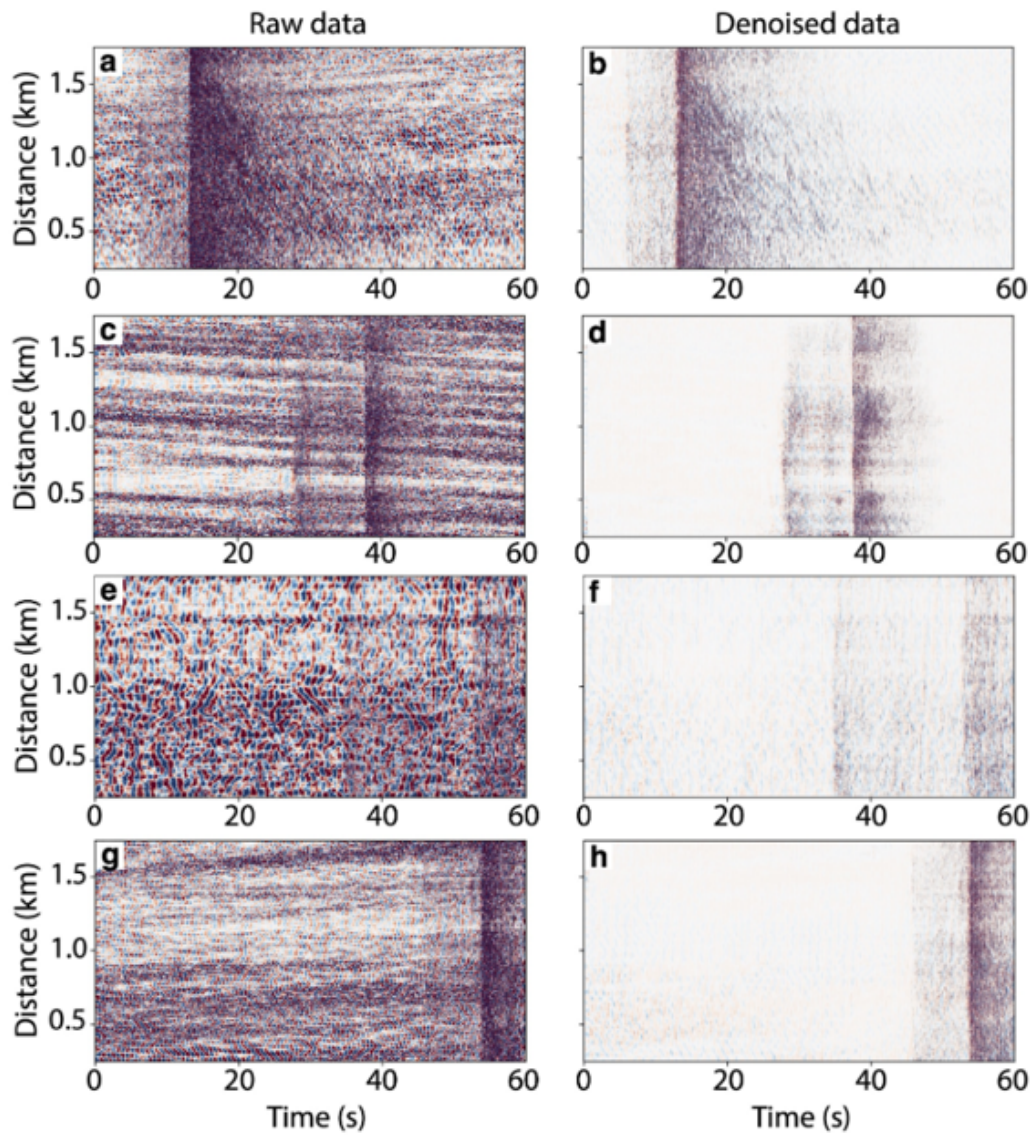


Figure 7: Example of impressive denoising results (source: [124]). All images are plotted using the same color scale



6 Swiss DAS landscape

6.1 Swiss dark fiber network and key players

Switzerland possesses a substantial fiber-optic network infrastructure that can be adapted for DAS applications. With the convergence of telecom, energy, and transport networks, the total fiber length for sure exceeds 5000 km and therefore provides a wide range of opportunities (potentially across lakes) for advanced monitoring and real-time sensing, making DAS a promising solution for multiple applications. These networks are typically employed for operational purposes, but with the owner/operator (e.g. Swisscom broadcast) agreement, a large portion of this infrastructure could be repurposed for continuous, real-time monitoring, among others of geothermal activities.

There are two main DxS related swiss companies. **Omnisens**, based near Morges, offers product and services for continuous, reliable monitoring mainly for energy industry assets (e.g. pipelines and power lines). They can provide a range of solutions for early detection and location of events which may threaten the integrity of an infrastructure, using the whole DxS family, i.e. Raman DTS, Brillouin DSS as well as Rayleigh DAS. They operate throughout the world, either directly or through specialized solution providers, via dedicated application, commissioning and customer service teams (<https://www.omnisens.com/presentation.html>). They quite focus on long-distance fiber optic sensing for real-time asset integrity monitoring solutions, less on geophysics and subsurface imaging/characterization. The other key player is **Solifos AG**, a supplier of fiber optic cabling and associated systems for demanding applications (<https://solifos.com/en/about-solifos/>). They can deliver customized solutions to fit specific customer needs, including all type of DxS enabling cables. As a consequence, their FO cables enable a broad number of applications in sensing and communications across various research and industry sectors including defense, energy, infrastructure and telecom. **Marmota Engineering AG** is another Swiss company focusing on fiber-optic sensing solutions (e.g. boerhole installation), mainly for geotechnical applications.

From a research point of view, Distributed Fiber Optic Sensing has gained significant traction in recent years at **ETH Zurich** and in the field of geophysics with the establishment of the **FOSlab** (<https://foslab.ethz.ch/> under construction). This initiative, supported by multiple groups in the Institut of Geophysics, highlights the growing importance of DFOS technologies in advancing scientific research in general and seismic monitoring in particular. FOSlab primary objective is to contribute to the development/implementation of fiber-optic sensing technology and establish its potential in various contexts via pilot tests and the development of appropriate tools, for instance at SED, where seismic monitoring is carried out on cantonal mandates to support cantons to fulfill their regulatory oversight duties, e.g. via the GEOBEST2020+ initiative funded by the Swiss Federal Office of Energy (SFOE). FOSlab is involved in most activities below.

6.2 Main DAS projects in Switzerland

The pilot and demonstration project **CITru** (CO_2 pilot injection in Trüllikon), led by ETH Zurich and supported by the Federal Offices for Energy and Swisstopo together with the Canton of Zurich (among others), is examining the feasibility of a CO_2 injection test through a disused borehole in the municipality of Trüllikon (ZH). The exploration phase of CITru started in autumn 2024. It includes in-depth investigations of the local subsurface at a depth of over 1,000 metres using seismic measurements, computer simulations of various feed-in scenarios and the distribution of CO_2 at depth, as well as detailed risk assessments. DAS, in a first stage (March 2025), will be utilized for a preliminary VSP experiment. At the time of writing, succesfully acquired data analysis is ongoing. If the project proves to be sufficiently safe, environmentally friendly and financially viable after completion of the



exploration phase at the end of 2025, the implementation phase would start, with the whole DxS technology becoming a crucial comprehensive monitoring tool.

The **Bedretto Underground Laboratory for Geosciences and Geoenergies** is a research infrastructure of ETH Zurich in which DxS plays an important role ([112]). Equipped with state-of-the-art technology, the tunnel (5.2 km long, 1.5 km below the surface) and its multiple boreholes offers ideal conditions for studies focusing on the behaviour of the deep underground to gain new scientific knowledge in areas such as earthquake physics and geothermal energy for instance via controlled mesoscale in situ experiments to further improve our understanding of hydro-seismo-mechanical processes taking place in fractured crystalline rock masses ([90]). [135] demonstrates that the application of borehole-deployed DAS in monitoring hydraulic stimulation can provide additional constraints on the location and source characteristics of the larger seismic events. The recorded strain rates of the detected events could be used to fit a local DAS-based magnitude (M_{DAS}) that aligns well with the local geophone-based magnitudes, emphasizing that although DAS detection sensitivity is lower than the Acoustic Emission sensors, it can be used to obtain a similar catalog of larger-magnitude events with the advantage of a high location accuracy. Findings from the BedrettoLab illustrate the feasibility of using DAS for high-resolution microseismicity monitoring, with detected events of magnitude as low as $M_w - 2.5$. Scaling up from the BedrettoLab to larger operational settings, where seismic monitoring typically depends on sparse borehole sensor networks and larger stimulation volumes produce higher-magnitude events, borehole-deployed DAS could be a valuable addition to monitoring systems. It can enhance event detection and localization while also providing magnitude estimates and source moment tensor analysis.

The **Mont Terri Rock Laboratory** is another underground research facility in Switzerland. It is dedicated to studying the geological, hydrogeological, geochemical, and geomechanical properties of the Opalinus Clay formation. Its primary research objectives focus on evaluating the feasibility and long-term safety of deep geological storage of radioactive waste, as well as advancing underground construction techniques, CO_2 storage, and deep geothermal energy applications (Bossart et al., 2018). DFOS plays there an important role with high-resolution DAS and DSS measurements, allowing scientists to investigate rock behavior under various stress conditions and simulate repository conditions.

DAS capabilities are also assessed at ETHZ ([70]), with the analysis of the seismic cluster recorded 3km east of the **Frontier Observatory for Research in Geothermal Energy (FORGE)** site, Utah, in collaboration with, among others, Geo Energy Swiss (GES). They show that downhole DAS data quality allows the detection of very low-magnitude earthquakes several meters or kilometers from the well, with advanced relocation techniques (HADES-R, [134]) enabling to retrieve the shape of out-of-network clustered seismicity across scales, to produce more accurate depths as well as uncertainty distribution. To avoid azimuthal ambiguity, they show that even a slight deviation of the wells can greatly aid in the recovery of robust locations, supporting the employment of longer-term experiments to keep exploring downhole DAS suitability for continuous passive microseismic monitoring.

Another interesting DAS implementation was initiated in fall 2023 in Vaud near Eclepens, in the context of the **GeoCogen geothermal project** driven by Swiss Geo Energy (SGE) and subsidized by SFOE. 16 km of dark fiber following a pipeline could be interrogated during a 3D seismic campaign covering 104 km². The main purpose was to gain technical insight into the use of the technology in the geothermal industry, by assessing the quality of acquired DAS data using preinstalled telecommunication FO cables and determine the sensitivity to microseismic events for future continuous monitoring (Hirsch et al., 2025, in prep for Swiss Bulletin for Applied Geology). More than 13 thousands vibroseis shots were recorded as well as modest (1kg) quarry blasts, as a proxy for induced microseismicity. This experiment



further emphasized the directional limitation of DAS, with relatively poor sensitivity to the wavefield propagating perpendicular to the fiber. Quarry blast signals could however be captured over more than 10 km over the fiber. In addition, a 40 km distant earthquake, occurred near Saint (VD) on the 23rd of October 2023 at 17:29:35 with magnitude 1.3) could be identified over the entire fiber length. The signal was detected through the Swiss Seismological Service (SED) database, but this observation highlights the promising future of the DAS methodology in induced microseismic monitoring, in particular for enhanced coverage using offshore FO cable under Swiss lakes. Technical developments/implementation are under way at SED to integrate DAS data into the national seismic network, with tremendous progress since fall 2023.

7 Perspectives

As demonstrated by the exponentially growing body of literature and the increasing number of projects utilizing DxS technologies, the question is no longer whether it holds promise, but rather how quickly and to what extent it will revolutionize various fields of geophysics. DAS in particular introduces a paradigm shift in the acquisition of high-resolution seismic data, with ongoing developments addressing key limitations such as sensing sensitivity, coupling challenges, and the single-component nature of its measurements. Both industry and academia are investing substantial effort into overcoming these challenges, with continuous advancements in laser interrogation techniques (e.g. [93]), signal processing algorithms, and engineered fiber-optic solutions for enhanced backscattering (e.g. [73]). Methods to improve the DAS amplitude-frequency response and convert strain(-rate) measurements into conventional motion are being developed (e.g. [131]). Advances in the theoretical understanding of fiber-optic coupling ([116, 121]) and numerical simulations ([22]) are leading to optimized coupling strategies ([47]). Collaboration with cable manufacturers, such as Solifos AG, could further accelerate progress in this area. Similarly, innovations in cable design, like helically wound fiber structures ([53, 137, 129]) and broadside sensitivity enhancements ([144]) are paving the way for multi-component DAS measurements that may soon provide full strain-tensor information ([60, 61, 106, 107]). Additionally, machine learning applications are increasingly contributing to data interpretation, offering new opportunities for real-time monitoring and predictive analytics.

While DxS technology is evolving quickly, its core components are generally consistent across applications, even though specific interrogators or fiber cables may vary widely depending on the particular use case. This flexibility allows DxS systems to be tailored for a wide range of monitoring applications. As the global community transitions toward sustainable energy solutions, DxS is emerging as a transformative tool, particularly in carbon capture and storage and geothermal energy. The technology can contribute to ensure both operational efficiency, environmental safety, and regulatory compliance. The concept of measurement, monitoring, and verification (MMV) can benefit from the DAS technology to ensure that subsurface conditions are well understood and that operations remain within safe and sustainable parameters. DAS potentially offers an end-to-end framework, covering everything from initial site characterization to long-term surveillance and regulatory compliance. The comprehensive technology may fundamentally redefine conventional MMV methodologies by effectively/seamlessly involving vertical seismic profiling, crosswell seismic imaging, microseismic monitoring, and injection profiling, thereby enhancing reservoir characterization, fracture monitoring, and well integrity assessments, ultimately further optimizing resource extraction and/or sustainability ([72]). The technology, collectively, delivers comprehensive and novel insights into the dynamic behavior and structural integrity of geological reservoirs. This holistic approach bolsters the reliability and safety of geoenergy operations throughout their lifecycle, mitigating risks and enhancing stakeholder trust.

A notable advantage of DAS lies in its cost-effectiveness. DAS presents a compelling eco-



conomic and operational option, particularly in contexts where high spatial resolution and long-term deployment are critical. From a cost perspective, the technology offers a significant advantage: a single interrogator unit, typically priced around 200,000 CHF, can extract data from tens of thousands of virtual sensing points along a single optical fiber, resulting in an effective cost per channel of just a few francs. This is in stark contrast with conventional technologies, where even optimized nodal acquisition systems typically exceed 100 CHF per physical channel. The economic advantages of DAS are further amplified when existing dark fiber infrastructure is available. In such cases, the cost of sensor deployment is reduced to almost zero, as the fiber is already installed. If permitted, this re-use of passive telecom infrastructure enables access to dense, large-scale monitoring networks with minimal additional investment, making DAS uniquely scalable in favorable contexts. Public or private networks running through industrial zones, along pipelines, railways, or highways can thus be leveraged to turn otherwise dormant infrastructure into sensing systems of unprecedented spatial reach. In contrast however, deploying fiber specifically for DAS in areas without existing infrastructure remains a major operational and financial hurdle. In surface installations, the fiber must be properly coupled to the ground and therefore necessitates trenching or plowing, which are both labor-intensive and potentially disruptive. In urban or developed areas, where obstacles such as roads, utilities, or buildings are densely packed, deployment becomes even more challenging. Not only do physical obstructions complicate routing, but the surface impact of trenching may trigger regulatory delays, additional permitting, and substantial cost escalation. As such, self-deployment of fiber in urban or industrial zones is often prohibitively expensive.

The advantages of DAS are especially pronounced in borehole applications. Traditional geophone or hydrophone chains are typically limited to a few dozen sensors, with an instrumented length often restricted to several hundred meters. Acquiring full-well coverage in this context requires the sensor string to be lowered in discrete intervals and repositioned between measurement cycles. This practice not only introduces significant operational complexity. Since repeated shooting effort has to be repeated, the cost of data acquisition increases accordingly. The cumulative cost of equipment, rig time, and specialized personnel can easily exceed several tens of thousands of francs per deployment. By contrast, a cemented DAS cable provides permanent, full-length coverage of the borehole. Once installed, the fiber remains fixed, and no mechanical movement or repositioning is needed to acquire data at any depth. This greatly simplifies operations, reduces acquisition time, and enables efficient time-lapse or continuous passive monitoring without repeated interventions. The absence of downhole electronics further enhances system reliability. In summary, the economic benefits of DAS extend well beyond its initial capital cost. The technology offers exceptional scalability, in particular where dark fiber can be repurposed at the surface, while eliminating the need for the repeated deployment of expensive sensor chains in boreholes.

This economic viability not only streamlines operational costs but also encourages the widespread adoption of DAS across multiple geoenery sectors ([11]). For operators, the whole DxS family presents an opportunity to optimize reservoir monitoring, boost productivity and efficiency, enhance risk assessment, and reduce costs. Regulators focus may be more on the specific DAS technology, with which the most transformative potentials lies in its ability to utilize existing fiber-optic infrastructure, therefore significantly reducing the environmental footprint and cost associated with traditional seismic surveys. This fundamentally alters the landscape of geophysical monitoring. Institutions such as ETH/SED are actively developing real-time DAS integration into its operational seismic monitoring system, addressing challenges in metadata harmonization, and ultimately enabling automatic and manual event detection using standard tools like SeiscomP [94].

The widespread adoption of DAS over existing networks raises opportunities for both operators and regulators. Both could see this infrastructure as a cost-effective mean to expand



seismic monitoring capabilities with reasonable additional investment. Negotiating access to fiber networks and establishing clear legal frameworks will be essential to facilitate adoption. Despite these challenges, the potential of DAS in reshaping geophysical approaches is immense.

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