Review

Application of Distributed Acoustic Sensing in Geophysics Exploration: Comparative Review of Single-Mode and Multi-Mode Fiber Optic Cables

Muhammad Rafi 1,2,* , Khairul Arifin Mohd Noh 2, Abdul Halim Abdul Latiff 1, Daniel Asante Otchere 3, Bennet Nii Tackie-Otoo 1, Ahmad Dedi Putra 1, Zaky Ahmad Riyadi 1 and Dejen Teklu Asfha 1

1 Centre for Subsurface Imaging, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Malaysia; bennet.tackie@utp.edu.my (B.N.T.-O.)
2 Department of Geosciences, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Malaysia
3 Institute for Computational & Data Sciences, The Pennsylvania State University, University Park, PA 16802, USA; dao5333@psu.edu
* Correspondence: muhammad_22011458@utp.edu.my

Abstract: The advent of fiber optic technology in geophysics exploration has grown in its use in the exploration, production, and monitoring of subsurface environments, revolutionizing the way data are gathered and interpreted critically to speed up decision-making and reduce expense and time. Distributed Acoustic Sensing (DAS) has been increasingly utilized to build relationships in complex geophysics environments by utilizing continuous measurement along fiber optic cables with high spatial resolution and a frequency response of up to 10 KHz. DAS, as fiber optic technology examining backscattered light from a laser emitted inside the fiber and measuring strain changes, enables the performance of subsurface imaging in terms of real-time monitoring for Vertical Seismic Profiling (VSP), reservoir monitoring, and microseismic event detection. This review examines the most widely used fiber optic cables employed for DAS acquisition, namely Single-Mode Fiber (SMF) and Multi-Mode Fiber (MMF), with the different deployments and scopes of data used in geophysics exploration. Over the years, SMF has emerged as a preferred type of fiber optic cable utilized for DAS acquisition and, in most applications examined in this review, outperformed MMF. On the other side, MMF has proven to be preferable when used to measure distributed temperature. Finally, the fiber optic cable deployment technique and acquisition parameters constitute a pivotal preliminary step in DAS data preprocessing, offering a pathway to improve imaging resolution based on DAS measurement as a future scope of work.

Keywords: fiber optic technology; distributed acoustic sensing (DAS); single-mode fiber (SMF); multi-mode fiber (MMF)

1. Introduction

Subsurface imaging is a crucial aspect of geophysical exploration that involves characterizing the subsurface properties, which frequently contain essential information that can be utilized for hydrocarbon exploration and event detection. Seismic and reservoir monitoring activities offer geophysicists an array of data sources that can be examined to extract essential details regarding the attributes and physical properties. The data furnished by these sources can establish a connection with subsurface physical attributes, either individually or synergistically. Other commonly used methods include well logging for sonic and gamma-ray log for the characterization of reservoirs [1]. However, certain data interpretations encompass intricate and non-linear characteristics. Seismic data provide detailed images of structural features present in the subsurface with high imaging resolution, but their acquisition work is associated with high costs [2]. The information obtained from these data sources can be interpreted quantitatively in terms of subsurface
physical properties to provide pivotal information. The engineering sector has developed complex time- and cost-effective methods to infer geophysics measurements from seismic and fiber optic technology. The oil and gas sector has been recognized as one of the major players in adopting DAS technology to replace geophones in VSP, geophysics exploration in applied machine learning (ML), and the monitoring of reservoir integrity and imaging performance [3]. Numerous documented advantages of fiber optic technology surpass those of conventional empirical correlations within the scope of geophysics exploration through DAS [4,5]. The main reasons for these advantages of DAS include that it is a valuable tool in geophysics exploration, offering improved performance, reliability, and versatility compared to conventional empirical acquisition tools such as geophones [4].

DAS appears as an advanced seismic technology that utilizes fiber optic cable along the measurement length to detect acoustic waves. This makes it useful for continuous sensing, with the ability to perform real-time monitoring. This real-time monitoring of fiber optic cables by DAS helps achieve savings in terms of finances, time, and equipment. An elevated and refined subsurface imaging process necessitates a substantial and sustained level of resolution for further analysis and interpretation. This resilience serves to mitigate potential losses in terms of human resources and investments [6]. Over the past two decades, DAS has been utilized with typical fiber optic cables made of two important parts, namely a silica glass core and silica glass cladding. The two major types of fiber optics used for DAS applications are SMF and MMF [7]. This review focuses on these fiber types.

Over the years, SMF has evolved as a type of fiber optic cable in DAS systems for various applications and is commonly used in subsurface seismic monitoring. The most widely used technique for SMF employed in DAS is the detection principle of Rayleigh backscattered light. This technique enables distributed strain sensing, where the fiber optic cable itself acts as the sensing element in DAS. This allows for the detection of acoustic frequency strain signals over large distances [8]. This capability of DAS can be applied to address various applications requiring distributed strain sensing [9]. Some advantages of using SMF is that it reduces signal dispersion and external interference, and SMF with a single light input can reduce light scattering. On the other hand, the main disadvantage of SMF is the presence of tighter tolerances that create coupling light due to the smaller size of the fiber core [3,10].

According to Bisyarin et al. (2017), the revolution in fiber optic sensing technology has brought about a paradigm shift in distributed multi-parameter acquisition, accompanied by applications that harness its potential [11]. This distributed sensing technology has been effectively applied in many industries and has attracted interest from industry practitioners all over. MMF has been effectively implemented in reservoir environments to monitor and enhance VSP. The use of fiber optics for VSP surveys for optimum data enhancement has evolved into a reasonably established application for DAS [12,13]. Some merits of these fiber optic technologies include their capability within a narrow instrument deployment, offering distinct advantages, such as small size, light weight, immunity to electromagnetic interference (EMI), and embedding capability [14–17]. Therefore, in this paper, we provide a comprehensive comparative review of the use of SMF and MMF in geophysics exploration. The literature research used in this review is dependent on the type of geophysics exploration conducted, mostly focused on the deployment of fiber optic cables, as well as their performance and measurement efficiency, amongst other parameters. This comparative review also considers the ML approach using data acquired from both types of optic cable.

1.1. Aim and Scope

Currently, there is no specific comparative review regarding the performance of these fiber optic cables based on DAS measurement and the desired output within the scope of relevant geophysics exploration. Hence, the primary objective of this review is to provide a comparative overview of the relative performance and evaluation of SMF and MMF in geophysics exploration based on VSP, reservoir monitoring, and microseismic event
detection in terms of ML processing. Accordingly, this review presents a comparison of SMF and MMF in terms of acquisition factors like spatial resolution, cable deployment method, and measurement result particularly tailored to the applications. The advantages and limitations of using SMF and MMF for subsurface imaging in DAS measurement are also highlighted, as each cable type has certain advantages. The pertinent information regarding their comparative performance will help in the selection of suitable fiber optic cables for deployment in DAS data acquisition for future geophysics exploration research. The combined deployment of SMF and MMF cable for subsurface imaging is also reviewed to distinguish the utility of each cable when deployed in the same fiber optic cables. This review also aims to enhance the application of SMF and MMF in geophysics exploration when DAS data acquisition is applied for each type of fiber optic cable using an ML algorithm, as it provides the best choice in terms of improving prediction, minimizing error, and generating a high-accuracy model for geophysics exploration.

This paper comprehensively reviews the application of fiber optic cables in DAS paradigms, assessing their effectiveness and potential for subsurface imaging over conventional geophysics exploration methods such as seismic and VSP geophone applications. The literature forming the foundation of this review was selected based on a search of various geoscience and electrical engineering academic databases, such as Geoscience World, Society of Exploration Geophysics journal, and IEEE Xplore. Accordingly, we used specific keywords, which include SMF, MMF, and specific applications in geophysics. Based on the literature search conducted for this review paper, most of the SMF and MMF geophysics applications are DAS VSP or fiber optic cables deployed along the wellbore instead of surface DAS. Therefore, most of the reviewed papers discuss DAS VSP. The innovation of enhancing the fiber optic cable data efficiency of these DAS data processing frameworks through an ML approach is also reviewed. This review also present the conclusions of our comparative study, as well as possible routes for the future development of optimized DAS data for various applications in geophysics exploration.

Other types of fiber optic cables, like Few-Mode Fiber (FMF), are also applicable as a sensing medium in optical fiber sensing [18]. FMF cable has the advantage of having a higher nonlinear threshold level, as well as a higher capture fraction for scattered light [11]. However, FMF can have larger splicing loss compared to SMF, which can negatively impact its performance and might cause coupling between modes, which can degrade its performance in DAS systems, although it can be useful for other applications [19]. The selection of these two fiber optic cable types stems from the fact that SMF is the most utilized in DAS acquisition, whereas MMF has lower consumed costs associated with its devices and components that are installed during acquisition; furthermore, the coupling light input of MMF requires less stringent tolerances, corresponding to its distributed temperature sensing (DTS) ability [12].

1.2. Brief Explanation of DAS

The adoption of fiber optic technology to address subsurface monitoring problems has gained significant traction across various industries, including the petroleum sector. While most studies published using DAS as fiber optic technology have focused on fibers deployed in wells, several studies have explored oil and gas production and CO₂ sequestration. The implementations reported in these studies were designed for microseismic monitoring during hydraulic fracturing [20,21], repeatable VSP imaging [10,22,23], or fluid flow monitoring through production [10]. A notable discovery from this research indicates the significance of installation techniques; cables securely clamped to the well’s side exhibited superior performance compared to loosely laid straight fibers, and cables embedded in cement outperformed clamped cables [22]. Ideally, geophysicists should be able to use a dense array of high-resolution, multi-component receivers. However, the deployment and sustainable maintenance costs of such an array might be difficult, particularly in crowded areas where permitting permission is more challenging to maintain and theft and damage to sensors are more significant concerns. In terms of these objectives, the fiber optic cable
deployment methods exhibited substantial variation, with less emphasis on standardizing installation techniques for diverse near-surface and shallow seismic recording objectives due to the high-spatial-resolution advantage compared to more concerted efforts among geoscientists engaged in downhole seismic recording [24]. Fiber optic cables can be effectively buried within a trench or even placed within an existing telecommunications conduit, mitigating potential permitting issues. Trenching burial for surface DAS measurement is the most common deployment of fiber optic cables to increase coupling with the ground due to its measurement sensitivity [7].

DAS applications for subsurface imaging have undergone great development due to the improvements in geophysics exploration, starting from the year of 2000, when the author of [25] introduced fiber optic seismic sensors to conduct field experiments. A summary of research applying DAS for geophysics exploration throughout years is illustrated in Figure 1 below. Furthermore, DAS fiber optic cables were initially deployed within the wellbore; utilized for well monitoring [26]; and deployed in unconventional reservoirs for hydraulic fracturing monitoring [27], trials of DAS VSP [23], microseismic detection [21], and DAS for the assessment of CO₂ storage [28].

![Figure 1. Research progress of DAS in geophysics exploration [21,23,25–29].](image)

The latest progress of DAS techniques has also been described with respect to ML [29], including a study of the application of ML algorithms in pipeline surveillance systems based on DAS measurement. Further research activity within the scope of ML in the coming years is expected to be applied to DAS data with a robust grounding in the utilization of thorough methodologies.

DAS employs a single-laser interrogator unit powered by a single source to investigate data acquired through fiber optic cables. This probing process derives an axial strain-rate profile along the fiber over time, transforming it into an array of numerous seismic sensors with a density spanning only a short distance. Subsequently, an interrogator unit linked to one end of the fiber consistently emits brief laser pulses through the fiber, as depicted in Figure 2. Reflected photons are then subjected to interferometry with the transmitted reference pulse, resulting in a quasi-linear phase shift proportionate to the total strain along the fiber’s direction. A laser repeatedly pulses a short distance into the cable; then, an optical interferometry sensor captures the backscattered light and gates that signal into short segments in time, correlating changes in the backscattered light signal at the two-way travel time of light in the fiber to a location in the fiber. Changes from one ping of the fiber to the next are converted into changes in the strain-rate profile [22]. Furthermore, the optical instru-
mentation is comparable to optical time-domain reflectometry (OTDR) technology [24].

Figure 2. Schematic diagram of DAS measurement using the OTDR principle to detect the seismic wave incident.

The signal is segmented into channels, leading to data comprising time series that reflect the strain within individual fiber optic channels. The optical interferometric sensing process involves the tallying of photons across a certain gauge length. Over this range, optical phase shifts are measured, and the results indicate a nearly linear relationship with the degree of stretching or compression of the corresponding fiber section [30]. Channels might overlap if the gauge length value exceeds the channel spacing. When devising an interrogator unit or deciding on the emerging trade-offs of recording parameters, an expanded gauge length might compromise spatial data resolution but concurrently diminish statistical uncertainty across the gauge, whereas a narrower channel spacing has the potential to augment spatial resolution but might result in challenging data volume management and data processing. The main reasons for further research on the principle and processing of DAS are to enhance computational efficiency and set optimized acquisition parameters.

2. Single-Mode Fiber (SMF)

2.1. Theory and Sensing Principle

SMF is a common type of fiber optic cable in DAS systems. Within an SMF, the core glass typically maintains a diameter of approximately 9 µm, ensuring the predominance of a solitary, straight signal propagation path along the fiber. Silica, a form of glass, remains the predominant and most widely used material for fiber optics. Silica’s suitability for fiber optic cables is attributed to its exceptional characteristics, including extremely low optical attenuation (signifying minimal loss of light intensity) and its ability to be drawn into fragile fibers while maintaining remarkable tensile strength [31]. However, it is noteworthy that SMF facilitates the propagation of two polarization-state modes that are orthogonal and degenerate. In this scenario, the total power is distributed between these two polarization modes [7]. In this context, the relative phase relationships of the two polarization states can undergo alterations due to variations in elastic stress and temperature along the fiber. This phenomenon holds particular significance in interferometric sensing applications, notably in scenarios like DAS.

Utilizing such fiber optics results in exceedingly feeble Rayleigh backscattered light, causing the optical sensing signal’s signal-to-noise ratio (SNR) to be notably diminished, ultimately leading to poor SNR conditions [9]. Moreover, due to the activation of a laser pulse with a slim linewidth and heightened coherence in the fiber, the interference arising from Rayleigh scattering points within a single pulse gives rise to interference cancellation. This phenomenon leads to the coherent attenuation of backscattered light, consequently creating a loss zone along the sensing range [32]. Recently, efforts have been directed toward addressing the limitations of low SNR values and the susceptibility to phase demodulation in SMF DAS systems. Various noise attenuation technologies, including coherent fading, have been developed to counter these issues by performing median filtering in the data.
preprocessing step [7]. However, these advancements have augmented system complexity and elevated costs, entailing trade-offs in terms of the response frequency band and sensing range [33,34]. Furthermore, it is important to improve the efficiency of the sensing fiber. The development of specialized fibers tailored for DAS technology presents substantial potential for future advancements [9]. When a pulse wave is emitted along the fiber, it induces axial strain, resulting in a change in the phase of the Rayleigh backscattering signal within the fiber. The concept of Rayleigh scattering is a type of elastic scattering that does not involve nonlinear effects, and Rayleigh-scattered light from a distinct location might be differentiated by its reflection time back to the fiber launch point. The optical fiber phase extraction technique, which is specifically reliant on phase-sensitive OTDR, has become widely used within DAS systems [35,36].

2.2. Limitations of SMF

Although SMF DAS technology has found applications in diverse fields in subsurface imaging, including reservoir monitoring, microseismic event detection, and oil exploration, and boasts attributes like distributed detection, superior spatial resolution, and heightened sensitivity, it still grapples with limitations arising from interference fading and inadequate signal consistency. When a seismic wave strikes the optical fiber, axial strain is produced by the fiber [9]. This results in a phase difference of the Rayleigh backscattering; Equation (1) shows the relation between axial strain and the SMF optical-phase difference, referring to the photoelastic effect.

\[ \Delta \varphi = \beta \left[ 1 - \frac{n^2}{2} (p_{12} + 2p_{11}) \right] \Delta X \]  

\[ (1) \]

where \( p_{12} \) and \( p_{11} \) are fiber tensor coefficients, \( n \) is the fiber refraction index, and \( \beta \) is light propagation. The phase difference between points C and D can be measured, and the quantitative parameter of the acoustic seismic signal can be identified. Specifically, when the pulse-width value is short enough upon measuring the arrival time of the backscattered light, the Rayleigh backscattering signals originating from points C and D (Figure 3) can be identified. An emitted laser travels through the SMF core glass with minimum scattering in a single, simple path and is highly sensitive to axial strain changes in response to the seismic wave signal. The probe pulse defines a pulse width, and because the probe lights increased coherence, the Rayleigh scattering signals from scattering points within this pulse width often interfere with one another [9,37]. The interference outcome of Rayleigh scattering merely portrays a segment of the fiber in proximity to points C and D.

![Figure 3.](image-url) The sensing principle of SMF cable in DAS.

The presence of inhomogeneous doping during the optical fiber’s fabrication introduces randomness to the Rayleigh scattering interference pattern, thereby exerting an inevitable influence on the efficacy of phase demodulation. To precisely characterize the Rayleigh scattering phenomenon within SMF, researchers formulated a dedicated scattering model for SMF [38]. In cases where interference signals undergo interference cancellation, the signal’s intensity weakens, leading decreased optical SNR. This cancellation in light
intensity eventually brings it to the level of acquisition noise, effectively submerging the
demodulated phase information within the noise domain. This phenomenon gives rise to a
region of blind detection termed interference fading. Furthermore, owing to the stochastic
nature of the reflectivity amplitude associated with the corresponding scattering point, the
positions corresponding to the signals received at different time instances show variance [9].
In essence, the unpredictability inherent in the intensity and positioning of Rayleigh scattering
within conventional SMF engenders challenges like interference fading and insufficient
temporal consistency of the signal in DAS. These issues hinder the seamless execution of
exact sound wave tracing, particularly when scrutinizing the inherent attributes of the
medium’s interior [32].

3. Multi-Mode Fiber (MMF)
3.1. Theory and Sensing Principle

MMF is another typical type of telecommunication fiber used in DAS systems. Differing
from SMF, MMF has notably larger glass cores, typically ranging from 50 µm to 62.5 µm
in diameter (Figure 4). These large core sizes facilitate the phenomenon of multipathing,
wherein multiple paths of light allow for propagation within the fiber. Hence, multiple
lasers propagate within larger glass cores, increasing the dispersion of lasers and light
collected back by the DAS interrogator unit. The optical source is essential, with as many
as several hundred modes, each accounting for a proportion of the total power being trans-
mittted. Owing to the larger core size of MMF, a significantly greater amount of light can be
efficiently introduced into the fiber. Each light pulse experiences temporal spreading due
to intermodal distortion or intermodal delay in MMF. This phenomenon restricts the fiber’s
maximum length or bandwidth product and also makes MMF measure for a wider range of
angles of incident and modes in fiber optics. The limitation primarily stems from chromatic
dispersion caused by a non-zero-source spectral linewidth. Optical sources are defined
by their small spectral bandwidths and are extensively more preferred in long-distance
fiber optic sensing systems. This choice is based on their high modulation speed, optical
power-coupling efficiency, and minimum wave chromatic dispersion characteristics [7].

![MMF Core glass](image)

**Figure 4.** The sensing principle of MMF cable in DAS.

Despite its sensing principle, MMF can accommodate several hundred modes, with
the entirety of these modes collectively contributing to its sensing capabilities. This is
primarily due to the simpler approach of diminishing intermodal coupling by augmenting
the discrepancy between the propagation constant values of individual modes [39]. The
sensing principle of MMF that causes a phase difference in Rayleigh backscattering is the
same as that of SMF, as mentioned in Equation (1); however, the measured axial strain is
different and might affect the data resolution [40].

In contrast to SMF, MMF has achieved extensive and broad prevalence due to its
inherent insensitivity to alignment and cost-effectiveness. Consequently, MMF finds wider
use, particularly in short-distance applications [22]. A notable instance is the installation of numerous MMFs in general hydrocarbon wells for diverse applications, including DTS [41]. A study highlighted the utilization of an MMF to measure concurrently distributed sensing of acoustic signals and temperature variations. This exemplified the capability of MMF in easing applications within the scope of DAS [42]. The capabilities of MMF have been utilized in the last few years for DTS applications [40]. Contrary to SMF, MMF stands as the favored platform for DTS measurements. This preference is mostly caused by the substantial specific area and high threshold power of nonlinearity present in standard MMF. These attributes enable the sustenance of requisite high injected pump power without compromising the overall performance of DTS systems that measure differences in backscattered light according to changes in temperature [22]. The work reported in [39] showed a compromise of MMF in performing DTS measurement, resulting a high spatial resolution and the desired temperature variation across extended measurement distances. This configuration involved the development of a fiber optic DAS using phase-sensitive OTDR.

3.2. Limitations of MMF

The use of fiber optic cables has experienced significant growth and progress in the past few decades, primarily owing to their distinctive advantages in terms of suitability for operation in challenging environments. In various sensing applications demanding the utilization of high optical power, standard MMF is employed, as it possesses a notable nonlinearity threshold [43]. Conversely, employing MMF as a main alternative for multi-parameter DAS is sometimes not advisable because of the significant and frequently unpredictable intermodal coupling associated with MMF. This intermodal coupling invariably introduces noise into most MMF-based sensors [44], demanding complex control systems [45]. In terms of mode-dependent absorption sensing, the intensities of the modes in MMF undergo rapid fluctuations throughout the fiber due to intermodal coupling, even in the absence of interaction with a measured parameter. As a result, intermodal coupling’s impact can significantly reduce the effectiveness of MMF mode-dependent, absorption-based sensors [46].

Optical fiber designed for sensing implementation requires two different operation principles and systems, specifically Rayleigh scattering for DAS and Raman scattering for DTS [47,48]. In contrast to a Raman signal, Rayleigh scattering exhibits comparatively higher intensity and does not demand the same elevated pump power levels required by DTS systems [49]. Hence, when below the fiber’s nonlinearity threshold, it is feasible to use MMF for DAS measurement. However, the efficacy of DAS depends on the coherent interference of Rayleigh signals reflected by scattering centers on the cable throughout the fiber optic [48]. In this context, MMF introduces notable levels of noise within DAS images. The reason for this is that a common MMF accommodates the propagation of a significant number of modes, and each of these modes possesses a distinctive interference pattern. These patterns collectively generate a resultant Rayleigh signal that remains independent of vibrations [46].

The type of fiber optic cables in DAS measurement has a significant impact on the acquisition of data, and each type has advantages and limitations that affect DAS data. Table 1 summarizes the trade-offs between SMF and MMF discussed above.

Table 1. Summary of advantages and limitations for each fiber optic cable type.

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<thead>
<tr>
<th>Fiber Optic Cable Type</th>
<th>Advantages</th>
<th>Limitations</th>
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<tbody>
<tr>
<td>SMF</td>
<td>Most widely used in DAS monitoring and imaging Higher spatial resolution Lower signal loss that minimizes signal attenuation</td>
<td>Sensitive into acquisition optical noise Interference fading</td>
</tr>
<tr>
<td>MMF</td>
<td>Capable of DTS measurement Lower manufacturing cost Suitable for short-distance DAS measurement</td>
<td>Unpredictable signal that can produce noisy data Intermodal coupling due to multiple paths of laser travel</td>
</tr>
</tbody>
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4. Application of Fiber Optic Cables in Geophysics Exploration

4.1. VSP of SMF

Single-mode researchers such as the authors of [23] have introduced DAS for borehole seismic applications. DAS has the potential to expand beyond its initial use and encompass other surveillance domains, including production and completion reservoir monitoring. This extension is made feasible by leveraging existing fiber optic networks for enhanced data acquisition and monitoring capabilities. However, applying a suitable DAS data acquisition and processing workflow is also crucial in obtaining the best images; hence, many papers have utilized diverse DAS outputs that are applicable to exploration activity. VSP data are used to complement seismic data through the process of separating the signals from multiple sources that overlap in time and were acquired by deploying seismic sensors in a wellbore and recording the response of the subsurface to a controlled seismic source [50]. Figure 5 shows a schematic deployment for land VSP acquisition. DAS offers the distinct advantage of remarkable spatial sampling, spanning the complete length of a well.

**Figure 5.** Schematic layout of a typical land DAS VSP acquisition system modified in [28].

Furthermore, as the underlying technology, SMF optic cable presents enhanced robustness compared to conventional geophones. This robustness mitigates the potential hazards of deploying mechanical and electrical components within a well [51]. This makes SMF an excellent tool for replacing geophones, providing subsurface properties, in addition to having been used widely in various subsurface applications.

In 2015, the authors of [52] located an indication of a reservoir of the Aquistore CO$_2$ geological storage project through elementary imaging using DAS in Paleozoic carbonates and Mesozoic sandstones and shales. SMF optical fiber cables were permanently installed inside steel tubing, strapped behind casing, and cemented in placed in observation wells during completion, even though it was only the fiber optic cable deployed in the observation well that eventually operated well. SMF within the observation well was employed to conduct comparisons with geophone VSP measurements. A processing framework was executed for each shot obtained through both DAS and conventional geophones. The general processing framework encompassed trace balancing; correction for spherical divergence, notches, and low-pass filtering; and a frequency-wavenumber filtering algorithm of the down-going wavefield. To compare it with geophones, DAS trace gathering was superimposed with the geophone traces within a specific depth range. SMF DAS and
vertical-component geophone traces were also imaged for analysis. The results indicated that geophone data distinctly showcase a higher SNR than DAS data. However, it is worth noting that the DAS for SMF SNR has significant room for enhancement through the application of noise attenuation techniques and the averaging of data over cable lengths, as it is used in geophone results. In contrast, numerous equivalent reflections are obscured by noise within the DAS data for the same depth range. However, DAS still has the advantage of potentially replacing many geophones within one SMF. This may potentially generate subsurface images by notably enhancing spatial resolution and coverage when compared to traditional geophones. Moreover, this improved performance can be achieved at a relatively lower cost.

DAS VSP has also proven to be useful in acquiring VSP data in carbon capture and geological storage (CCS) projects [53]. By applying multiwell 3D DAS VSP data acquired at the CO₂CRC Otway, DAS data were processed and analyzed for their applicability for continuous time-lapse monitoring of CO₂ injection. The acquisition process was performed by deploying four SMF cables cemented along the well, where two SMF cables were connected with constellation fiber (CF) and each SMF cable was connected to an iDAS v3 interrogator unit. The DAS data were recorded under a strain rate with a 5 m depth interval and correlated with vibroseis source sweep data, enabling first-breaks picking. Further DAS VSP data processing included vertical stacking until 3D migration and plotting with 3D seismic cross sections. This helped in clearly imaging the key stratigraphy horizon and CO₂ injection target within the SMF cable. This resulted in a good correspondence in the seismic reflectors in the datasets while comparing a 3D DAS VSP image with surface 3D seismic imaging. The 3D DAS VSP shows higher image resolution and provides enhanced precision in determining the depth of reflectors within the well area. Therefore, the implementation of multiwell DAS VSP emerges as a viable approach for continuous monitoring systems. The results of multiwell DAS VSP could have been improved by taking more action to tackle missing seismic volumes from different typical wells.

In 2016, the authors of [54] conducted research to validate DAS VSP data integrity with a conventional geophone at the Aquistore site for subsurface CO₂ storage. This data acquisition used an SMF cable with a total fiber length of 5.4 km, and the configuration involved the embedding of the initial portion of the cable near the surface, while the subsequent section was permanently cemented behind casing and vertically positioned along the cable deployment. The acquisition also involved active sources, such as dynamite and vibroseis, to cover entire boreholes. Each near offset and far offset shot were applied to dynamite shot gather to indicate direct arrival, reflection events, and ground roll in shallow sections. These three DAS events were compared with geophones in terms of noise characterization and identified the noise as optical system noise, optical fading, common mode noise, or checkerboard noise. Initially, the raw DAS data on strain rate were also converted to geophone-equivalent units to achieve a good comparison of the two raw data acquisitions for further assessment. Both up- and down-going events managed to match the polarity between geophone and DAS data. The up- and down-going wave separation might have been enhanced by a suitable denoising filter between the two input trace gathers. The result indicated that converting DAS VSP data to equivalent geophone data can help with the up- and down-going separation step without using deep filters. With the mitigation of depth calibration in seismic DAS, the data processing workflow can be improved.

The authors of [55] carried out a DAS VSP field survey to evaluate the effectiveness of fiber optic DAS by comparing four cable deployment approaches, namely with cables behind the well casing, behind an inflatable liner, clamped to production tubing, and deployed with wireline logging. The SMF cable was lowered along the well with a different approach and connected to a DAS interrogator. To generate seismic waves, active sources were employed using P-wave and an Envirovibe S-Wave Vibrator. During the final imaging of VSP for Common Depth Point (CDP) transform, DAS data attenuation accrued for all cable deployment methods. Noise attenuation reduced the SNR, influencing the quality
of the seismic image. The results indicated that the deployment method with the fiber cable cemented behind casing was considered the most effective method for cable coupling with the subsurface layer, with a high-quality generated image in the pre-defined velocity model. Such an improvement can be generated by a depth-calibrated SMF cable against a reference to account for source statics resulting from variations in elevation. This correction was essential in achieving optimal resolution in the subsurface imaging.

Further DAS measurement research was carried out by the authors of [56] to conduct real-time DAS VSP acquisition and processing using an SMF cable with seismic-source synchronization and real-time DAS data processing to provide contemporary work. The SMF cables were deployed outside the casing in vertical and lateral sections along the wellbore. The configuration of the DAS system used a homodyne DAS interrogator, which was systematically connected to fiber stretchers. This configuration was used for its capacity to integrate all supplementary seismic source signals that directly connected into the optical data stream while the obtained data were in velocity. This integration was accomplished with a sequence of piezoelectric fiber stretchers positioned in line with the SMF cable. The DAS system was able to continuously monitor the stretching fiber. The DAS maximum data sampling frequency for SMF was able to reduce the noise power spectral density of the DAS data stream to achieve real-time processing. The data processing workflow was conducted by converting raw DAS data to strain rate with weighted stacking for certain shot points and correlated with vibroseis sweep wavelets and common-mode noise denoising in SEG-Y format. The signal strength for SMF cable from DAS VSP shot records was computing SNR in the first break, and the noise level from RMS energy indicated a lower SNR along the channel. The findings demonstrated that utilizing an SMF cable in a DAS system facilitates an efficient data acquisition process and enables real-time generation of seismic and navigation data sampled at specific intervals. These DAS data adhere to geophysics seismic data formats, reducing the time delay between data acquisition and the transfer of field data outputs.

Reservoir Monitoring of SMF

Fiber optic applications have achieved remarkable outcomes when deployed in high-spatial-resolution seismic sensors using cost-effective telecommunications fiber optics installed along the drilled well to monitor hydrocarbon reservoirs [57–59]. Permanently installing a seismic array cable within a borehole can streamline equipment deployment, decrease operational complexities, and offer notable advantages such as enhanced repeatability and the potential for real-time data acquisition [60]. SMF has been widely used to monitor reservoirs in various subsurface targets.

Research was conducted to evaluate DAS image quality of subsea carbon storage reservoirs and assess monitoring design concepts [61]. Subsea DAS was deployed within a single ultra-low-loss signal transmission SMF cable through subsea infrastructure that connects the DAS interrogator unit to a borehole SMF deployed within a dual-transmission SMF with a remote circulator. This concept was employed to counteract diminished optical signals by using an enhanced backscatter of SMF. The synthetic shot records were augmented with raw DAS records in terms of optical noise to replicate the varying SNR in SMF scenarios, namely a base case involving a dry tree with common SMF and a subsea scenario entailing a single transmission fiber and common SMF. The subsea environment with a single transmitting fiber and standard SMF had a negative value of net DAS noise gain and lower DAS pulse repetition rate loss. The alteration in the DAS noise floor within the context of the two scenarios involving SMF was assessed by analyzing the overall gains or losses resulting from various physical factors influencing system performance. The result highlighted the repercussions of low SNR in terms of subsea DAS image resolution. The authors concluded that employing a single transmitting fiber with standard SMF was not preferable for the subsea environment, especially for characterizing reservoir formations. The single signal transmitted in fiber optics with standard SMF was filled with noise, in contrast with the other situation for subsea transmission fiber. These findings can inform the selection of reservoir monitoring and data acquisition designs using SMF during
offshore reservoir research. A possible further improvement of subsea DAS is enhancement by selecting an appropriate vendor of DAS SMF interrogator units to handle noise. This would involve the choice of a relevant interrogator vendor before conducting the subsea DAS survey.

Subsequently, a DAS SMF with active sources generated by rotary seismic sources was applied to facilitate autonomous permanent reservoir monitoring in the CO₂CRC Otway Field Site, Australia [62], by utilizing rotary seismic data as an active source that accurately controls routinely operated signal systems (ACROSS) [63,64]. The DAS data were continuously collected and recorded in five wells with SMF cable cemented behind the casing and underwent automated processing at the close of each day. The data collected through the permanent reservoir monitoring system using DAS SMF and rotary seismic receivers yielded a notably higher SNR ranging from roughly 50 dB to over 100 dB for near-offset data shot. The DAS using SMF cable successfully showcased favorable data quality attributes, encompassing SNR and data repeatability. This was evident in time-lapse operations for the monitoring carried out using the DAS system. This research can be improved by enhancing the spectral-frequency content of seismic data by using dual-motor rotary seismic sources, subsequently combining high-resolution images for time-lapse acquisitions and the achievement of a high SNR for autonomous reservoir monitoring. Research applying SMF cables to VSP input DAS data is summarized in Table 2 below.

Table 2. Summary of VSP applications of SMF cables in relevant studies.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Scope of Work</th>
<th>SMF Deployment</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harris et al. [52]</td>
<td>DAS VSP</td>
<td>Installed inside steel tubing, strapped to the casing, and cemented in the well</td>
<td>Comparison of seismic images obtained by a baseline DAS and traditional geophone VSP at a CO₂ storage site</td>
</tr>
<tr>
<td>Yurikov et al. [53]</td>
<td>3D DAS VSP</td>
<td>Cemented along the four wells</td>
<td>3D DAS VSP imaging of key stratigraphy horizon and CO₂ injection target</td>
</tr>
<tr>
<td>Olofsson and Martinez [54]</td>
<td>DAS VSP</td>
<td>Permanently cemented behind casing</td>
<td>Conversion of DAS VSP data to equivalent geophone data proved to help in the up- and down-going separation step without using deep filters</td>
</tr>
<tr>
<td>Mad et al. [55]</td>
<td>DAS VSP</td>
<td>Four deployments strategies: cemented behind casing, cable behind an inflatable liner, strapped to production tubing, and wireline deployment</td>
<td>Cementing the fiber cable behind casing was considered the most effective method for coupling with the subsurface formation</td>
</tr>
<tr>
<td>Ellmuthaler et al. [56]</td>
<td>Real-time DAS VSP</td>
<td>Permanently deployed behind casing in vertical and lateral sections of a well</td>
<td>Utilization of SMF cable in the DAS system facilitated efficient data management and enabled real-time generation of seismic and navigation data sampled at specific intervals</td>
</tr>
<tr>
<td>Wilson et al. [61]</td>
<td>Subsea reservoir monitoring</td>
<td>Attached to subsea infrastructure and deployed in a borehole</td>
<td>The repercussions of increased noise on the subsea DAS image quality</td>
</tr>
<tr>
<td>Correa et al. [62]</td>
<td>Autonomous permanent reservoir monitoring</td>
<td>Cemented behind casing inside a borehole</td>
<td>Evident in time-lapse operations carried out using the DAS SMF system with favorable data quality attributes and encompassing SNR</td>
</tr>
</tbody>
</table>

4.2. Microseismic Monitoring of SMF

The use of DAS fiber optic sensing technology has been demonstrated to be efficient in providing sufficient sensitivity to detect a significant subsurface event. In such scenarios, established reservoir surveillance techniques, including subsurface seismic imaging and microseismic analysis, are employed. Each of these techniques possesses its own set of advantages and drawbacks, collectively contributing to an enhanced comprehension of the treatment processes [65]. The analysis result of the DAS images shows that contemporary optical fiber technology offers sufficiently higher sensing sensitivity to measure a notable count of microseismic events. These events can then be integrated with data pertaining to the strain rate and temperature changes, as demonstrated by previous research [66]. The
researchers applied SMF cable to analyze microseismic events in a single horizontal DAS using guided waves [67]. The DAS data were acquired with an OTDR interrogator unit conducting on SMF and measuring in terms of strain rate. The acquisition parameters were 1 m channel spacing and 10 m gauge length, with 2000 samples per second. The SMF cables were installed in a single horizontal well outside the casing in a deviated well that expanded into an unconventional reservoir formation. SMF cable was also deployed schematically with offset wells and vertical logging wells. With the aid of an ML learning approach, the guided waves and DAS measurement were able to automatically detect microseismic events with high accuracy. The microseismic events were detected based on a localization process grounded in guided wave dispersion. These properties were predicted in situ using known perforations as references. Directional measurement DAS with SMF resolved the uncertainty in certain event locations with guided waves. The result showed that SMF arrays have excellent potential for event detection due to their spatial resolution and affection for microseismic events. The research output indicated that the initial utilization of microseismic event localization using SMF could be achieved and considered inept without a guided wave.

4.3. ML Application in SMF Processing

Efficient automated processing schemes for raw DAS data have achieved significant importance. SMF cables have the capacity to consistently monitor acoustic signals and vibrations across extensive distances, offering high sensitivity and an elevated update rate [68,69]. DAS SMF measurement conventionally captures numerous complex backscatter profiles in a short time and performs real-time data processing. Given the substantial volume of generated data, it is essential to devise automatic, efficient, and precise tools for signal processing. As optical data are complex, have a high bitrate, and must be processed in real time, state-of-the-art machine learning techniques are ideal for extracting relevant information [70]. Furthermore, ML can potentially decrease the amount of storage space needed for data and minimize the time required for data processing to facilitate comprehensive analysis [71]. Figure 6 shows general ML processing applied to DAS data and its output.

![General ML processing workflow on DAS data.](image)

Recent research reported in [72] applied classical ML and deep learning algorithms to SMF DAS event detection. ML was compared with the deep learning result, and the benefits and limitations of both methods were analyzed for each applied algorithm. The classical ML workflow involved DAS data collection, preprocessing, feature extraction and classification, model creation, tracking, and evaluation of event detection. DAS data were acquired using a simple sensor unit with standard SMF and connected to an interferometer. SMF cable
was deployed in a 17 km cable length, with a gauge length of 10 m and a phase-sensitive OTDR interrogator unit. The DAS data were collected in a suburban area near Vienna, Austria. The used ML algorithms were random forest, decision tree, and support vector machine (SVM), while the deep learning algorithms were deep neural networks (DNNs) and convolutional neural networks (CNNs). Deep learning techniques were employed for SMF event detection, utilizing the ability to automatically extract relevant attributes from the raw DAS data. This approach obviates the necessity for extensive domain knowledge. The implementation of this method offers an achievable approach for optimum sensor fusion in SMF sensors in DAS systems. A comparative analysis of outcomes between ML and deep learning methodologies demonstrated that DAS could detect various continuous events along the pipeline, such as human digging and tapping. Moreover, it can identify significant events in other SMF systems.

Despite the numerous benefits, DAS data can still be contaminated by various types of noise from the ambient environment and the optical instruments. Supervised ML techniques were applied to target specific noise types to improve the SNR and denoising (noise reduction) of DAS data [73]. Recent research implemented supervised ML method DAS-N2N (Noise2Noise) to denoise DAS data without clean data [74]. The DAS data were acquired in SMF cable laid out in a 1 km cable length, with sampling at 1000 Hz, channel spacing of 1 m, and a 10 m gauge length. SMF cables placed within the cable jacket were spliced at one end to build a looping cable. The results obtained from DAS-N2N were contrasted with the outcomes of conventional bandpass filtering. In this comparison, DAS-N2N demonstrated its ability to attenuate noise within a frequency range identical to that of the target signal, a task that frequency-based filtering cannot achieve. Furthermore, DAS-N2N exhibited a processing speed approximately ten times faster than self-supervised learning methods. The result indicated that DAS data are remarkably lightweight and efficient and more capable of data processing compared to the acquisition time when fine-tuned with a single GPU. DAS-N2N outperforms conventional frequency bandwidth filtering routines enhanced using compiled low-level computation regarding processing speed. Further improvement in SMF data imaging could be achieved by optimized supervised ML models compiled and compressed for DAS processing on suitable high-performance devices and edge networks, which will be appropriate for offshore or remote monitoring scenarios. Table 3 highlights a summary of all research on SMF for microseismic monitoring and the ML applications discussed above.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Scope of Work</th>
<th>SMF Deployment</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karrenbach et al. [66]</td>
<td>Microseismic event detection</td>
<td>Installed in a horizontal well behind casing in a deviated drilled well</td>
<td>Automatic detection of microseismic events with high accuracy in an unconventional reservoir</td>
</tr>
<tr>
<td>Bublin [72]</td>
<td>Machine learning algorithm</td>
<td>Laid out on a surface in a suburban area</td>
<td>Machine learning and deep learning applied to DAS data could detect various intrusion events along the pipeline, including manual digging and tapping</td>
</tr>
<tr>
<td>Lapins et al. [74]</td>
<td>Machine learning-assisted</td>
<td>Deployed on the surface in an ice stream</td>
<td>The supervised ML method was able to denoise DAS data automatically with a higher SNR and faster processing speed</td>
</tr>
</tbody>
</table>

4.4. VSP of MMF

The subjectivity of VSP usually depends on the interpretation and calibration of the downhole seismic arrays that can be addressed by applying fiber optic installations. Field research in a hybrid wireline using MMF cable was conducted to assess the results of a borehole seismic survey [75]. Two MMF cables with 62.5 µm core diameters were deployed within a 5 km hybrid optical–electric wireline cable and connected via splicing at the cable head. This fusion created a length of 10 km up-going and down-going DAS. A real-time
active system source controller with a 6 kg dynamite shot triggered the DAS interrogator. The recording configuration was established to capture measurements at intervals of 0.25 m, with a sampling rate of 1 ms and encompassing 8 km along the MMF cable. The MMF cable was set to acquire the strain rate (rate change) within the fiber as the physical property. Raw DAS VSP data in the preprocessing step showed that there was a high coherence in MMF cable slapping and ringing noise; this noise was further processed in the following VSP sequence: seismic trace editing, denoising filter, spherical divergence correction, up–down separation, and deconvolution. DAS walkaway VSP imaging data were processed to build a velocity model. This resulted in a wider lateral image from a single well with a larger vertical aperture than VSP with a geophone. The processing of DAS data yielded improved outcomes, addressing certain practical challenges associated with the hybrid wireline in borehole deployment. The result indicated that DAS with MMF cable walkaway VSP provided an excellent result with vertical and lateral imaging resolution and managed to detail the structure in the objective area. The application of MMF in the exploration field can help minimize the operation costs of VSP in vertical wells, owing to its utilization of a DAS system and its expanded applicability and reliability.

The authors of [56] used fiber optic installations with MMF cable for sensing according to the principle of Raman DTS applied to real-time DAS VSP data acquisition and processing. MMF cables were synchronized with seismic sources by directly encoding auxiliary seismic signals onto the optical data stream. This was applied through the incorporation of piezoelectric fiber optic stretchers aligned with the sensing fiber cables. Inside the schematic interrogator unit, MMF cables were connected to SMF cables using an SM–MM converter. MMF cables were deployed through the circulator and sensing fiber along a far offset of the measurement. MMF was deployed as a scrambler to transfer energy from the fundamental mode to all the (low-loss) modes. This is essential to increase the amount of light power emitted. The DAS VSP shot record for MMF was recorded at a 16 kHz pulse rate and a gauge length of 20 m. The MMF result, in terms of system performance, indicated that MMF yielded a 2 dB reduction in SNR for DAS VSP, while the optical settings of DAS interrogators were placed at 5 dB. This implies that MMF measurement managed to have sufficient capacity for the DAS interrogator and acquired DAS VSP data in the MMF cable with 8 dB loss. However, a limitation of the researchers findings is that the MMF installation has shallow image due to the increase in attenuation with significant hydrogen darkening. For future work, there should be a sufficient SM–MM converter for DAS sensing of MMF deployed in legacy DTS installations to improve SNR and signal loss.

Reservoir Monitoring of MMF

Improving reservoir monitoring relies on many factors like real-time data analysis and detailed subsurface imaging, leading to a better utilization of fiber optic technology. Accurate imaging of these fiber optic measurement data is essential in lateral and vertical spatial distributions in reservoir monitoring. In their advanced research on 4D reservoir monitoring, the authors of [76] applied DAS 4D VSP to MMF cable in a deep-water environment to reveal injected water-sweep dynamics. MMF was deployed in active wells to perform detailed monitoring of the water flood injection in two deep hydrocarbon reservoirs in a field in the Gulf of Mexico. In the technology trials, the research compared DAS VSP and Ocean Bottom Node (OBN) to obtain the 4D imaging performance of the two data sources. The DAS data were continuously measured over the years to understand the influence of small active sources and active well noises in 3D and 4D DAS VSP on MMF imaging resolution. The progression began with a DAS VSP recording in 2015 within an active well while water flooding injection operations were ongoing. Subsequently, DAS fibers captured in a P-cable trial featuring 300 events from three sources in early 2017 served as benchmarks for additional iterations. Furthermore, in late 2017, a standalone DAS VSP survey was conducted, distinct from the simultaneous OBN deployment, encompassing three active injector wells. The measurements encountered additional challenging conditions for DAS, including notable well deviation that resulted in diminished sensitivity to desired reflections, as well as the presence of extended MMF lengths that contributed to
heightened levels of optical noise. However, this measurement endeavor yielded crucial insights into acquisition and processing methodologies. It was discovered that DAS 4D images exhibited qualitative similarity to OBN 4D outcomes. Furthermore, the repeatability of DAS images proved to be exceptional, as demonstrated by a well-controlled Normalized Root Mean Square (NRMS). The reservoirs are sandstone reservoirs with turbidite deposits with high-quality sands composed of different lobes with varying thicknesses across the field located on deep-water acreage. The results of DAS MMF and OBN were compared in two reservoirs within the same vertical conformity of the time-lapse signals in both datasets. These results show that frequent 4D DAS VSP can assist in characterizing all phases of a water flooding injection; the data were also used for sweep monitoring of the evolution of the injector. On the other hand, the survey result demonstrated that the associated costs remained reasonable, while the resultant seismic images proved to be well-suited for monitoring the immediate surroundings of wells. These images facilitate the assessment of injector performance, the evolution of sweep processes, the progression of water towards producers, and the containment dynamics within the reservoir. However, the study highlighted several limitations of DAS in MMF VSP regarding flow- and injection-related well noise. Injection noise predominantly presents itself through the propagation of robust tube waves along the wellbore, characterized by comparatively lower velocities in DAS data. A data processing framework should be developed to incorporate insights from 4D DAS VSP data modeling, adding well log data to extract physical properties of reservoirs and consider the understanding of reservoir dynamics behavior. Nevertheless, an improved 4D DAS VSP may offer a promising starting point for real-world DAS of MMF for reservoir monitoring in a thick sand layer. Future research should delve into comparative analyses with other active seismic sources, explore the deployment MMF cable with evolving technologies, and assess DAS acquisition parameters involving deployment in reservoirs. Table 4 below summarizes the works reviewed in this section.

<table>
<thead>
<tr>
<th>Author</th>
<th>Scope of Work</th>
<th>MMF Deployment</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yu et al. [75]</td>
<td>DAS VSP</td>
<td>Deployed within hybrid optical–electric wireline cable</td>
<td>Excellent vertical and lateral imaging resolution and detailed subsurface structure</td>
</tr>
<tr>
<td>Ellmauthaler et al. [56]</td>
<td>Real-time DAS VSP</td>
<td>Permanently deployed behind casing in vertical and lateral sections of a well</td>
<td>Reduction in SNR for DAS VSP and MMF had sufficient capacity for the DAS interrogator</td>
</tr>
<tr>
<td>Kiyashchenko et al. [76]</td>
<td>4D reservoir monitoring</td>
<td>Deployed in active deep-water wells</td>
<td>DAS 4D images exhibited qualitative similarity to OBN 4D outcomes and subsurface images, facilitating the assessment of water flood injection to the reservoir</td>
</tr>
<tr>
<td>Wilson et al. [61]</td>
<td>Subsea reservoir monitoring</td>
<td>Attached to subsea infrastructure and deployed in a borehole</td>
<td>The repercussions of increased noise for subsea DAS image quality</td>
</tr>
<tr>
<td>Correa et al. [62]</td>
<td>Autonomous permanent reservoir monitoring</td>
<td>Cemented behind casing inside a borehole</td>
<td>Evident in time-lapse operations carried out using the DAS SMF system, with favorable data quality attributes and encompassing SNR</td>
</tr>
</tbody>
</table>

**4.5. Microseismic of MMF**

Fiber optic cables have the capability to be permanently installed by cementing them behind a protective casing or temporarily deployed using a wireline method [77,78]. Once a fiber optic cable has been deployed in a downhole environment, it can serve various functions, including the monitoring of microseismic activity. Despite the utilization of MMF, DAS can effectively produce estimations and source mechanisms that provide sufficient coverage for obtaining a singular-moment tensor solution in microseismic measurements. Characterization of source parameter estimation using DAS with MMF-recorded microseismic data was conducted in [79]. An MMF cable was deployed within a treatment well located in the Meramec Shale Formation in Oklahoma. This cable spanned the whole vertical distance of the well, extending from the surface down to the desired depth. Figure 7 shows an illustration of microseismic event measurement in hydraulic fracturing by DAS...
fiber optic cables. As a result, almost 1000 channels were recorded through this installation. During the treatment of two wells, comprehensive measurements were conducted to assess DTS, strain, and microseismic activity along the full depth of the wells. DAS on MMF achieved excellent waveform imaging for two microseismic events with S-wave polarity reversals. This is because DAS microseismic events with consistent amplitude patterns were observed using event classification considering polarity reversals and horizontal and vertical MMF distance along the fiber. The resulting variation in nodal planes for DAS microseismic events showed a shear-wave amplitude pattern and even managed to generate a nodal plane angle picked manually by considering the horizontal and vertical axis distances of the microseismic event from the treatment well. The result of using DAS for seismic monitoring indicated that the MMF was more accurate in characterizing source features, specifically in estimating moment tensors. Future endeavors might to improve signal processing techniques and consider anisotropy in subsurface properties and its effects on the propagation of seismic waves detected by DAS systems.

Figure 7. Illustration of DAS microseismic detection for hydraulic fracturing measurement.

ML Application in MMF Processing

Machine learning methodologies have been extensively employed to enhance the efficiency and precision of data processing [80–82]. Several ML strategies have been tested in academic literature to increase the rate of processing of DAS microseismic data; another such strategy is the utilization of deep learning [83].

The authors of [84] proposed a new and efficient data processing workflow for MMF DAS microseismic data using an ML-assisted approach. A convolutional neural network (CNN) algorithm allowed for microseismic event detection, and U-Net modeling was used for both P- and S-wave arrival-time picking. MMF cables were previously deployed with two multiwell DAS datasets acquired during hydraulic fracturing well completions in western Canada. MMF was deployed using a 4 m gauge length, 4 m channel spacing, and a 2000 Hz sampling rate, and data were converted to strain. The developed ML-assisted workflow was highlighted in the event detection and 1D arrival time picking after raw DAS data denoising. The results of applying the CNN algorithm were compared to the conventional short-term average/long-term average (STA/LTA) approach and geophone for microseismic event detection. The CNN detection method demonstrated a decreased false-positive ratio, contributing to a reduction in the time required for quality control. This makes it suitable for effectively handling the substantial volumes of data generated by DAS MMF. The findings indicated that the CNN method exhibited a reduced false-trigger rate and led to an expansion in the size of the microseismic event catalogue. A CNN model can automatically detect microseismic events (hypocenter location) recorded by low-SNR DAS with MMF cable data with excellent model accuracy and superior efficiency. Subsequently,
the result of microseismic comparison with a 3C geophone revealed that DAS images have a lower sensitivity in weak events and low frequencies compared to geophones. The innovative aspect of this work lies in the implementation of ML algorithms, specifically the CNN model workflow. This workflow can be retrained as additional data become accessible, enabling the implementation of transfer learning. In other words, it becomes feasible to train a network using DAS data from one well and subsequently apply it to DAS data obtained from other wells. This approach presents an effective way to automatically address the DAS processing workflow through the use of an imaging algorithm. The author indicated that the limitation of this work was that the number event detection results of the 3C geophone was more detectable than that of DAS-CNN. However, the outcomes indicated reasonable counts of microseismic event occurrences observed during each step, indicating the reliability of the CNN algorithm. Future work could focus on developing more automated tools to make use of intricate phase data, including reflections, guided waves, and coda waves. A summary of the relevant literature on microseismic detection and ML can be found in Table 5 below.

Table 5. Summary of microseismic and machine learning applications of MMF cables in relevant studies.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Scope of Work</th>
<th>MMF Deployment</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karrenbach et al.</td>
<td>Microseismic events</td>
<td>Installed in a horizontal well behind a casing in a deviated drilled well</td>
<td>Automatically detected microseismic events with high accuracy in an unconventional reservoir</td>
</tr>
<tr>
<td>Ma et al. [84]</td>
<td>Machine learning</td>
<td>Deployed on multiwell DAS datasets acquired during hydraulic fracturing well completions</td>
<td>Machine learning algorithm and CNN automatically detected microseismic events (hypocenter location) recorded in low-SNR DAS data</td>
</tr>
</tbody>
</table>

4.6. Subsurface Imaging of Combined SMF and MMF

The development of subsurface imaging by utilizing DAS technology rely on many elements, like fiber optic cables, which enable compatibility with an interrogator and data acquisition. The selection of optical SMF and MMF for DAS measurement is contingent upon the specific application and desired aim. Combined SMF and MMF have not been widely employed for the purpose of DAS measurement as a prevalent practice. DAS commonly depends on SMF cables, owing to its capacity to preserve signal integrity at extended distances and deliver measurements with high resolution [79]. However, it is conceivable that advancements have taken place in the scope of fiber optics and distributed sensing, considering the potential evolution of technology and practices in subsurface imaging. The combination of the two types of fiber optics is usually contained inside a single cable equipped with optical SMF and MMF, where MMF is commonly used for DTS measurements and SMF for DAS measurements.

The authors of [28] carried out simultaneous acquisition of DAS VSP with SMF and MMF cables at the Aquistore CO2 storage facility. This field acquisition also utilized a (3C) wireline geophone array for quantitative comparison with DAS measurement results. The fiber optic cables comprised one MMF cable loop utilized for DTS measurements, alongside one SMF cable employed for telemetry to downhole gauges and to conduct DAS measurement. During the first well completion process, the cables were installed outside of the well casing using cement. The simultaneous DAS VSP acquisitions of SMF were used as data for the full 3D surface explosive survey as an active source, and MMF was used for a significant fraction of the survey. All active sources shot data were measured with a geophone array, and a 3C VSP geophone and DAS fiber optics were used for recording. The obtained raw measurement data were recorded as strain rate, with further data processing converting them to particle velocity for equivalence with geophones for comparison. The SMF and MMF measurement results were compared within the same source shot map. The comparison result indicated that there was no quantitatively significant distinction in the quality of the two recordings. However, it was observed that the SMF data exhibited
a slightly higher level of noise. This discrepancy is likely attributed to a little variation in the used interrogator units rather than being influenced by the type of fiber deployed. Other findings include that MMF was quite efficient because of the numerous wellbores in which MMF was deployed for DTS measurement. The comparison of DAS VSP data with geophone response was consistent, showing similar trace gather within each shot point. Further DAS VSP data processing in weighted stacking revealed in improvement in SNR and 3D migrated DAS VSP imaging. Data acquired from SMF and MMF with identical coupling in the fiber optic demonstrated comparable SNRs and sensitivity. The comparable SNR and sensitivity of MMF installed in a borehole for DTS can be considered for VSP acquisition as well. The result of DAS VSP migrated image volume in this field acquisition at the Aquistore site for continuous monitoring can be expanded to 3D imaging in future work.

In the study reported in [85], DAS measurements of seismic properties were conducted on the Store Glacier ice sheets, recording englacial and subglacial seismic properties. DAS measurements were recorded along seismic shots as an active survey to obtain P-waves and S-waves at a depth of 1043 m in the formation, and VSP and data were sampled at 10 m with vertical resolution. The fiber optic cables were installed enclosed in a gel-filled, stainless-steel capillary tube in a borehole on Store Glacier. This cable consisted of two SMFs for DAS measurements and four MMFs for DTS measurements. The interrogator unit was set to a 4000 Hz sampling frequency, with a sample length every 1 m along the cable and a 10 m gauge length for approximately half the expected seismic wavelength. A seismic source was generated using a sledgehammer along the shot 1 m away from the well surface and 500 m offset from the wellbore. The fiber optic cables were recorded continuously without any source. The DAS VSP measurements were able to image 0 m offset and 300 m offset VSP and detect direct SV-waves and P-waves. The utilization of the DAS recording technique facilitated the quantification of changes in the properties of P- and SV-waves. This enabled the identification of transitions associated with ice-crystal fabric and environmental temperature, which influenced the seismic signal. Additionally, the presence of a subglacial layer composed of consolidated silt was successfully identified. The measurement result indicated that DAS offers evident advantages in the characterization of seismic properties of ice masses with a high image resolution. It is also worth noting that DAS cables possess the capability to be monitored for DTS, enabling the combined analysis of seismic and thermal data. Nevertheless, a limitation of DAS is the disadvantage of cables in terms of applicability as a surfaced receiver in P-wave seismic surveys; however, the ability of DAS to image distinct seismic responses at roughly 10 m intervals throughout the ice column can compensate for these drawbacks. Subsequently, the deployment of DAS interrogators incurs significant expenses, but these costs can be mitigated by the resulting improvement in survey effectiveness. Once permanently deployed, the DAS cable consists of SMF and MMF, enabling continuous field monitoring to focus solely on source deployment. In comparison, traditional seismic surveys necessitate ongoing efforts for the relocation and operation of both source and receiver systems. In future work, MMF cables for DTS measurement should be observed in the same vertical borehole to verify the depth in DAS VSP.

The research reported in [86] applied DAS technology for seismic exploration to image subsurface geothermal reservoirs in magmatic environments. DAS technology was used to mitigate the deficiency of downhole seismic survey results for subsurface geothermal exploration. The fiber optic cables were equipped with an SMF for DAS and MMF for DTS measurement, operating at temperatures above 400 °C; hence, the cable was coated with copper. The conceptual acquisition design of the DAS cable installation was based on a surface layout (buried in a trench) of optical cable deployed in the x and y directions and along the wellbore installation in the z direction to achieve a three-dimensional cable array. The cable installation result indicated that the main effect on the SNR of the measurement was caused by the coupling between the wellbore and fiber optics. DAS data were recorded along fiber optic cables with a 5.9 km cable length and
settings of spatial resolution of 1 m and measured as strain rate. A seismic vibrator truck was used for DAS measurement as its active source. Subsequently, conventional VSP used a swept-impact seismic technique as an active source. Further data preprocessing steps such as shift and stack correlation were performed to generate estimated SNR and processed along with data recorded by a seismic station network. Measured DAS and geophone vertical components were compared in terms of SNR at certain depth intervals, indicating that significant result in terms of quantitative SNR values. The measured signals of surface optical fiber and a 3C geophone were compared to detect the signal generated by the seismic vibrator with an appropriate SNR value. Combining the DAS data with data from a seismic network deployed on the surface increased the resolution of the seismic survey imaging. These research findings also highlight the use of DAS as an option to overcome the operating temperature limitation of conventional geophones, as well as the specifications within a magmatic geothermal environment required for fiber optic cable material to be able to tolerate the geothermal reservoir temperature. When used to image a subsurface geothermal reservoir, the result proved that DAS is well-suited to be used for seismic applications in high-temperature wells.

The research reported in [87] discusses the sensing sensitivity improvement of a surface-deployed DAS fiber configuration to detect steep-angle P-wave reflections. The aim of this DAS measurement was to enhance the sensitivity of the existing surface DAS tests conducted at the site. The sensitivity was improved by augmenting the total vertical alignment of the fiber inside experimental setups consisting of both helical and straight fiber segments. The test was conducted using fiber optic cables that consisted of two SMFs and two MMFs placed inside a stainless-steel tube and wrapped with 0.61 mm stainless-steel armor wires and a polyethylene jacket. For the horizontal configuration, the cable was placed along a shallow trench. The specified DAS VSP settings of the acquisition parameters were a gauge length of 10 m, spatial sampling of 1.02 m, and a fiber cable length up to 4288 m. The DAS recording was measured as strain rate. During the 3D seismic survey conducted at the designated site for the DAS test configurations, data were collected simultaneously. A total of 401 dynamite shots used as active sources were captured by the DAS test cable. The raw data for single dynamite shots and NMO-corrected receiver gatherers were compared to assess their similarity to geophone data. The variability in the responses of the various configurations along the test cable was observed to proceed with significant data processing, NMO correction, and trace stacking. The DAS configurations of these measurements, the buried geophone, and a receiver from the permanent DAS fiber were compared, indicating surface coupling within amplitude variation offset (AVO) plots referring to the data. Subsequently, numerical modeling was applied to assess the DAS response of the asymmetric helical fiber. This modeling result indicated that the recorded field response was mostly influenced by the fiber shape rather than the borehole coupling. The results of the sensitivity analysis showed that the asymmetric helix and vertical straight fiber configurations had the maximum sensitivity increases with steep-angle P-wave reflections, which were attained by decreasing the surface-wave response and increasing the signal response. However, the research result indicated that it was still associated with uncertainties in locating channels along the fiber and gauge length within the shot configuration. For future DAS testing, increasing the configuration cable length to the gauge length is necessary to associate the seismic measurement observed on multiple channels and reduce the uncertainties of channel authorization using tap tests to obtain the best cable coupling of the DAS fiber.

The research reported in [88] involved a time lapse of DAS VSP imaging in the Aquistore CO$_2$ reservoir. The Aquistore project utilized 4D VSP to perform volumetric reservoir assessment and locate the injected CO$_2$ plume over time. Further processing and resulting imaging discrepancies in the VSP data for extremely closely spaced images were analyzed to estimate the time-lapse noise from field recordings. During the data imaging process, the reduced SNR of the DAS data was mitigated by a noise attenuation algorithm as measured by NRMS values. Nevertheless, it is clear that the SNR of the DAS data was
lowered by the NRMS attenuation of noise. The DAS measurements used fiber optic cables consisting of two MMFs for DTS and two SMFs for DAS measurement. The cable was deployed inside stainless-steel production tubing clamped to the outside of the well casing and cemented in place, as illustrated on Figure 8. The DAS data were recorded using a 10 m gauge length and 2.036 m sensor spacing and measured as strain rate. The obtained DAS VSP data were further processed and converted to high time-lapse NRMS values and an image of the horizon of the reservoirs. The processing and imaging results indicated that the reservoir baseline exhibited fluctuating SNR characteristics. However, it still achieved an acceptable level of repeatability to identify time-lapse noise. The research outcome highlights that DAS VSP is considered a useful technique for time-lapse monitoring of CO₂ reservoirs. For future enhancements in DAS VSP results, more attempts should be made with respect to the processing step and the development of its framework.

![Figure 8. Schematic illustration of SMF and MMF along a wellbore.](image)

All relevant literature discussed in this section is summarized in Table 6 below.

**Table 6. Summary of subsurface imaging applications of combined SMF and MMF cable used in relevant studies.**

<table>
<thead>
<tr>
<th>Authors</th>
<th>Scope of Work</th>
<th>Cable Deployment</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daley et al. [28]</td>
<td>Simultaneous DAS VSP</td>
<td>Cemented outside of the well casing</td>
<td>No significant difference in the comparison of SMF and MMF recording results, and SNRs were improved by weighted stacking of DAS VSP data</td>
</tr>
<tr>
<td>Booth et al. [85]</td>
<td>DAS VSP on Store Glacier</td>
<td>Installed in a borehole enclosed in a gel-filled, stainless-steel capillary tube</td>
<td>DAS VSP was able to detect the sediment layer and interpret temperate ice and seismic properties in transitions of ice-crystal fabric and temperature regime</td>
</tr>
<tr>
<td>Reinsch et al. [86]</td>
<td>Seismic exploration in geothermal areas</td>
<td>Surface layout (x and y directions) and deployed behind casing inside the well (z direction)</td>
<td>DAS with data from the seismic network deployed at the surface increased the resolution of the seismic data and proved to be suitable for geothermal environments</td>
</tr>
<tr>
<td>White et al. [87]</td>
<td>DAS VSP configuration test</td>
<td>Cemented behind well casing and buried in a shallow trench (surface)</td>
<td>Surface DAS fiber configurations increased the sensitivity to steep-angle P-waves of seismic reflections</td>
</tr>
<tr>
<td>Harris et al. [88]</td>
<td>Aquistore reservoir imaging</td>
<td>Inside stainless-steel tubing clamped to the outside of the well casing and cemented in place</td>
<td>DAS VSP produced time-lapse monitoring and accurately imaged NRMS values and CO₂-based anomalies at specific reservoir depths</td>
</tr>
</tbody>
</table>
5. Conclusions

As fiber optic technology, DAS has been shown to be efficient in geophysics exploration such as VSP, reservoir monitoring, microseismic detection, and the application of ML approaches, as discussed in the previous chapter. Over the years, the oil and gas sector has made advancements in implementing DAS technology, mostly due to its cost-effectiveness in deploying optical fiber cables along linear assets like pipelines and wells [89]. However, considering prevailing economic conditions, there arises a necessity to optimize data processing within subsurface images and harness existing datasets for enhanced reservoir monitoring in the application of DAS. Based on the reviewed literature, it can be concluded that SMF has been shown to be a better fiber optic cable than MMF, as it is more widely used and capable in long-distance and higher-resolution sensing [28,57]. The cable deployment method and acquisition parameters become essential in evaluating these two types of fiber optic cable in geophysics exploration. VSP provides high confidence in seismic data along the borehole, and reservoir monitoring is a good tool for exploring reservoirs, whereas microseismic measurement provides physical data at low frequencies but is limited in terms of operation for accessible exploration. These DAS data sources are highly complex and, in most cases, are contaminated by optical noise, although they have been employed to obtain accurate and excellent measurements of subsurface images. The integration of many data sources is beneficial in enhancing imaging capabilities, with DAS data specifically proving valuable for subsurface imaging purposes. SMF has been shown to be effective in subsurface imaging but faces some limitations, such as interference signals in Rayleigh backscattered light [90], as well as existence of the noise floor [62]. These limitations are addressed by employing proper active DAS measurement sources, enhanced spatial resolution, and SNRs; the use of a deliberate cable deployment method; and selection of relevant acquisition parameters. Although MMF also faces its own inherent limitations, its strengths make it preferable when it comes to DTS and shorter-distance cable-length deployments due to lower prices. Combined SMF and MMF in the same cable deployment provides various places for measurement, with SMF used for DAS and MMF used for DTS measurement. The primary conclusions of our review are presented below.

1. Successfully employed SMF cables in the domain of surface and subsurface geophysics exploration was inspected in this review. The various SMFs were used to record acoustic properties of a signal along the cable and have become the most used type of fiber optic cable for DAS. However, in this review, when SMF and MMF were combined, MMF was found to be preferable for DTS measurement in most research studies in terms of temperature variations and high bandwidth.

2. The cable deployment technique is a crucial initial factor, leading to considerable efforts with respect to its DAS data processing and application in the field of geophysics exploration. This can be improved by the enhancement of preprocessing steps not limited to the control of DAS acquisition parameter optimization, improving SNR values, in addition to a comparison with other seismic measurement tools such as conventional geophones.

3. DAS VSP is the most popular technique used to image the subsurface along the borehole. Furthermore, DAS for microseismic measurement was able to detect small microseismic events with high resolution. Although this method works well, it has some major drawbacks that may lead to reduced imaging resolution due to various noise for both SMF and MMF. To achieve a satisfactory resolution of the DAS data, preprocessing steps are imperative to improve data denoising. Subsequently, the ML algorithm approach offers automated DAS data denoising with high accuracy.

The application of DAS is here to stay as petroleum geoscientists are progressively turning from conventional geophone arrays for boreholes and surface seismic measurement. Individual conventional geophones carry vital information about seismic imaging. However, when combined with DAS, they are more efficient in terms of accurately and continuously capturing obtained seismic signal behavior rather than spending time and
cost carrying complicated field acquisitions. Field data acquisition is a critical initial step in subsurface imaging, and the application of DAS has been proven to be effective, as it is able to acquire data in hard-subsurface environments and can be used for real-time monitoring. The cost, number of signal data samples along the measurement array, and time to acquire seismic data can be significantly reduced with the application of DAS if a proper deployment of a DAS SMF or MMF cable is used to help improve data acquisition parameters and the data processing of conventional geophones as a comparison for high-resolution subsurface imaging. SMF and MMF cable deployment has served as the benchmark for research in this endeavor as more advanced DAS data processing work is being developed to address this issue.

The enhancement of the data processing framework to obtain higher-resolution images of subsurface values for the evaluation seismic images has a huge impact on geophysics field exploration. In the case of fiber optic cables combined with SMF and MMF, the deployment of an MMF cable is yet to be explored in acoustical parameter sensing. Its application can be more useful for DTS measurement than SMF, especially when deployed to record temperature variations. These deployment mechanisms for both SMF and MMF cable can be employed to enhance the signal resolution and improve the processing of DAS data, leading to improved seismic imaging and interpretation. This will help to fully utilize conventional geophone arrays for efficient measurements and imaging of subsurfaces. Incremental research advances, whether in the study of DAS data acquisition or processing, play a crucial role in improving the decision-making process within geophysics exploration, making future development studies crucial. Future research on the development of SMF and MMF to improve DAS measurement can be started with a focus on the surface DAS acquisition layout; these types of fiber optic cables deployed along long-distance trenches can be compared with geophone responses to find the most suitable acquisition parameter settings. Subsequently, for further data processing enhancement, it is always better to begin with synthetic simulation for SMF and MMF responses to understand the processing framework, including a filter for conversion of the DAS strain rate to geophone units and exploration of more ML algorithms that might result in better data or model classification and denoising.

Author Contributions: The M.R. contributed to study conception, the literature review, material preparation, data collection, and analysis. K.A.M.N., A.H.A.L., D.A.O., B.N.T.-O., A.D.P., Z.A.R. and D.T.A. reviewed the manuscript and offered advice. All authors have read and agreed to the published version of the manuscript.

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References


7. Willis, M.E. Chapter 4 Fiber optic cables. In Distributed Acoustic Sensing for Seismic Measurements—What Geophysicists and Engineers Need to Know; Society of Exploration Geophysicists: Houston, TX, USA, 2022; pp. 45–52. [CrossRef]


44. Bao, X.; Chen, L. Recent Progress in Distributed Fiber Optic Sensors. *Sensors* 2012, 12, 8661–8639. [CrossRef]


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