Seismic Monitoring With Distributed Acoustic Sensing From the Near-Surface to the Deep Oceans

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(Invited Paper)

***Abstract*—Distributed acoustic sensing (DAS) delivers real-time observation of physical perturbations such as vibrations or strain variations in conventional optical fibers with high sensitivity. The high density of sensing points and large network footprint provided by a single DAS system, along with the availability of a vast optical fiber network already deployed both in land and in oceanic regions, contrast with the high deployment and maintenance cost of conventional instrumentation networks for seismology. This situation has triggered a rapid growth of DAS deployments for seismic monitoring in recent years. Photonic engineers and geophysicists have joined efforts to prove the value of optical fibers as distributed seismometers, which has resulted in a wide panoply of tests demonstrating diverse applicability across the geosciences. For example, DAS has been successfully applied recording local to teleseismic earthquakes, monitoring glacial icequakes, and observing oceanographic phenomena at the sea floor. Most of the realized tests have been performed using commercially available optical fiber interrogators based on phase-sensitive optical time-domain reflectometry. Among them, DAS based on chirped pulse distributed acoustic sensing have provided optimized performance in terms of both range and sensitivity, particularly at low frequencies. In this communication, we provide a comprehensive review of the current situation of DAS for seismology applications, focusing on near surface monitoring, where already deployed optical fibers can be repurposed as sensor networks.**

***Index Terms*—Distributed acoustic sensing, fiber optics sensors, optical time domain reflectometry, Rayleigh scattering, remote sensing and sensors, seismicity, velocimetry.**

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I. Introduction

THE performance of distributed optical fiber sensors has been continuously improving since their conception in terms of resolution, number of monitoring points and sensitivity. As a result, distributed sensors have increasingly expanded their applicability over more and more areas [1]–[5]. About 7-8 years ago, one kind of distributed optical fiber sensor based on Rayleigh scattering, known as distributed acoustic sensor (DAS), attracted the attention of geologists and geophysicists for its use in the monitoring of seismic activity. The principal reasons for this recent and heightened interest are the high sensitivity achievable by DAS in the bandwidth where most of seismic events occur (1 mHz to 100 Hz), and the high number of intrinsically synchronized channels (i.e., monitoring points) attainable in a single, conventional optical fiber (approaching 10^5, with ranges over 100 km and spatial resolution in the order of meters). DAS has been successfully employed in active and passive seismic monitoring, particularly in downhole deployments. In these studies, dedicated fibers have been installed in boreholes for recording seismic signals at depth, with interesting advantages over traditional downhole receivers, e.g., the higher robustness of the fiber in extreme temperature and pressure over electronic components, the simpler installation procedure and the higher spatial resolution. A recent publication reviews the applications of downhole DAS [6]. In near-surface studies, researchers have leveraged the existing network of pre-existing optical fibers around the world, resulting in reduced deployment and maintenance cost for seismic monitoring instrumentation relative to conventional technology. This last application is particularly interesting in oceanic regions, where the presence of ocean bottom instrumentation is severely limited due to the elevated cost of deployment and the reduced durability of the instruments. The repurpose of submarine fibers as distributed seismographs may lead towards a revolution in the field of marine seismicity and Earth tomography, and recent studies and field tests already offer promising results.

It is worth noting that, even if the DAS instrumental response has been relatively well characterized (the literature contains numerous of studies on the effects of noise induced by the system components [7]–[10] and calibrating DAS with conventional instrumentation [11], [12]), the sensing response strongly depends on the coupling between the optical fiber and the ground, the type of cable and the conditions of the fiber installation. Generally, the individual response of a single DAS sensing point is significantly worse than that attained by a traditional seismograph. However, the fact that DAS delivers a high density of sensing points (separated by the spatial resolution, usually in the meter scale) distributed over a certain length of fiber (typically tens of kilometers) opens the door for attaining new detection capabilities by performing advanced signal processing of the detected strain array, even superior to that of existing seismometer arrays [13]. Field tests in a wide variety of terrains have proven the strong potential of fiber cables to record seismicity. Researchers have gathered information from quiet regions using specifically deployed fibers in a certain geometry [14], [15], urban areas with heavy anthropogenic noise using already deployed telecommunication cables [16]–[18], ocean-bottom fibers [19]–[23], fibers deployed in glaciers [24] and so on.

Several reviews of the use of DAS in seismology can be found in the literature [25]–[28], mainly from a geophysical point of view. In this communication, we aim at performing a review of DAS in seismology from an engineering/instrumental point of view, mainly focusing on horizontal, near-surface deployments. In Section II, we review the principles of DAS. Then, we describe the particularities of the optical fibers to be used for a cost-efficient operation (Section III). In particular, we remark the latest studies on coexistence of DAS with coherent communication systems. The characteristic performance expected from DAS systems specific to studies in seismology is described in Section IV. Section V includes existing algorithms employed to detect certain physical processes (such as seismic waves) from the measured strain values. Next, we revisit several examples of DAS deployments in which DAS offers comparable or better performance than traditional instrumentation (Section VI). Finally, we sum up the main conclusions that can be extracted from the current status of this line of research.

II. Principles of Distributed Acoustic Sensing

Distributed acoustic sensors are one kind of distributed optical fiber sensors capable of measuring perturbations of physical parameters in the proximity of an optical fiber in real time and within an acoustic bandwidth (in the kHz regime). To fulfill these performance features, DAS is based on Rayleigh backscattering. A probe pulse, which is typically a highly coherent transform-limited pulse, is injected into a conventional single-mode fiber. The Rayleigh-backscattered light is monitored in the time domain, which is associated with fiber position using the time of flight of the light pulses in the fiber. As coherent pulses

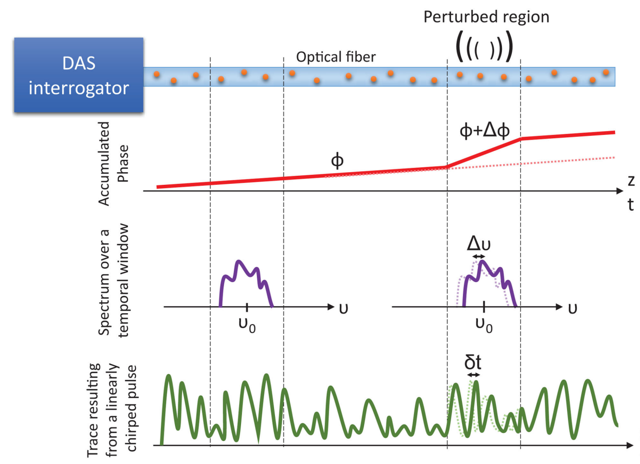

Fig. 1. Description of the principle of operation of a DAS system. The accumulated phase over the length changes its slope in the perturbed region proportionally to the applied perturbation. This effect translates into a bandwidth shift of the spectrum over the perturbed time window. Under certain conditions, a chirped pulse probe induces a frequency-to-time mapping that translates the bandwidth shift into a local temporal delay in the trace intensity.

are used, the DAS signal will be the result of the coherent interference between the fields which are Rayleigh backscattered from multiple scattering centers along the fiber. A perturbation in the surroundings of the fiber due to a strain or a temperature change may cause a relocation of the fiber scattering centers due to a fiber elongation, Δd, and/or a local change in the fiber refractive index, Δn. This perturbation modifies the temporal intensity profile of the detected backscattered traces in a nonlinear fashion. The straightforward method to quantify the ongoing perturbation is through the demodulation of the optical phase of the trace. The phase accumulated over the light propagation is proportional to the fiber refractive index and the distance, i.e., $\phi = k \cdot n \cdot 2z$, where k is the wavenumber ($k = 2\pi/\lambda_0$, with λ_0 the light central wavelength), n is the refractive index and $2z$ is the two-way length that the backscattered light travels. When the fiber suffers a perturbation, the accumulated phase varies locally as $\phi + \Delta\phi$ (Fig. 1), where

$$\Delta\phi = \frac{4\pi}{\lambda_0}\Delta n \cdot \Delta z + \frac{4\pi}{\lambda_0} n \cdot \varepsilon \cdot \Delta z, \tag{1}$$

Δz being the perturbation length, and $\varepsilon = \Delta d/\Delta z$ the perturbation-induced strain. In general, the effect of the ongoing perturbation can be seen as an effective refractive index variation, in such a way that (1) can be rewritten as

$$\Delta\phi = \frac{4\pi}{\lambda_0}\Delta n_{eff} \cdot \Delta z, \tag{2}$$

with $\Delta n_{eff} = \Delta n + n \cdot \varepsilon$. Hence, temperature and strain perturbations on the fiber are virtually indistinguishable. The phase of the photodetected trace can be readily obtained by employing any type of coherent detection [29], [30]. By comparing the trace-to-trace accumulated phase over certain gauge length (imposing the sensor resolution), the effective refractive index variation can be quantified.

In addition to the propagation of a transform-limited pulse, researchers have also tested coded waveforms to increase the spatial resolution of the system or to improve the signal-to-noise ratio (SNR) [31], [32]. In these cases, the traces are typically decoded in the digital domain by the application of e.g., matched filters to the coherently detected traces. However, coherent detection presents several shortcomings. First, the phase cannot be properly demodulated in some points called fading points. Fading points arise from the fact that the amplitude of the detected trace has a Rayleigh distribution owing to the coherent interference. Hence, in a considerable number of regions, the amplitude has very low value, so that the phase reference is lost. Additionally, the dependence of the phase demodulation with the amplitude of the trace in each point leads to an uneven sensitivity of DAS points [10].

To avoid fading points, a number of phase demodulation strategies have been reported in the literature, such as detection using a Mach Zehnder modulator with a 3x3 coupler [33], the use of a probe signal composed of phase modulated pulses to emulate the previously mentioned scheme [34], the use of a dual-pulse probe with different central frequencies [35], the use of a spectral extraction and remix method [36], etc. In general, the effect of fading points is mitigated by applying post-processing interpolation algorithms [37], [38].

An alternative method to quantify the perturbation from the direct detection of the traces relies on the use of linearly chirped probe pulses [39], [40]. If the chirped-induced bandwidth of the probe pulses ($\delta \upsilon_p$) is much broader than the bandwidth of the transform-limited pulses ($\sim 1/\tau$, with τ the pulse width), a frequency to time mapping occurs in the trace. Under a perturbation over a length Δz, the bandwidth of the propagating light experiences a constant shift locally on the perturbed region proportional to Δn_{eff} (Fig. 1). From (2), we can write the accumulated phase as a function of the propagation time,

$$\Delta\phi = \frac{4\pi}{\lambda_0}\frac{\Delta n_{eff}}{n}\cdot\frac{\Delta t}{2}\cdot c = 2\pi\cdot\upsilon_0\cdot\frac{\Delta n_{eff}}{n}\cdot\Delta t, \quad (3)$$

where c is the speed of light in vacuum and υ_0 is the carrier frequency. The frequency shift suffered along the perturbed fiber region (of duration Δt) can be expressed as

$$\Delta\upsilon = \frac{1}{2\pi}\frac{d\Delta\phi}{d\Delta t} = \upsilon_0\cdot\frac{\Delta n_{eff}}{n}. \quad (4)$$

The frequency to time mapping produces then a local temporal shift in the trace δt that accomplishes [40]

$$\frac{\delta t}{\tau} = -\frac{\Delta\upsilon}{\delta\upsilon_p}. \quad (5)$$

Substituting (4) into (5), we obtain the temporal shift proportional to the ongoing perturbation (Fig. 1),

$$\delta t = \upsilon_0\frac{\Delta n_{eff}}{n}\frac{\tau}{\delta\upsilon_p}, \quad (6)$$

which can be obtained by performing trace-to-trace correlations over a window equal to the pulse width, τ, corresponding with the spatial resolution. Among the advantages of this technique, we can mention the simplicity of the optical setup, as simply direct detection is required avoiding the need for polarization diversity coherent detection; insensitivity to fading points which leads to even sensitivity of all points along the trace [41], and the

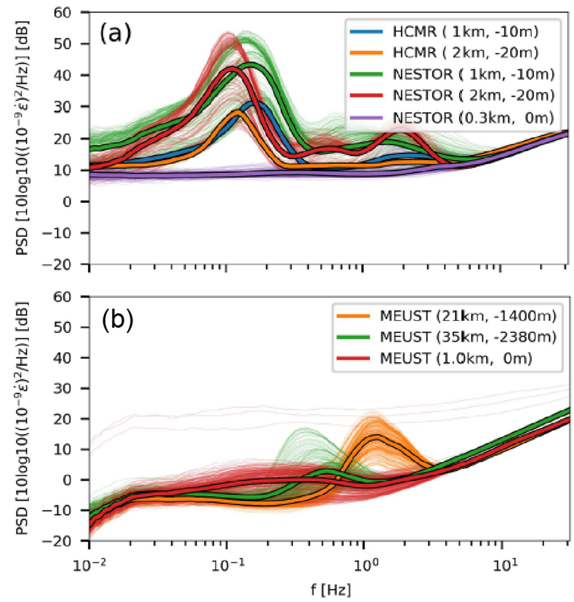

Fig. 2. Comparison of DAS nanostrain-rate for two phase-demodulation commercial DAS (a) and a chirped-pulse commercial DAS (b). Different lines indicate power spectral densities (PSD) at specific distances from the interrogator and water depths, as indicated in the panel legends. Figure extracted from Ref. [21].

possibility of compensating the laser phase noise [42] permitting very high sensitivity even when using moderate linewidth lasers. Besides, it has been demonstrated that the chirped-pulse configuration offers better performance at low frequencies (i.e., $<$1 Hz). The reason is the more sporadic need for reference updates for a proper quantification of the strain [43]. This is attained at the cost of higher requirements in terms of detection bandwidth for the same spatial resolution (at least one order of magnitude). However, this good performance at low frequencies is critical particularly in seismology applications (Fig. 2) [21]. In particular, in [21], up to 30 dB reduction in the noise floor has been measured in chirped pulse DAS with respect to phase demodulation DAS (both of them being commercial equipment) at frequencies of 0.01mHz.

There is an alternative strategy to quantify the perturbation based on an analysis in frequency domain, where the shift that compensates for the refractive index variation (4) is searched via frequency-domain correlations [44]. However, this method requires the generation of arrays of traces at different frequencies, hampering the ability of sensing perturbations at acoustic frequencies.

Nowadays, commercial DAS interrogators are based on either phase demodulation (with or without matched filtering) or direct detection with chirped pulses. Both types of DAS devices are currently used in seismology research with very promising results.

III. Towards Cost-Efficient Sensing Fiber Networks

In the literature, even if it is possible to find references where the fiber cable has been specifically installed for the development of near-surface seismological tests [14], [45], [46], most of the published works employ existing fibers deployed for different purposes, mainly for telecommunications. The principal reason is that the use of DAS in this field seeks the leverage of existing technology and infrastructure with reduced costs.

Generally, demonstrations of seismic monitoring using DAS to interrogate installed fibers make use of dark fibers, i.e., unlit backup fibers included in the cables [16], [19]–[21], [47], [48]. However, employing dark fiber implies reserving the full fiber strand for the DAS operation, usually comprising only one-wavelength signaling. This is very inefficient for wide scale deployment of sensing networks. Moreover, the huge capacity demand for optical fiber and the onset of new markets offering private services on dark fiber networks have caused a shortage in certain regions. Hence, the search for solutions that make a more efficient use of existing infrastructure has become a priority. The coexistence of both data and sensing information on the same fiber offers the most powerful and cost-effective solution by additionally turning entire networks into distributed sensing systems. The requirements for coexistence of 100G/200G optical coherent channels and a chirped-pulse DAS on the same optical fibers have been analyzed in [49], in both a co-propagating and contra-propagating configuration. The sensing probe signal is launched in the fiber at a different wavelength than that of a single coherent channel and a set of WDM channels. The induced nonlinear crosstalk is analyzed for different DAS probe peak powers and pulse widths. In this study, it was concluded that the sensing performance of the DAS upholds nearly invariant in all the tested scenarios. Co-propagation of the DAS probe with communication channels needs to accomplish strict requirements on pulse power and width (See Fig. 3) for proper operation with existing commercial coherent transceivers based on polarization multiplexed - quadrature phase shift keying (PM-QPSK) format. In particular, the bit error rate (BER) of the coherent channels increased as a function of the peak power of the probe pulse, hindering the information transmission even after the post processing of forward error correction (FEC) algorithms. However, it has been proven that counter-propagation works for all different testing scenarios. This study offers appealing perspectives for the repurposing of existing telecommunication fiber networks. Nowadays, most of the oceanic optical networks employ two unidirectional fibers for communication, ensuring the availability of one fiber to be interrogated by a probe counter-propagated with the transmitted data. Further studies in this promising work line are expected to be realized in the near future.

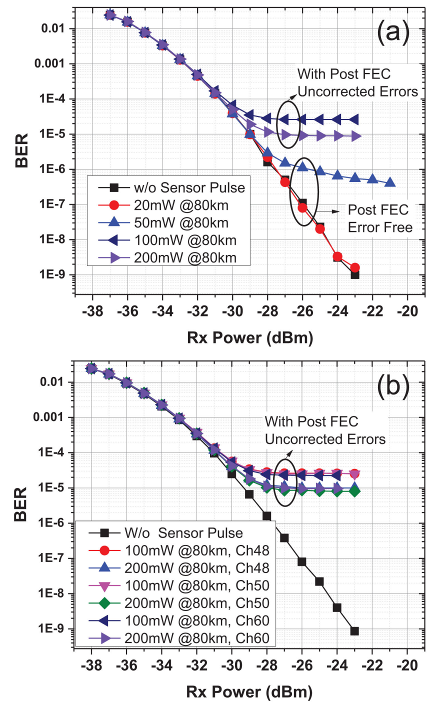

Fig. 3. Coherent channel pre- and post-forward error correction (FEC) bit error rate (BER) results in coexisting setup: (a) Single-channel PM-QPSK with sensing signal. (b) PM-QPSK WDM channels with sensing signal. Figure extracted from Ref. [49].

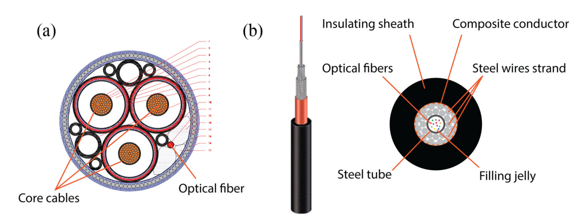

Fig. 4. Examples of cables incorporating optical fibers that have been employed in DAS field tests for seismic applications. (a) Cable employed in Ref. [19], including three core metallic cables and one optical fiber. The cable is heavy and it is buried. (b) Cable employed in Ref. [50], including 12 optical fibers and a metallic armor. The cable is lightweight and it is loose on the ocean bottom.

IV. Performance of DAS in Seismology

The quality of the DAS recordings is strongly dependent on the cable coupling to the ground, the cable sensitivity related to its internal structure and the topography/bathymetry along the fiber route. Different types of cable structures have been employed in field tests, from passive loose-buffered cable non-buried to more complex and heavier cables carrying electrical power with an optical fiber incorporated to monitor the cable integrity (Fig. 4) [19], [21], [50]. When discussing the repurpose of already deployed optical fibers as seismograph arrays, it is important to consider that typically, cables installed for the sole purpose of power and data transmission are not mechanically coupled to the ground in a uniform fashion. On-land cables may have overhead line sections; sections deployed leveraging existing channelization, etc. [16]. Telecommunication fiber cables dropped into deep ocean bottom are typically lightweight and are not buried. Outdoor fiber deployments typically use loose tube cables, with the goal of avoiding strain coupling to the cable to minimize losses, which in turn reduces the sensing performance. Conversely, active cables or cables deployed in shallow waters are usually heavy and/or buried to avoid damaging due to ship anchors or fishing activities. This panoply of possibilities severely affects the quality of the measured data for earthquake detection. Although there is a large variety of possible cables and deployments, almost all these installations do provide some sensitivity to seismic stimuli, which in many cases is sufficient to detect seismic ambient noise for use in tomographic studies.

Directly buried, tight-buffered cables should be the ones ensuring the best strain coupling between the ground and the fiber, increasing the reliability of the measured data.

Studies in submarine regions have shown that the recording quality is additionally correlated with the bathymetry and the apparent phase velocities of recorded waves [21]. Flat or smooth bathymetric slopes create conditions for better fiber coupling to the seafloor and even eventual burial, while irregular bathymetry prevents sediment deposition and may represent regions of erosion. In both onshore and offshore DAS experiments, it has been observed that for the same ground motions (in terms of particle velocity or acceleration), slower waves induce higher strain rates and thus are more readily detected than faster waves. For this reason, some studies have determined that underwater DAS detection capabilities are superior to those of on-land fiber segments, owing to lower velocities at the seafloor.

As already mentioned, one of the most interesting attributes of DAS is that it provides a dense network of point sensors distributed all along the fiber length. However, only single component measurements are obtained, oriented along the fiber. This contrasts with the 3D measurements of traditional seismometers and accelerometers, based at a single location. The employment of optical fibers with a geometry including orthogonal sections has been already tested aimed to implement 2D sensing, although it has not been fully exploited yet [14], [16], [51]. Additionally, cables providing broadside sensitivity have been also tested, in which the fiber is helically wounded within the cable [52], [53]. However, this solution is not compatible with the repurposing of already deployed telecom cables.

Concerning the attainable range in the published studies, the vast majority attain ranges of several tens of kilometers. One of the longest fiber lengths interrogated by a single DAS sytem is 60 km [50]. Under laboratory conditions, DAS has attained ranges over 150 km [54]. Although very efficient for spatio-temporal signal processing, seismic wave detection, and phase velocity determination, these ranges are still far from achieving the pursued instrumental coverage of the Earth surface and oceans.

Regarding the instrument noise, reported sources are temperature drifts, laser noise and fading points [16], [21]. Fluctuations in the temperature of the interrogator cause non-seismic noise, since temperature variations and strain cannot be readily uncoupled from the recorded measurements (1). Laser noise due to the linewidth of the laser source plays also an important role. This source of noise can be mitigated by a median stacking of channels at the cost of spatial resolution, although this solution may affect the precision in the seismic wave measurements [15], [55]. In chirped-pulse DAS this source of noise can be readily measured and compensated with no cost on the measurement quality [42]. The uneven sensitivity and the existence of fading points of phase demodulation DAS is another source on non-seismic noise [10]. As previously mentioned, this effect is nearly inexistent in the case of chirped-pulse DAS [41].

V. Post-Processing Algorithms

Once the strain experienced by an optical fiber is obtained, different post-processing algorithms are applied to extract the desired seismic information from the fiber. The variability in the measurand reliability of DAS systems has led to the development of different algorithms and post-processing strategies, in the search for a steadier and simpler dataset.

A. Conversion of DAS Recorded Strain

Traditional seismometers record particle velocity in three dimensions, while DAS record ground strain in one dimension (i.e., along the fiber length). Studies comparing measurements from different instruments are critical for a proper characterization and calibration of DAS. This implies a conversion from ground strain to ground motion.

The particle velocity measurements recoded on two nodal seismometers separated by a small distance L can be converted into the average longitudinal strain rate $\dot{\varepsilon}$ between the two modes as

$$\dot{\varepsilon}(x) = \frac{1}{L}\left[\dot{u}\left(x + \frac{L}{2}\right) - \dot{u}\left(x - \frac{L}{2}\right)\right], \tag{7}$$

where $\dot{u}$ is the particle velocity in the direction parallel to the positional difference vector between the two nodes. This average strain rate is proportional to the DAS strain measured along a gauge length L whose end points are co-located with the nodes [46], [56]. However, the strain rate loses coherence for waves with relatively fast velocities (e.g., body waves in earthquakes) (see [21]). Hence, the integration of DAS strain rate data along the cable to obtain phase velocities has proven to dramatically improve the waveform coherence and beamforming performance of DAS, which have been used for source location in local seismicity [56].

Converting the raw strain dataset acquired by DAS into strain rate (i.e., derivative of strain over the time) [21], [23], [57] is still a common practice in order to facilitate direct comparison with traditional seismic or hydroacoustic instrumentation. Yet, it is worth noting that signal differentiation works as a high-pass filtering process, severely increasing the noise at low frequencies and hence tampering with one of the most interesting features of DAS.

B. Denoising Algorithms

Denoising is critical in seismological applications. All kinds of vibrations within a broad spectral band (about 5 decades) in the surroundings of the interrogated fiber are detected with a sensitivity of about 0.1 n$\varepsilon/\sqrt{\text{Hz}}$ when using chirped pulse DAS [50] and 1 n$\varepsilon/\sqrt{\text{Hz}}$ for phase demodulation DAS [57].

There is little control of the exact placement of the fiber with respect to a seismic source, especially in those cases where fiber was deployed for completely different purposes, e.g., telecommunication fibers in urban regions or loose fibers in oceanic regions. Depending of the target in a particular study, signals of interest may have very low amplitude, even below the noise level (considering all the non-interesting detected waves to be noise, including ambient seismic noise and coherent near-field environmental or anthropogenic seismic sources). The high density of monitoring points available in an optical fiber provides spatio-temporal information about the wave, which can be employed

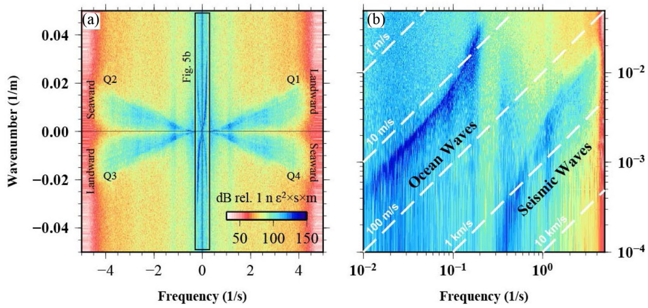

Fig. 5. (a) Frequency-wavenumber power spectrum of 1 h of strain data acquired from a submarine optical fiber already deployed the North Sea for monitoring of a power cable connected to a wind farm. (b) Detail of the quadrant 1 of (a), corresponding to landward-propagating waves. Darker blue represents bursts of energy corresponding to ocean waves and seismic waves. 2D linear filtering would permit isolation of these types of waves due to their different phase velocities. Contours of constant phase velocity are represented in dashed white lines. Image extracted from Ref. [19].

to perform 2-dimensional (2D, i.e., time-wavenumber) linear filtering [31]. This enables removing spatially or temporally incoherent noise from spatio-temporally coherent waves, and permits isolation of waves with different phase velocities. As an example, in [19], a submarine fiber in the North Sea was interrogated using a chirped-pulse DAS. Fig. 5 shows ocean waves and seismic waves propagating at different phase velocities, i.e., tens of m/s for ocean waves and about 1 km/s for seismic waves.

Besides 2D linear filtering, the use of median filters and stacking of several channels is also common to alleviate the time-varying noise generated from temperature fluctuations and optical noise [25].

Machine learning approaches such as convolutional neural networks (CNN) have also been applied to reduce noise in DAS recordings [17], [58], [59]. CNN are widely employed in image denoising. Hence, CNN are applied on the three-dimension array of strain vs. fiber length vs time. The main disadvantage of supervised neural network algorithms is that previous knowledge of the noise level and features of the signals to be detected is necessary. This information is not always available, limiting the applicability of the system to pre-defined seismic signal detection.

More recently, self-supervised denoising algorithms based on machine leaning and, more specifically, on deep learning approaches have been proposed [60], [61]. These blind-denoising methods typically achieve a higher level of signal to noise ratio than linear filtering when removing spatio-temporally incoherent noise, with no need to provide noise-free ground truth.

C. Compression of DAS Data

One property of DAS systems is that the attainable sampling frequency can be limited by the fiber length, reaching the kHz regime. If smoother features are to be monitored, as in the seismic case, where a sampling frequency of 100 Hz or even lower is sufficient, averaging of traces is usually employed to reduce the sampling rate while increasing the traces SNR. In this case, uncompressed records can still be as high as 1 TB/day, considering a 16-bit recording of the strain at each channel.

In some installations, instrumental noise [40] and noise due to the poor cable coupling can make that about one third of channels provide no strain information [57]. Those channels can be readily discarded, which is a considerable reduction of the dataset. In order to keep a uniform spatial sampling in posterior data processing, missing channels can be filled with e.g., white noise.

Compressed sensing techniques have been proposed for denoising and signal compression. In [62], compressed sensing was validated numerically for microseismic signal denoising. More recently, a wavelet-curvelet compressive approach has been proposed aimed at turning the recorded seismic records into a single structured form that treats the wavefield as a coherent 3D entity [63]. The application of the temporal wavelet analysis and the weighted curvelets for spatial analysis also considers that the produced data must be adequately described by a seismic wave-physics framework including self-consistent spatial and temporal derivatives. This approach simultaneously produces a denoising effect and a compression of data, which is useful when the wavefield is sufficiently coherent. In that work, the authors attain a compression ratio of 8.3.

VI. Applications

With the current technical maturity of DAS, it has been possible to observe a wide variety of phenomena of high interest in geophysics and oceanography. The first reported works focused on relatively short period seismic waves, such as body waves (principal or P waves and secondary or S waves) and surface waves (e.g., Rayleigh waves). Such seismic waves are used to locate earthquakes and perform tomographic studies to determine the internal structure of the Earth. Additionally, near surface seismic imaging has particular interest in applications such as securing drilling operations, wind farm constructions, pipeline surveys, etc. DAS has enabled instrumentation of hardly accessible locations, such as glaciated or submarine regions [20], [64]. With the increased adoption of the technology, long period waves (e.g., tidal waves) and non-seismic wave detection have been also reported, unveiling the strong potential of DAS in combination with pre-existing fiber as a multipurpose, ubiquitous, broadband and relatively cheap sensing instrument. Here, we provide some examples of use of DAS for geophysical applications.

A. Earthquake Detection

One of the more evident applications of DAS in seismology is the detection of earthquakes. The arrival time of earthquake first-motions to a seismographic station depends on the distance to the epicenter and the type of wave (direct arrival of P or S waves, or reflection and refractions of these waves on the Earth inner layers). In general, earthquakes are detected at frequency bands ranging from 0.1 mHz to 100 Hz, though in practice only frequencies between 10 mHz and 10 Hz are typically used in earthquake detection/location and most tomographic studies. Frequencies lower than 10 mHz are only sensitive to deep Earth structure, and frequencies higher than 5–10 Hz are only used in strong ground motion studies or microseismic monitoring.

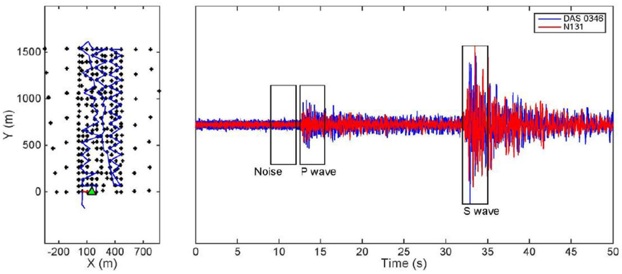

Fig. 6. Example of the comparison between normalized DAS strain rate (in blue) and raw geophone coil-case velocity (red). The box in the left hand size of the image shows location of DAS (blue line) and geophone (green triangle). Image extracted from Ref. [46].

The DAS recordings have captured earthquakes of different magnitude that have been extensively reported in the literature. For example, in [46], a moderate size M_L (i.e., local magnitude, also known as Richter magnitude) 4.3 earthquake was recorded at 150 km from the epicenter. An excellent match is shown between P and S phase arrivals from the DAS recordings and a nearby geophone (Fig. 6). In [65], a M1.9 local earthquake was detected, mainly via S waves. P waves were barely visible both in the DAS recordings and in a close seismic station, which was explained as a result of wave attenuation and source radiation pattern. In [20], a M_W (i.e., moment magnitude, developed for a more reliable means to estimate the size of large earthquakes) 3.4 earthquake was recorded using DAS in a submarine cable in California. Different body waves (namely, P, pP, PP, S and SS phase arrivals) were detected and matched predicted arrival times obtained from traditional instruments. In [19], a M_W 8.2 earthquake was detected from a location 16000 km away from the epicenter, which is known as teleseismic (i.e., detection of earthquakes originated >1000 km from the measuring point). This earthquake was simultaneously detected from an urban telecommunication fiber 9000 km away from the epicenter [16]. In this case, heavy anthropogenic noise was subtracted using frequency-wavenumber filtering.

B. Microseismicity

Microseismicity consists of small-scale earthquakes caused either by natural phenomena, such as debris flows, or by human or industrial activities, e.g., mining, or underground gas storage. Microseismicity is a power tool to study landscape-shaping processes and for early detection of hazardous mass movements, especially important in mountain chains and glaciers. Optical fibers have been deployed in poorly instrumented locations, such as glaciated regions, to that end [64]. Microseismicity has been also employed to detect hydraulic fracturing in unconventional gas reservoirs, and can also be induced or triggered by hydrocarbon production or wastewater disposal. A drawback of DAS with respect to geophones is the uniaxial strain recording, which hinders the identification of directionality and polarization of incoming waves. Array-based analysis of DAS records has made it possible to determine the polarity of the recorded waves even in anisotropic media, which is essential for microseismic event location and source mechanism determination [66].

C. Subsurface Characterization and Deformation Monitoring

DAS have been used to interrogate telecommunication fibers to obtain ambient seismic field recordings in urban areas, where geotechnical surveys are difficult to perform. Array processing of the ambient seismic field is employed to produce maps of shear-wave velocity in the shallow subsurface, which enables seismic site response estimation on a block-by-block scale within cities [18].

A similar analysis has been performed also in the ocean floor using seismic signals from ambient noise and earthquakes [21].

D. Submarine Instrumentation

Given that 70% of Earth's surface is underwater, the instrumentation of the ocean bottom is fundamental for the development of our understanding of the internal structure of the Earth and towards our ability to detect the source mechanisms of submarine earthquakes and landslides that can trigger tsunamis. However, deploying vast networks of seismographs in such regions is extremely challenging. Synchronization of ocean bottom instruments is difficult since GPS clocks are not available. Besides, the battery duration and the memory capacity are limited, while the costs of the instrument maintenance (including battery replacement, memory reset, and required reparations) are high. Fiber optics arise as an excellent solution to this lack of instrumentation in oceanic regions. Currently, there exists an extensive network of already deployed submarine optical fiber for telecommunication. Different tests have been performed employing dark fibers from submarine cables.

Submarine earthquake detection has been performed and analyzed. In particular, in [57], the authors demonstrate that the performance of high-frequency (>1 Hz) seismic observations from an ocean-bottom DAS is comparable to that of ocean-bottom permanent stations, provided the cable is well coupled with the seafloor [21].

Submarine structural characterization based on ambient noise DAS has been also analyzed. Scholte waves are extracted from DAS recordings, and the study of the Scholte wave migration provide sharp lateral contrasts in subsurface properties, particularly shallow faults and depositional features near the sea floor [22], [67].

The hydroacoustic capabilities of DAS have been also evaluated via active sources (air-guns from a ship based seismic survey), proving that the operation bandwidth of DAS is similar to that of hydrophones (from 0.1 Hz to tens of Hz), while maintaining the coherence over few kilometers (Fig. 7) [23].

1) T-Waves: T-waves are acoustic waves that propagate in the SOFAR (Sound Fixing And Ranging) channel of minimum sound velocity, which acts as a waveguide for acoustic energy in the oceans. They are excited by acoustic sources such as earthquakes, volcanic activity at the ocean floor, icebergs collisions, etc. T-waves provide insight into seismic sources in the oceanic environment. A report of T-waves recorded using chirped-pulse DAS has been recently published [50]. In this case, the fiber was poorly coupled to the bottom, what translates to high level of noise in the recorded dataset.

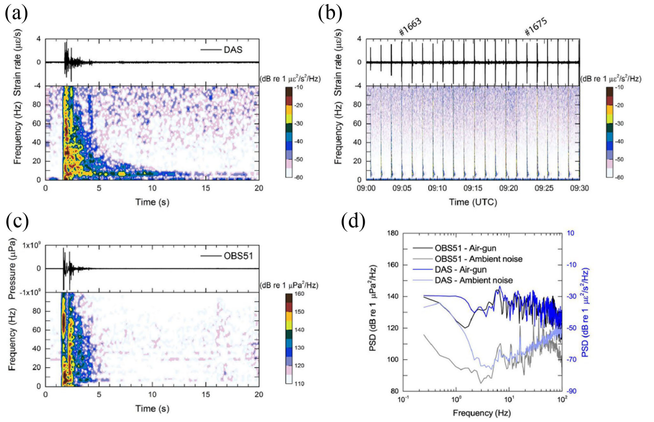

Fig. 7. (a) Hydroacoutic recording of an air-gun shot from a DAS measurement at a cable length of 20 km. (b) A series of air-gun shots recorded by the DAS. (c) Hydroacoustic signal initiated from the same explosion of (a) recorded by a hydrophone. (d) Poser spectral densities of the same signals recorded by the DAS and the hydrophone, comparing the ambient noise between air-gun shots. Image extracted from Ref. [23].

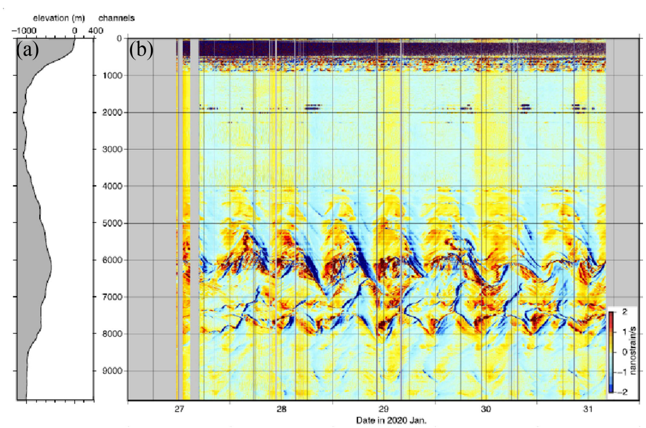

Fig. 8. (a) Bathymetry profile along the cable route of the Comprehensive Seafloor Monitoring System off Cape Muroto, consisting of a 50-km-long DAS observation section. (b) Space-time plot of the average strain rate (5-min interval) for an observation period of 5 days. Semidiurnal periods can be observed from the channel 1000 to 4000, while semidiurnal periods are observed from the channel 4000 to the end of the fiber. The ordinate axis, labelled as Channels, corresponds to fiber locations separated by a spatial resolution of 5 meters. Figure extracted from Ref. [57].

2) Internal Waves: Ocean internal waves play a significant role in ocean dynamics. Internal waves are associated to the mixing and transport of ocean energy budget. The observation of this kind of waves is pursued by oceanographers as a means to understand ocean mixing processes, e.g., affecting the thermohaline structure of water masses and its impact in coastal ecosystems. To date, the recording of internal waves via DAS has not been fully addressed, but researchers have hypothesized its observations, e.g., in [20].

3) Tidal Waves: DAS interrogators are able to detect long period waves that can be even considered as quasi-static, such as tidal waves (periods of 12 h or 24 h, corresponding to frequencies of tens of μHz) [57]. In this case, the detected strain amplitude varies widely along the fiber due to the differences in the cable-seafloor coupling due to complex bathymetry along the cable route. The authors analyze the strain rate, obtaining variations with a daily cycle in a certain deep-water fiber section, and stronger variations with a two cycles/day in a different region where the cable passes a ridge about 500 m higher than the rest of the instrumented ocean bottom (Fig. 8). Even if the recorded strain variations are too high to be explained by tidal deformation, the period of the variations clearly indicated that those are controlled by ocean tides, opening the door for a new field of research for oceanographers.

4) Non-Seismic Marine Acoustic Waves: DAS can be used as an array of hydrophones, opening up new opportunities for the investigation of acoustic sources in the oceanic environment. In particular, in the literature we can find reports of recordings of non-seismic signals such as thunderstorms, mammal vocalizations or ships [50], [68], [69]. Other non-seismic waves recorded by ocean-bottom DAS are seafloor pressure perturbations from ocean surface gravity waves (ocean waves) [19], [20], [65].

VII. Conclusion

DAS arises as an excellent alternative to traditional seismometers in poorly instrumented regions. Special attention is paid on regions hardly accessible such as the ocean bottom, where seismograph networks are sparse and the cost of deployment and maintenance is high. DAS converts any conventional optical fiber, such as that already deployed for telecommunications, into a dense network of microphones, and has already proven capable of detecting seismic waves in an intrinsically synchronized fashion, with high sensitivity and with performance comparable with traditional instrumentation. Over the last 7–8 years, extensive research have been done to develop mechanisms to fully optimize DAS technology for this particular applications, including: (i) denoising methods specially for the low frequency (sub-Hz) band, (ii) compression of acquired data, (iii) development of fiber configurations to circumvent the uniaxial sensitivity, etc. The coexistence of DAS with data transmission coherent channels has recently aroused interest for more efficient use of existing telecommunication networks as seismic monitoring systems. The strong potential of DAS in seismology is being unveiled, and applications such as global earthquake detection, active seismic monitoring, detection of oceanic waves such as T-waves, tidal signals, etc. have been already documented.

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