Title: Advances in Distributed Fiber-Optic Sensing for Monitoring Marine Infrastructure, Measuring the Deep Ocean, and Quantifying the Risks Posed by Seafloor Hazards

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PAPER

Advances in Distributed Fiber-Optic Sensing for Monitoring Marine Infrastructure, Measuring the Deep Ocean, and Quantifying the Risks Posed by Seafloor Hazards

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ABSTRACT

Distributed optical fiber sensors provide new opportunities for monitoring the marine environment. We review the physical foundations of this sensor technology and discuss how it can be applied to radically augment the networks of subsea sensors that help monitor fundamental marine processes and to complete our understanding of local, regional, and global interactions in this environment.

Keywords: distributed fiber-optic sensors, subsea infrastructure monitoring, seabed stability, turbidity currents, subsea seismic activity

Introduction

Distributed optical fiber sensors (DOFS) form a class of sensors that provide a continuous reading of measurands (e.g., temperature, strain) as a function of distance along the sensing fiber (Hartog, 2017). Although the technology emerged more than 30 years ago (Hartog, 1983), it continues to evolve and improve as new physical principles, optical interrogation methods, and signal processing techniques are applied to it. This class of sensor has gradually gained acceptance as a tool in industrial applications and a research tool, particularly in environmental science (Kobs et al., 2014; Striegl & Loheide, 2012; Tyler et al., 2008).

Techniques for distributed measurements of temperature, static strain, and vibration (dynamic strain) are now very well established, and recent work has allowed very fine spatial resolution (<5 cm) and extremely long lengths (>100 km) to be interrogated. Although there is a trade-off between performance parameters and the finest spatial resolution cannot usually be achieved over the longest range systems, addressing more than 1 million points on a single sensing fiber has been reported (Denisov et al., 2016).

A global push toward faster communication and efficient digital data transfer is underpinned by a growing network of more than 420 undersea optical telecommunications cables that cover a distance of over 1.1 million km (Routley, 2017). The opportunity to use spare capacity on this global network for environmental monitoring is intriguing. However, this must be tempered with a few considerations, namely, (a) the operators may have no capacity that they can make available; (b) the risk of cross-talk from sensor interrogators to communication channels through nonlinear optical effects needs to be evaluated; (c) the optical architecture may not allow two-way transmission beyond the first optical amplifier and will certainly not be possible beyond the repeater where signals are converted to the electrical domain, reformatted, and retransmitted; and (d) it should be appreciated that the undersea cable routes are designed for the efficient transmission of data, not necessarily high-priority locations for valuable environmental monitoring. For example, there is a very dense coverage across the Atlantic Ocean from New England to the United Kingdom, Ireland, France, and the Iberian Peninsula, with a few other transocean cables, for example, Latin America to Africa, as well as cables following the contours of the continents. This still leaves vast tracts of the ocean with no cable whatsoever, and this situation is far more marked in the southern oceans. New cable routes to interconnect Small Island Developing States and the proposed deployment of bespoke scientific cables provide future opportunities that could help to fill such geographic gaps in oceanic coverage (Howe et al., 2010).

The application of DOFS technology, therefore, offers opportunities for monitoring long, inaccessible assets in a cost-effective manner; however, so far, the approach has found relatively limited acceptance in a subsea context. This article provides a review of the technology, outlines some of the limitations, and discusses some of the attractive opportunities for applying DOFS in the marine environment.

Technology of Distributed Sensing

DOFS systems consist of a sensing fiber cable and an interrogation system. The sensing fiber is usually an optical fiber of the type used for long-distance telecommunications or local area networks. Therefore, sensing can be performed on unmodified fibers that were initially installed specifically for telemetry or telecommunications, on spare wavelength channels, or even on spare fibers within an existing cable. Sensing fibers sometimes deviate from such conventional designs in harsh environments. For example, fibers with special coatings or glass compositions are required to handle elevated temperatures. In the marine environment, the existing fiber cables used for telecommunications, energy interconnects, and tiebacks from offshore wind farms are usually suitable for some distributed sensing applications.

The cable structure is critical in distributed sensing. The fiber must be protected from mechanical and chemical damage and yet transfer the measurands from the external environment to the sensing fiber with minimal distortion. In the case of temperature sensing, the design of the cable is relatively straightforward in that the temperature at the fiber usually follows that on the outside faithfully and rapidly. In the case of strain measurements, the cable has the additional function of a transducer and its design affects the calibration of the sensors. The design of the cable becomes even more complex when it comes to transferring external pressure to the fiber while maintaining mechanical and chemical protection. For chemical sensing, the cabling problem is yet more challenging and has been solved in only very benign physical conditions.

The interrogation system is the set of optics, electronics, and embedded software that probes the sensing fiber and converts the returning, modulated light into a digital data stream that describes the state of the measurand(s) along the fiber.

Interactions Between Measurands and the Light Traveling in an Optical Fiber

Optical fiber communication systems are known for their ability to operate in harsh conditions, and the transmission formats and error correction codes make them insensitive, in their primary role, to environmental effects (e.g., temperature, strain electromagnetic interference). Nonetheless, a large body of research has demonstrated that, by interrogating the fiber appropriately, the effects of external conditions on many of the properties (e.g., intensity, phase, transit time, polarization) of the light that is transmitted can be exploited for sensing (Hartog, 2017).

Light scattering is central to the operation of distributed sensors, in providing the return signal and the sensitivity to the main measurands. Scattering is caused by very small-scale, naturally occurring fluctuations of the refractive index of the glass forming the fiber.

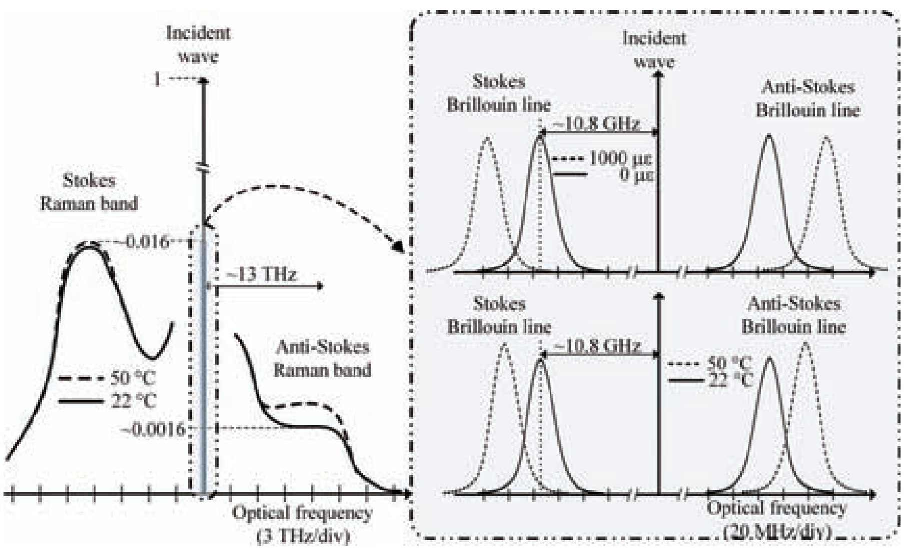
The highest proportion of the scattering (Rayleigh scattering) is caused by static inhomogeneities, which arise from fluctuations of density or composition of the glass. These inhomogeneities are thermodynamically induced during the high-temperature drawing of the fiber, when the material is still fluid and frozen in as the fiber cools. They appear on a distance scale much smaller than a wavelength of the incident light. The static nature of this type of inhomogeneity results in no exchange of energy between the glass and the incident light during the optical interaction, and so the frequency of the incident light is preserved in the process; that is, this is an *elastic* process.

Other inhomogeneities are dynamic, caused by thermally generated acoustic waves in the fiber. Very high-frequency acoustic vibrations (at c. 13 THz in silica) occur in the molecular bonds between the atoms forming the glass; their energy quanta are known as optical phonons. Raman scattering is an interaction between the incident light and these molecular vibrations; it results in an exchange of energy between the glass and the incident light in which the scattered photon loses energy equal to one phonon (Stokes Raman scattering) or gains that amount of energy (anti-Stokes Raman scattering), and so this process is *inelastic*. The anti-Stokes process requires energy to be transferred from the glass to the scattered light, and so it is strongly dependent on the temperature of the fiber at the point where the scattering occurs; in contrast, the temperature sensitivity of the Raman Stokes process is far lower (see Figure 1).

Brillouin scattering is another type of optical interaction with thermal

FIGURE 1

Schematic illustration of the spectra of the backscattered light in typical optical fiber for 1,550-nm (192.4 THz) illumination and their sensitivity to temperature. (Left) Broad frequency range encompassing all the spectral bands of interest. (Right) Expanded view showing the relationship between the Brillouin backscatter and the Rayleigh backscatter that returns at the same wavelength as the incident light. Lower right diagram applies to zero strain for two different values of temperature, and the diagram above it applies to 22°C for zero and 0.1% strain. Adapted from Hartog (2017).



acoustic waves that is also inelastic. In this case, the frequency of the acoustic waves is much lower (c. 11 GHz for an incident wavelength of 1,550 nm) than for Raman scattering, and the relevant phonons are known as acoustic phonons. Brillouin scattering occurs between the incident light and those acoustic waves that have the same acoustic wavelength as the optical wavelength of the incident light. Again, the scattered light can be upshifted in frequency (anti-Stokes scattering) or downshifted (Stokes) in the interaction. As shown in Figure 1, the intensity of the Brillouin spectra lines, as well as their frequency shift from the incident light, depends on temperature (lower right-hand diagram) and strain (upper right-hand diagram).

Thus, both Raman and Brillouin scattering processes result in new features appearing in the frequency spectrum of the scattered light. The analysis of this spectrum therefore allows several distinct physical effects to be resolved independently, and this forms the basis of most DOFS. The relative wavelengths and signal strengths of the backscattered light in typical optical fibers are illustrated in Figure 1.

Distance Resolution

The entire purpose of distributed optical fiber sensing is to provide an estimate of the value of the measurand as a continuous function of distance. Fundamental to the operation of DOFS is therefore a mechanism for resolving distance along the fiber. In almost all cases, it is the two-way transit time from the interrogator to the resolved location and back that provides distance discrimination. Thus, the measurement is conducted in a reflectometric configuration, similar to radar, sonar, or ultrasonics, but operating in this case in the 1-D confines of the optical waveguide. [Note that methods that use the difference in forward propagation time between different modes in a fiber have also been explored (Gusmeroli et al., 1989) but not commercialized probably owing to the far more challenging time requirements (three to four orders of magnitude) and their resulting inferior performance. There are, however, some examples of their use in the context of this article, for example, Dai et al. (2008)].

In most distributed sensors, the distance resolution is achieved through time-domain reflectometry: a probe pulse is launched into the fiber, and the optical signal that is returned to the interrogator is light that has been scattered, recaptured by the waveguide in the return direction, and guided back to the launching end.

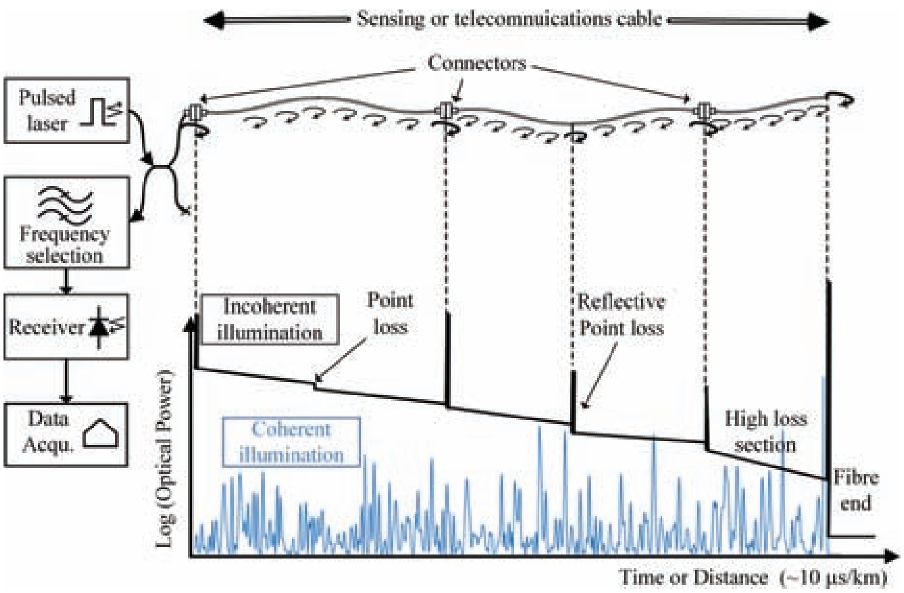
Optical time-domain reflectometry (OTDR) is a technique carried over from telecommunication practices (Barnoski & Jensen, 1976), where it is commonly used for checking the installation of new fiber cables and monitoring the state of installed links. It has been adapted for sensing by studying the signals returned from the fiber, and particularly their optical spectra, in far more detail than is required for the purposes of verifying the performance of optical communication circuits.

Distance z along the fiber is encoded into time t on the returning signal through the relation $z(t) = c \cdot t / (2N_g)$, where c is the speed of light in vacuum and N_g is the group refractive index for the sensing fiber at the operating wavelength. At 1,550 nm, N_g is typically 1.468 in a single-mode fiber, and this results in a delay of about 10 ns in the two-way transit time for each metre of sensing fiber.

The essential functional blocks in an OTDR (Figure 2) are a pulsed

FIGURE 2

Schematic diagram of an optical time-domain reflectometer and typical signals measured as a function of distance along the fiber. Black curve: with an incoherent source; blue curve: with a coherent source. Adapted from Hartog (2017).



laser source, a device for separating forward- and backward-traveling light, a receiver to convert the backscatter signal into an electrical voltage, and a data acquisition unit. In telecommunication applications, the source has low coherence (typically a relative bandwidth of 1–2%, i.e., 10–30 nm), and the signal takes the appearance of the black sloping line in Figure 2, which includes spikes caused by reflections and drops in signal power at localized loss points; its slope is indicative of the attenuation of the fiber. In distributed sensors, a frequency selection function is also used to choose the spectral components that are passed to the receiver.

Although the signal returning to the interrogator is continuous, it is invariably converted to a stream of digitized values and the sampling rate of the analog-to-digital converter determines the spatial separation of adjacent samples. This is one of the limitations on the spatial resolution of the system, another being the bandwidth of the probe signal (in usual cases, the reciprocal of the pulse duration) or that of the physical process generating the particular part of the scattered light used in the measurement.

Spread-spectrum methods, such as frequency-modulated, continuous-wave encoding or pseudorandom coding, borrowed from the field of radar, are also able to provide distance resolution based on two-way transit time and have been employed in distributed sensing (Glombitza, 1998; Park et al., 2006).

The techniques described here that are based on reflectometry differ from the recent article on earthquake detection using existing telecommunications cables (Marra et al., 2018), in which the optical fiber is looped back at the remote end and the signal is returned on a second fiber. In the case of the work of Marra et al. (2018), the signal that is measured is the integral of the dynamic strain over the entire fiber propagation path. This makes for a very sensitive measurement, but one that is not location resolved, unless multiple such measurements are available over diverse paths and can be triangulated for a location of the epicenter of the quake. It should also be noted that distributed vibration sensors, when connected to fibers that are straight, are insensitive to waves arriving perpendicularly to the fiber (Dean et al., 2015; Hartog, 2017). The sensitivity that is detected arises from the wave components that are parallel to the fiber, and this applies also the work of Marra et al. (2018). Thus, signals that are detected most likely originate from the curvature of the wave fronts of the seismic signals or from deviations of the sensing cable from a perfect straight line.

Sensitivity to Measurands

Collecting the light backscattered from a probe pulse provides information on the integrity of the optical transmission line, but it is not, in itself, useful for sensing. The sensitivity of distributed sensors to specific measurands arises from a more detailed use of the spectrum of the backscattered light. As discussed in the section on "Issues of Performance: Limitations," three types of scattering (Raman, Brillouin, and Rayleigh) are commonly used in distributed sensors to extract the information of interest from the backscattered light spectrum.

Raman-based distributed temperature sensors select the anti-Stokes Raman scattering; its intensity as a function of distance along the fiber is a proxy for local temperature (Dakin, 1984). Usually, a less temperature-sensitive spectral line (Raman Stokes [Dakin, 1984] or Rayleigh [Hartog et al., 1985] wavelength) is also captured to provide a reference to compensate for propagation losses in the path to and from each sensing point. The ratio of the anti-Stokes Raman and reference signals is used to calculate the temperature distribution. The Raman ratio derives fundamentally from the thermal excitation of molecular bonds in the material, from which the fiber is made, and it is therefore an absolute measure of the temperature of the core of the fiber at the point at which the scattering occurs. In practice, further compensation for the loss distribution along the sensing fiber and in the optics within the interrogator is required (Bolognini & Hartog, 2013; Hartog, 2017). Over short distances and limited time differences, the referencing to an anti-Stokes Raman backscatter trace acquired with a known temperature profile can be used for temperature compensation of other measurements that suffer from cross-sensitivity to temperature (Belal et al., 2010).

Raman distributed sensing technology is very well established with many thousands of installations in applications, from fire detection in tunnels, through the dynamic thermal rating of energy cables, to the determination of the flow profile in hydrocarbon wells (Bolognini & Hartog, 2013; Hartog, 2017). Systems vary in sophistication from relatively low-cost units able to monitor a few kilometers of sensing fiber with a resolution of order 2 m (and a few tenths of 1 K) to more advanced systems able to resolve 1 m or better over 10 km at a resolution of order 0.01 K as well as systems optimized for the long distances (30–50 km) required for monitoring subsea energy cables and flow lines.

Brillouin scattering is a far richer process for sensing than Raman scattering. First, it is a very narrow-band process (of order 20-MHz linewidth), and this, combined with the closer spacing between the incident light and the scattered light, simplifies the loss compensation problem in long-range systems based on the intensity of the backscattered light. Second, the frequency shift (ν_B) between incident and scattered light is itself sensitive to temperature and strain, and this provides an independent measurement that allows temperature and strain to be extracted from measurements of intensity and ν_B (Belal & Newson, 2012). Subject to prior calibration and separation of strain from temperature, ν_B is a measure of absolute temperature at the point of scattering. Finally, the fact that the Brillouin scattering spectrum is very narrow allows optical amplification techniques to be used to extend the sensing range while adding only acceptable levels of noise to the signal of interest.

The most important characteristic of Brillouin scattering is that it can readily be used in a stimulated mode in which two counterpropagating waves interact if their frequency difference is exactly equal to ν_B. Stimulated Brillouin scattering is a three-wave process involving the two incident light waves and a stimulated acoustic wave. Control of the two incident waves has allowed researchers to demonstrate remarkable features such as extremely fine spatial resolution (a few millimeters) and very fast update times (of order 10 ms) (Hotate, 2013; Motil et al., 2016) and, in some cases, apply them to practical problems (Imai et al., 2010; Kumagai et al., 2013). A related technique allows single, addressable points to be interrogated on a microsecond update time scale over short ranges (Mizuno et al., 2016).

We conclude this brief description of the main distributed sensing techniques with systems that measure rapidly changing, that is, dynamic, strain. Under broadband illumination, the Rayleigh backscatter signal is simply a measure of the probe power along the fiber and how effectively scattered light is captured by the waveguide in the return direction (Figure 2, black line). However, with narrowband illumination (where the native source bandwidth is far narrower than the inverse pulse duration; i.e., the coherence time of the source is much longer than the duration of the probe pulses), the backscatter signal acquires a completely different character (blue line in the lower part of Figure 2). In this case, the light returned from each resolvable section of fiber ($\delta z = c \cdot \tau / (2N_g)$, where τ is the pulse duration) is the coherent summation of the electric fields reradiated from each of the myriad of scatterers within δz. The relative phase of each of these re-emitters is therefore critical to the amplitude and phase of the optical wave arriving at the detector. Each section δz of fiber is thus functionally equivalent to a multipath interferometer, and minute changes in the relative locations of the scatterers can radically change the returned signal. Coherent Rayleigh backscatter is thus a very sensitive indicator of strain, with modern sensors resolving extensions of order 1 nm over distances of a few meters. Changes of local temperature, which alter primarily the refractive index of the sensing fiber, are also able to modulate the backscatter signal.

In coherent Rayleigh backscatter, the phase of the backscattered light, as well as its amplitude, is modulated by the measurand. The coherent Rayleigh backscatter signal is random (determined by the random dispositions of the scattering elements within each resolvable section) but stable if the fiber condition is itself stable and the frequency of the probe source is also constant. One is therefore exploiting dynamic changes of this random signal. The transfer function from strain to amplitude is itself random and nonlinear; nonetheless, these effects are commonly used in applications such as intrusion detection where the threats can be classified despite the nature of the sensor response.

In applications where signal fidelity is important, it is usual to determine strain from the phase change differentiated over a defined fiber interval known as the gauge length, wherein the differential phase varies relatively linearly with strain (Hartog & Kader, 2012). A number of different techniques have been devised based on this approach to achieve a distributed vibration sensor. Such a sensor not only returns the spatial existence of a disturbance but also quantifies the time-varying magnitude of the strain at each location along the fiber (Hartog, 2017; Hartog & Kader, 2012; Hartog & Liokumovich, 2013; Hartog et al., 2013), an extension by 1 nm of the gauge length resulting in ~9.4 mrad of phase change.

In the differential phase measurement, the measurand information that is represented by the phase is of course restricted to the $[-\pi, \pi]$ range, and when the underlying physical parameter varies sufficiently that this interval is exceeded, the measured value simply wraps around to remain within $[-\pi, \pi]$. In order to reconstitute the true time dependence of the measurand, it is therefore necessary to unwrap the phase, a nonlinear operation that can be performed reliably (Itoh, 1982) subject to the condition that the phase varies by less than π between successive samples.

These techniques are described as "vibration" or "acoustic" sensing, but they also respond to temperature very sensitively (about 800 rad/K for a gauge length of 10 m), and the separation of the two effects usually exploits the fact that the temperature signals have a much lower frequency content compared to the acoustic signal.

The three scattering techniques, when used together, reinforce each other. For example, combining Raman and Brillouin measurements is a robust means of measuring temperature and strain independently (Alahbabi et al., 2005b; Belal et al., 2010). Similarly, the Brillouin technique provides static strain measurements at a moderate strain resolution (Belal & Newson, 2011; Maughan et al., 2001) that can be complemented by the much more sensitive dynamic strain obtained from coherent Rayleigh backscatter. Here, we use the term "static strain measurement" to denote the fact that the results can be referenced to a datum for long durations and even if the equipment is disconnected. In contrast, a dynamic measurement loses its reference to a known initial state if the equipment is turned off or disconnected. Distributed vibration sensing offers a measurement that is three orders of magnitude more sensitive (nanostrain rather than microstrain), but this measurement is dynamic only; moreover, low-frequency measurements (<1 Hz) are challenging owing to the presence of a number of noise sources with 1/f-like spectra.

A further variant of the coherent Rayleigh backscatter technique, in which the measurement is conducted over a range of source frequencies, is capable of a static measurement, subject to an initial calibration of each resolvable section of the fiber (Froggatt & Moore, 1998; Hartog, 2017; Koyamada et al., 2009). In the case of Koyamada et al. (2009), a temperature resolution of 0.01 K at a spatial resolution of 1 m over a range of 8 km was demonstrated.

Issues of Performance: Limitations

Nonlinear optical effects set a fundamental limit on the performance of DOFS. At high optical intensities, the fiber responds nonlinearly: owing to the small size of the core (8–50 μm in diameter), moderate (1–10 W) light levels result in large optical power densities, and this brings about several undesirable effects such as stimulated Brillouin and Raman scattering. These stimulated processes build up along the length of the sensing fiber resulting in the transfer of available probe power to their corresponding Stokes lines, instead of delivering that power to the intended locations further along the fiber. This distorts any measurements based on the spontaneous versions of the processes. The refractive index itself is modified by the presence of high optical power densities (the Kerr effect) and results in broadening of the spectrum of the probe light, which degrades the measurement, catastrophically in some cases. The way in which these undesired effects limit the sensor performance depends on the physics that are used and the type of fiber. For example, the large core sizes of multimode fibers allow this fiber type to carry an order of magnitude more power than single-mode fibers, but their use complicates the design of the interrogators and the interpretation of the results (Hartog, 2017).

The noise at the receiver limits the sensitivity of the measurement, and its fundamental lower bound is shot noise, which is directly related to the number of photons that are returned by each section of fiber for each probe pulse. In most cases, the receiver itself further degrades the signal-to-noise ratio (SNR). In this context, it should be appreciated that the signal returned by distributed sensors is a small fraction of the energy launched. In the case of a sensor using 10-ns probe pulses (corresponding to $\delta z = 1$ m), the energy returned by each resolvable interval is about seven orders of magnitude below that of the forward-traveling probe pulse for Rayleigh backscatter; in the case of Brillouin and Raman scattering, the energy is further reduced by two and three orders of magnitude, respectively. The design of distributed sensors is therefore fundamentally affected by the SNR, and many schemes have been devised to overcome these limitations.

Long-distance (>10-km) sensors further compound the SNR problem with the cumulative propagation losses, and this applies to marine applications, where long sensing paths are expected. In addition to the progressive loss of signal, long sensor lengths impose a wide dynamic range on the signal that can then be difficult to digitize without loss of accuracy.

Performance: Opportunities for Enhancements

A few broad approaches have been applied to address issues of poor SNR and large dynamic range of the signal, for example, remote amplification, pulse coding, and specialty fiber design/use. The remote optical amplification (Hartog & Wait, 2009) has proven particularly effective in long-range applications such as the monitoring of terrestrial pipeline that can run for thousands of kilometers and up to ~200 km between sites where monitoring equipment can readily be installed. For sensors operating in the main telecommunication band (~1,550 nm), erbium-doped fiber amplifiers can conveniently be used both to amplify the pump and to preamplify the backscatter signal before it travels back to the launch end. Boosting the probe signal after it has decayed allows its power to be readjusted to the maximum allowable level (as limited by nonlinear effects), and amplifying the return signal remotely degrades the SNR far less than if the same amplification process were implemented in the interrogator, because this occurs while the signal is still relatively strong.

In one example, a system combining Brillouin reflectometry for temperature and strain measurement and coherent Rayleigh backscatter (for vibration sensing) was demonstrated over a 100-km route using discrete rare earth element–doped amplifiers sited at roughly 25-km intervals and pumped (powered) by light carried in separate fibers (Strong et al., 2008). In this case, the amplification is electrically completely passive, requiring no remotely sited electronics at all. Raman amplification, where energy is transferred from a pump wave at a somewhat shorter wavelength (1,450 nm for a sensing wavelength of 1,550 nm), has also been used to allow longer sensing lengths (Alahbabi et al., 2005a). The combination of Raman and erbium-doped fiber amplifiers has also been used to stretch the range of distributed sensors, including one example where the pump power for the initial distributed Raman amplification is also used to pump a further set of two erbium-doped fiber amplifiers, using a single fiber for sensing and conveying the optical power required for amplification (Cho et al., 2006). It should be noted that optical amplification approaches are particularly suited to sensors using Brillouin and coherent Rayleigh scattering on single-mode fibers. The optical amplification of the Raman backscatter is ineffective owing to the latter's very broad spectrum and the inevitably wide noise bandwidth that would accompany the optical gain. Similarly, the performance of optical amplifiers on typical multimode fibers (with a core diameter ≥ 50 µm) is far worse, and in practice, in-line optical amplification is not used with multimode distributed sensing systems.

Another route to enhancing the backscatter signal returned to the interrogator is pulse compression, a technique that is well known from radar (Richards et al., 2010) and other reflectometric measurements. The spatial resolution of a distributed sensor is limited by the pulse duration, so the narrower the pulse, the finer the spatial resolution. In a peak-power–limited system, a finer spatial resolution therefore implies a degraded SNR. The backscatter signal power, however, is proportional to pulse duration, and so there is a direct trade-off between spatial resolution and SNR. Pulse compression overcomes this dilemma by increasing the duration of the probe light without decreasing its bandwidth. The fine spatial resolution is encoded in the probe waveform; it is buried in the backscatter signal but can be recovered by applying a matched filter to the detected signals. A further constraint applies to long-range distributed sensors, namely, that the probe signal should not be continuous (e.g., frequency-modulated, continuous wave) because the strong backscatter from the near end of the fiber will swamp the weak backscatter from the remote end, given that these signals are present simultaneously at the receiver. The probe waveform must therefore be of limited duration, and this has led to the design of code sets [Golay complementary codes (Nazarathy et al., 1989) or simplex codes (Soto et al., 2010)] that are of finite duration and yet have the necessary correlation properties to allow a precise recovery of a signal that is equivalent to that produced by a single pulse, but stronger by a factor equal to the number of pulses in the code. The resulting improvement in the SNR is proportional to the square root of the code length.

Special fiber designs can also be used to tackle deteriorated SNR performance and/or dynamic range of the sensor. The physical processes described so far rely only on the natural state of the glass in the optical fiber. The measurements can, and usually do, use conventional fibers designed for telecommunication systems; however, specially designed fibers are used in more challenging applications. Thus, the coatings designed for the relatively benign telecommunication application are generally unsuited to high temperatures, and so specialized coatings able to operate at up to 300°C for polymer coatings and higher still for metallic coatings have been devised for these cases. In the harshest cases, a hermetic inner coating is used to retard the ingress of hydrogen and special glass formulations that are more resistant to the conversion of hydrogen into OH bonds (which render strong absorptions at some wavelengths of interest) are adopted.

In the case of Brillouin-based sensors, the cross-sensitivity between temperature and strain has led to research on fiber designs that have markedly different frequency sensitivity coefficients compared with conventional designs, to allow the cause of changes in the measured frequency to be disambiguated (Law et al., 2011; Sikali Mamdem et al., 2014).

Another strand of research in special fibers for distributed sensing concerns increasing the strength of the backscatter return for a given probe energy. Including dense, weak reflectors in the fiber achieves that objective without substantially increasing the propagation losses or lowering the threshold for nonlinear effects, because most of the energy extracted by the reflectors from the forward propagating light is coupled back into the fiber (Englich & Hartog, 2016). In contrast, the normal scattering process redirects the lost light almost uniformly in all directions. The efficiency in the reuse of the lost light increases by more than a factor of 100 in this approach, which however adds substantial cost to the sensing fiber. It will therefore most likely find applications where enhanced performance is required in a relatively limited zone, for example, to monitor a particular section of a subsea asset (perhaps a manifold running between a wellhead and a separator, electrical/communication cable or oil pipeline interacting with a rapid-flowing sediment density flow, etc.) with a higher resolution than the remainder of the infrastructure.

Opportunities in the Marine Environment

Oceans cover more than 70% of the Earth's surface. They play a critical role in climate regulation and global food supplies and are important foci for the production of energy (both fossil fuel and renewables) that impact our day-to-day lives (Favali & Beranzoli, 2006; Ocean Studies Board, National Research Council, 2000). These connected and dynamic water masses are changing in response to ongoing climate change, yet understanding how local, discontinuous measurements can be upscaled to understand an ocean-scale response is unclear (Favali & Beranzoli, 2006). Traditionally, oceanographic measurements have been made at isolated single-point moorings and/or landers at seafloor, or using arrays of surface floats (Riser et al., 2016). In light of a need to understand the oceans more holistically, there has been a recent upsurge in the deployment of seafloor observatories—monitoring nodes connected by cables (Delaney & Kelley, 2015; Favali & Beranzoli, 2006; Favali et al., 2015; Kelley et al., 2014). Nodes typically feature an array of instruments to make specific measurements of ocean properties and monitor active processes at the seafloor and within the water column at a fixed location (Lintern & Hill, 2010). While the primary purpose of the connecting cables is to provide power and to transmit data in real time, these links could also be used as distributed sensing pathways using DOFS. Therefore, measurement along these cables, existing commercial networks, and bespoke scientific arrays using technology such as DOFS enables sensing of large areas of the ocean floors in a truly distributed manner, thus providing an exciting opportunity to fill in some key gaps (You, 2010). This approach has obvious synergies with scientific programs such as the international Joint Task Force on SMART (Science Monitoring And Reliable Telecommunication) cables that aim to install sensor packages at optical repeaters on the existing global seafloor cable network to measure pressure, temperature, and three-axis acceleration (Howe et al., 2010, 2016).

We now discuss how DOFS could be used to address some specific challenges in ocean science and highlight some recent successful studies (Table 1). We first look at episodic hazards that can cause significant seafloor disturbance (and are therefore likely to be detected most easily by DOFS) and how DOFS can be used to monitor impacts of seafloor hazards and then focus on more subtle variations in ocean conditions (including ocean temperature and acidity) that may be tackled by ongoing and future developments in DOFS technology.

Monitoring Offshore Geohazards

The deep seafloor can be the site of highly dynamic processes. Natural hazards such as earthquakes, seafloor remobilization by tropical cyclones, slope instability (landslides) that may trigger tsunamis, powerful avalanches of sediment (density flows known as turbidity currents), and seafloor expulsion of fluids all pose a threat to critical seafloor infrastructure, including telecommunication networks, oil and gas pipelines and umbilicals, and wind farm interarray cables, as well as to coastal communities (Clare et al., 2017). A growing number of studies (many using legacy or in-service telecommunications cables) are demonstrating the utility of DOFS

TABLE 1

Some recent successful applications of optical fiber sensors to monitor a range of processes that occur on and below the seafloor.

Processes Monitored	Sensing Configuration	Location	Reference
Slope failure/displacement			
Slow seafloor displacement	Bespoke cable: strain measured over <10 km with strain resolution < 1 $\mu\varepsilon$	Offshore San Diego, California	Blum et al., 2008
Slope failure	Bespoke cable: stress measured over 0.5 km	Onshore Yangtze Province, China	Dai et al., 2008
Progressive ground displacement	Bespoke cable: strain measured over tens of meters with strain resolution > 2 $\mu\varepsilon$	Onshore London, UK	Hauswirth et al., 2014
Seismicity			
Earthquake P and S wave detection	Down-borehole deployment of bespoke cable over ~1,000 m used as an interferometer	Onshore California	Blum et al., 2008
Earthquake P and S wave detection	Bespoke cable array over 8,400 m	Onshore Nevada	Wang et al., 2018
Earthquake P and S wave detection	Bespoke cable array: 160-m length	Onshore Fairbanks, Alaska	Lindsey et al., 2017
Earthquake identification and localization	Conventional telecommunications cable: over 15 km	Onshore Reykjanes Peninsula, Southwest Iceland	Jousset et al., 2018
Earthquake identification and localization	Conventional telecommunications cable: over 79 km	Offshore Central Italy	Marra et al., 2018
Fluid flow			
Subsurface pressure and fluid movement detection	Bespoke cable: deployed as a passive hydrophone seafloor array	Offshore Sognefjord, Norway	Goertz & Wuestefeld, 2018
Oceanographic and cryospheric processes			
Lake bed temperature	Conventional telecommunications cable: temperature measured with a spatial resolution of 1 m over 30 km with a temperature resolution of <0.1°C	Lake Geneva, France/Switzerland	Selker et al., 2006
Tracking individual coastal waves	Power cable linking offshore wind farm to the mainland	North Wales, UK	Hartog, 2017
Ice sheet displacement	Down-borehole deployment of bespoke cable over ~1,000 m used as an interferometer	Ice sheet: Siple Dome, Antarctica	Blum et al., 2008

approaches to identify and characterize a range of seafloor hazards (Table 1).

As well as making direct measurements of temperature and strain, existing telecommunications cables may be used as passive seismic arrays. By using existing submarine cable networks, a significant gap in seismic monitoring can be addressed. Most of the Earth's surface is under water, yet most seismic monitoring stations are on land. Jousset et al. (2018) demonstrated how existing telecommunications cables can be used to record earthquake spectra by measuring dynamic strain. Earthquake events have also been observed on a communications cable belonging to Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Kimura et al., 2018). Field experiments using distributed acoustic sensing along fiber-optic cables in Alaska and California found a high degree of correlation with earthquake measurements acquired with a conventional seismometer and that only a minimal degree of cable-sediment coupling is required for P and S wave detection (Blum et al., 2010). This demonstrated application of fiber-optic cables thus opens up many further possibilities for indirectly measuring other active seafloor processes such as volcanic activity, tsunamis, slope collapses, sediment transport, and fluid expulsion and for detecting a wide range of seismic events, in a similar manner to recent monitoring efforts using hydrophones, ocean bottom seismometers, and broadband seismic arrays (Burtin et al., 2011; Caplan-Auerbach et al., 2014; Clare et al., 2017; Kimura, 2017a, 2017b; Lin et al., 2010; Lindsey et al., 2017; Sgroi et al., 2014). Clearly, calibration will be required for each of these processes and in a range of ocean settings, but the potential application is extremely promising. Other ambitious initiatives are ongoing, such as the use of legacy cables using Brillouin OTDR to determine strain induced by small-scale (mm-cm) displacements at tectonic faults that intersect the seafloor (Gutscher et al., 2017). These initiatives extend previous studies where standard fiber-optic cables were used to measure seafloor displacements due to creep (Blum et al., 2008; Gutscher et al., 2017).

Potential for Monitoring Geohazard Impacts to Offshore Infrastructure

Due to their fast speed (up to 20 m/s) and potential to travel over vast areas of seafloor (up to thousands of kilometers), processes such as landslides and turbidity currents can be particularly damaging for valuable seafloor infrastructure such as cables and pipelines (Pope et al., 2017). While few direct measurements have been made of these processes (Azpiroz-Zabala et al., 2017; Talling et al., 2015), much of what we know about the velocity and run-out distance of these hazards comes from the documented timing and location of sequential telecommunications cable breaks (Burnett & Carter, 2017; Carter et al., 2014). As the global network of telecommunications cables transmits more than 99% of all digital data traffic worldwide (including the Internet), better understanding the threat posed by such processes is of global importance (Kelley et al., 2014). Recent measurements have revealed that not all of these seafloor processes will necessarily cause a cable or pipeline to rupture, however (Clare et al., 2017). Instead, they may cause drag, loading, and/or displacement on the structure (e.g., Dai et al., 2008). These pronounced effects would all be recorded as localized and variable strain along an optical fiber; hence, DOFS sensing could provide new insights into the timing, duration, magnitude, and spatial extent of such seafloor events with unprecedented spatial coverage (Clare et al., 2017; Talling et al., 2015) as well as much needed information on the integrity of the seafloor structure itself during these hazardous events and over its engineering lifetime (20–40 years; Hartog, 2017).

Cables are often the potential weak points in offshore wind developments. Fibers are commonly embedded in electrical energy interconnectors and in the cables transmitting the power generated by offshore wind farms back to land. These fibers have already been used to detect the occurrence of damage (e.g., from fishing vessels; Hartog, 2017) using distributed strain and/or vibration sensing. This locating capability enables accelerated repair or intervention. Using existing fibers for the detection of anthropogenic, natural hazards or incipient structural damage is particularly attractive because it provides the potential for an early warning system, for example, ensuring that buildup in strain due to repeated impacts by hazards such as turbidity currents does not reach a critical threshold. In such a situation, mitigation measures (e.g., reconfiguration of cables on the seafloor) could be taken before a break occurs, thus minimizing any losses in connectivity.

A distributed vibration sensor connected to a subsea energy cable was able not only to reveal the sea state but also to track individual waves (Hartog, 2017).

Addressing the Challenges of Measuring Ocean-Wide Climate Change

There is much uncertainty in how temperatures are changing close to seafloor due to the paucity of monitoring stations globally; hence, the possibility of temporally continuous and spatially distributed measurements using DOFS is appealing. Legacy fiber-optic telecommunications cables have been used to make measurements of submarine processes and temperature in Lake Geneva, where high-resolution daily fluctuations in lake-bed temperature were recorded to a resolution of 0.1°C (Selker et al., 2006). While such lacustrine and shallow water environments may show >1°C daily temperature variations, we recognize that similar short-term background variability in deep-sea temperature may be at the limits of detection using DOFS systems (10–20 mK); longer-term (annual to decadal) changes in ocean temperature (in the order of 0.1–0.5°C rise per decade; e.g., Bethoux et al., 1990; Danovaro et al., 2004) are well within the measurement capabilities of DOFS, however. Longer-term variations are key inputs to future climate models. Furthermore, ephemeral processes in the deep sea may induce much greater short-lived temperature variability (>1°C) that is more easily detected, such as that due to cascading of cold, dense shelf water (Canals et al., 2006); influx of warmer water introduced by turbidity currents (Xu et al., 2010); or sudden seafloor emission of warmer subsurface fluid (Von Damm et al., 1995). In the case of distributed temperature sensors, marinized systems have been deployed for research purposes in, for example, subsea methane hydrate production (Kanno et al., 2014; Sakiyama et al., 2013) and studying the heat emitted by mid-ocean ridges (Nishimura et al., 1995). While some distributed chemical sensors have been demonstrated and developed, they are in general suitable for benign environments such as inside buildings. While advances in cable-connected seafloor systems now enable high-resolution discrete measurement of CO_2 at specific deep-sea locations (Mihaly, 2010), there is at present no truly distributed sensing capability for CO_2 content or pH suitable for deployment on the seabed. In the short term at least, it will be necessary to rely on discrete measurement at seafloor observatories or proxies based on the distributed measurements of physical quantities.

Development of Bespoke Cables for Distributed Sensing

Notwithstanding the benefits of repurposing existing cables for sensing, dedicated sensing cables can offer improved sensitivity and discrimination between measurands, for example, cable designs including fibers that are strain-coupled to the cable structure and others that are packaged in loose tube. In this design, the temperature and strain are measured independently using Brillouin OTDR to interrogate one of each type of fiber. The strain-relieved fibers measure only temperature, and this information is then used in its own right and to correct the measurements on the strain-coupled fibers that respond to temperature and strain (Strong et al., 2008).

Although distributed vibration measurements are found to respond well to small, dynamic strains even in loose-tube packages (Mullens et al., 2010; Strong et al., 2009), it should be noted that the distributed vibration measurement is in fact a measure of dynamic axial strain (Dean et al., 2015, 2016). As a result, the measurement is insensitive (Papp et al., 2016) to compressional acoustic waves arriving at right angles from the fiber axis. Omnidirectional cables have been designed (Kuvshinov, 2016) and tested (Hornman et al., 2013), in which the fiber is wrapped helically around a central former, with the fiber segments being exposed roughly equally to components of the sound wave arriving from any direction. In seismic applications, there is also an interest in multicomponent sensors; to this end, cables with specific sensitivity to one geometrical component and several concepts have been proposed, with some based on imposing particular patterns to the fiber in the cable (Kragh et al., 2012; Hartog et al., 2014), including inertial mass (Crickmore & Hill, 2014; Den Boer et al., 2012), or attaching the fiber periodically along the cable, allowing it to vibrate between attachment points (Farhadiroushan et al., 2015).

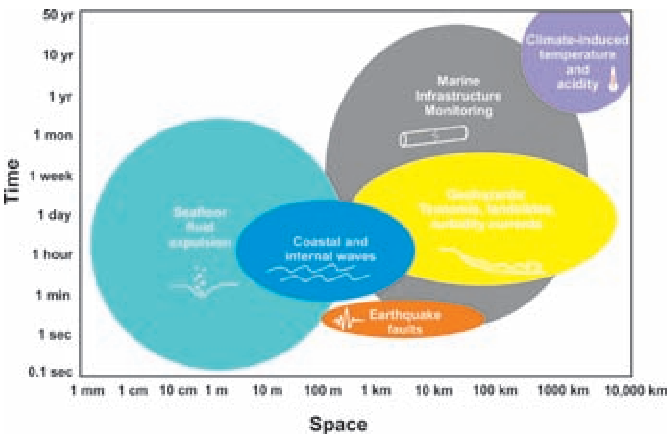
Concluding Observations

DOFS is a proven set of technologies that now allows us to make high-resolution measurements of key variables for both structural health monitoring and sensing the natural environment. A growing number of studies and projects are proving how powerful the technique can be in the marine environment as passive sensor arrays (e.g., seismicity), in measuring the direct impact caused by dynamic processes (e.g., turbidity currents), and in ambient conditions (e.g., subtle changes in temperature).

Recent strides forward in DOFS sensing technology enable the use of existing and legacy infrastructure (of which there is a considerable amount of >1 Gm), thus adding a significant value to already laid networks such that we can better understand scientific, societal, and industrial opportunities and risks. Further technological advances in interrogation, cabling,

FIGURE 3

Space-time relationship for various processes across the range of scales in the marine environment that have been successfully monitored using DOFS, as detailed in the text and in Table 1. Adapted from Lampitt et al. (2010).



and installation methods will enhance the capability of newly installed systems to have better performance and a longer range and the ability to profile more measurands.

A holistic approach is required to understand the oceans dynamic response to global warming, quantify the risks posed by hazards, and ensure that critical global networks (that supply power and communications) continue to run safely and effectively. The time scale and spatial range of the processes that DOFS could contribute to monitoring are mapped in Figure 3. The ability of DOFS to perform continuous temporally and spatially resolved sensing across large distances of the seafloor at low power and cost offers a new and complementary approach to traditional oceanographic monitoring. Adoption of DOFS technology provides a valuable opportunity to fill in spatially extensive gaps between existing isolated oceanographic monitoring stations, to unlock additional potential of cabled seafloor observatory networks, and, in turn, to deepen our understanding of the world's oceans.

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