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Submarine Cable Protection and the Environment

An Update from the ICPC, Written by Marine Environmental Adviser, Dr Mike Clare

Using cables to monitor the ocean

SUBMARINE CABLE PROTECTION AND THE ENVIRONMENT

An Update from the ICPC, Written by the Marine Environmental Adviser (MEA)

PUBLISHER

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If you have been around the submarine cable industry for the last ten or so years, you have undoubtedly heard of SMART (Scientific Monitoring and Reliable Telecommunications) cables. If you have been around the industry for the last five or so years, you have undoubtedly heard of DAS (Distributed Acoustic Sensing). And if you have been around the industry for the last two or three years and have attended industry conferences, you have undoubtedly listened to a presentation or panel discussion on cable sensing. But what does it all mean?

Seafloor observatories that involve sensors connected by cables have been used by academics for decades, to monitor seafloor biology, offshore earthquakes, and for tsunami detection. The use of sensing along the fibre-optics within cables themselves has only started to see application offshore in recent years, but has been used in the oil and gas industry for years. But the entrance of using cable sensing technology on commercial submarine fibre optic cable systems is a relatively new marriage of two existing technologies that has seen technological improvement on both fronts.

From an industry perspective, cable sensing has the potential to be used as a cable protection tool. The method that appears to be advancing the most in this regard is sensing methods where the fibre in the cable is used as the detection tool to discern statistically categorised frequencies of acoustic noise or other vibration sources. Fibre sensing can be used to detect a whale, a vessel, an earthquake, among many others and requires no alteration to the cable or fibre itself. This method can be applied through the lens of cable protection, but it also has many applications for collecting environmental data as well.

The second avenue for sensing is using separate sensor bodies incorporated into a cable system to collect data. SMART cables is are one such methodology that uses external sensors incorporated into the repeaters of a submarine fibre optic cable system to collect environmental data in the ocean. While this method is more geared towards environmental data collection, it has potential applications for cable protection as well.

There is a real opportunity to expand the use of submarine fibre optic cables in other dual uses such as sensing, which can provide another tool for cable protection but also add to our understanding of the environment and the oceans. These are exciting times and if the trajectory remains, it is quite feasible that most modern cable systems developed today will incorporate some form of sensing as a secondary use of the cable. But as with any development, there are challenges with this emerging field. Data collection, storage, even permitting or regulatory hurdles are some of the challenges that lie ahead. But the development of these technologies and the need to overcome these challenges means there is a continued opportunity for collaboration between the submarine cable industry, innovations in engineering, and physics and ocean scientific researchers.

Cable sensing has strong potential to be used as an early warning system for natural hazards, to monitor the ocean's response to climate change, as well as to better understand the threads to cables in the ocean. This issue of *Submarine Cable Protection and the Environment* looks to explore these opportunities.

Sincerely,

Ryan Wopschall

ICPC General Manager

FIBRE-SENSING: MORE THAN JUST A CABLE PROTECTION TOOL?

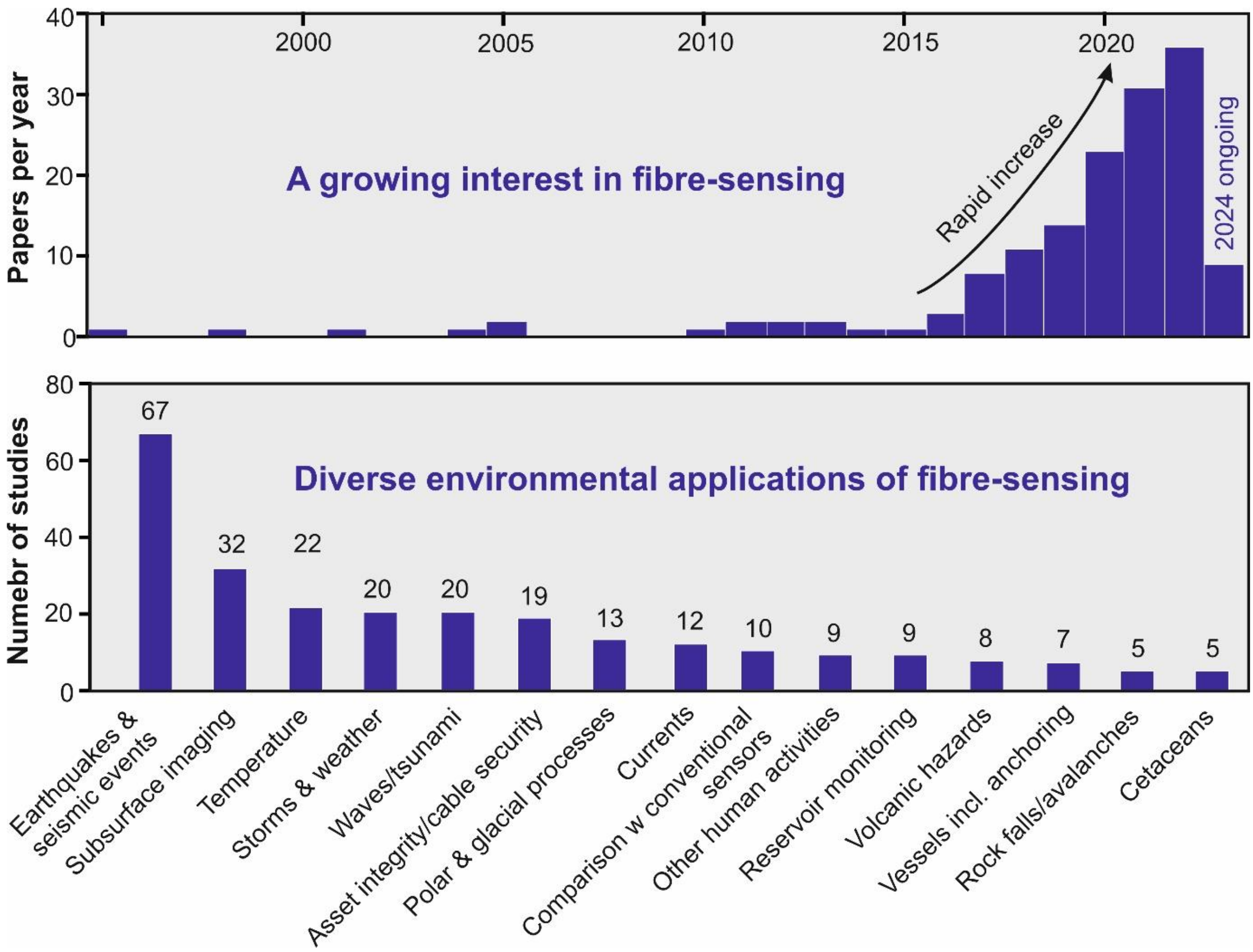
A global network of more than 1.6 million kilometres of underwater cables crosses the oceans. This network of cables, that are typically no wider than a garden hose, transfers critical telecommunications between continents, connects remote islands, and carries more than 99% of all digital data traffic worldwide. This traffic includes the internet and trillions of dollars in financial transactions every day. Our demand for digital communications, and our reliance on this network, continue to grow every year, requiring new and higher capacity cable systems to provide these critical global links. Advances in fibre-optics (the glass fibres at the core of modern telecommunications cables) and the technology to transfer data along them, are enabling greater volumes of data to be carried than ever before, to stay ahead of demand. In addition to the benefits provided by increased capacity, these technological developments have led to some unexpected discoveries. Environmental disturbances, even at a very small scale, can cause changes in the passage of the light along optical fibres, that are becoming increasingly used to monitor the health status of submarine cables in real time, providing a new method of cable protection. For example, fibre-optic sensing has been used to detect temperature variations that may indicate overheating of power cables, to assess where a cable is being moved around by the effects of seafloor currents that can lead to progressive damage as a result of abrasion, to detect the locations of bottom contact fishing close to a cable that could lead to damage, and to determine the locations of cable faults far from shore so that repairs can be more effectively targeted.

It is becoming more and more apparent that fibre-optic sensing may yield other valuable information, in addition to its primary purpose for cable protection. A growing number of studies are starting to show the broader utility of fibre-optic sensing to make scientific measurements in the marine environment. Fibre-optic sensing can be used to detect natural hazards such as earthquakes and tsunamis, to gather data that has potential value for ocean and climate monitoring, and even to detect sounds made by animals that live in the deep sea. The potential to observe environmental conditions in the ocean using fibre-optic sensing along unmodified telecommunications cables is particularly exciting for scientists given the global reach of the submarine cable network and the limited monitoring that currently exists in the deep ocean, despite it being the largest habitable space on our planet and one that is under growing threat from the impacts of climate change.

This issue of Submarine Cable Protection and the Environment provides an overview of the different techniques that have been developed in the field of

fibre-optic sensing and how they are increasingly being used to monitor the marine environment around them. This overview explains how the different techniques work, what they can be used to observe, and provides examples of their application on both commercial cables as well as those used specifically for scientific purposes, to gain a better understanding of the ocean and our planet as a whole.

▼ **Figure 1:** Top graph illustrates the growth in scientific studies that use fibre-optic sensing to monitor the environment over recent years. Note the rapid growth in the application of this sensing technology since 2015. Lower panel shows the range of processes and human activities that have been detected by fibre-optic sensing along cables.



DIFFERENT TYPES OF SENSING THAT RELIES UPON SUBMARINE CABLES

It is first important to point out that there are a number of uses of submarine cables in environmental monitoring, some of which have been in use for a significant time. These include:

Cabled seafloor observatories are designed and developed specifically for ocean and other environmental monitoring and do not themselves carry commercial telecommunications traffic. These systems include arrays of seafloor observatories or nodes that host individual or many different types of scientific sensors by cables that are connected to the shore by cables that enable both power and data transmission. Examples include those offshore Canada (NEPTUNE - North East Pacific Time-series Underwater Networked Experiments), USA (OOI - Ocean Observatories Initiative), Taiwan (MACHO - Marine Cable Hosted Observatory) and Europe (through ESONET-NoE - European Seas Observatory NETwork-Network of Excellence and recently with the infrastructure project EMSO - European Multidisciplinary Seafloor Observatory) (Favali et al., 2010). Some of the most sophisticated systems include those in Japan (S-Net - Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench and DONET - Dense Oceanfloor Network system for Earthquakes and Tsunamis) that are designed to monitor offshore earthquakes and provide a very dense grid of seafloor nodes that detect the passage of tsunami waves to provide the critical early warning to enable the most effective evacuation of vulnerable areas. The main driver for this dense monitoring network was due to the unexpectedly large impacts of the 2011 Tohoku-oki earthquake, which was the most powerful earthquake ever recorded in Japan and the costliest natural hazard in history (economic costs estimated at least at $235 billion; Zhang, 2011).

Scientific Monitoring and Reliable Telecommunications (SMART) cables, which in contrast to cable seafloor observatories, are

systems that involve the transfer of commercial telecommunications traffic at the same time as making scientific measurements. SMART cables integrate several scientific sensors within or adjacent to repeaters, which are devices used to boost the optical signal required for long distance trans-oceanic telecommunications. These sensors include temperature, pressure and acceleration which enable the measurement of key ocean variables at spacings of tens of kilometres to observe climate changes and to monitor tsunamis and earthquakes (Howe et al., 2022). While the SMART approach permits telecommunications traffic at the same time as making scientific measurements, it requires a specialist cable design that must be specified at the manufacturing stage and cannot be retro-fitted to an existing submarine cable system.

Fibre-optic sensing using standard telecommunications cables, which is the primary focus of this issue**.** Small changes in the light that travels along an optical fibre are interrogated to determine environmental changes, such as vibrations, pressure, and temperature changes. This family of cable-based sensing includes many approaches including: i) Distributed Acoustic Sensing (DAS); ii) Distributed Temperature Sensing (DTS); iii) Interferometry or Phase with HLLB (High Loss Loop Back); iv) State of Polarisation (SOP). A fundamental difference of these types of techniques for sensing is that they use the optical fibre within a cable itself to make measurements. This therefore does not require modification of standard commercial telecommunications cables to add environmental sensing capabilities and includes techniques that are routinely used in the monitoring of telecommunication performance, integrity and security, and that are compatible with data traffic, sometimes in the same fibre, with no degradation of the transmitted data stream (Marra et al., 2023).

***See tables 1 and 2 on the following page*.**

DIFFERENT TYPES OF SENSING THAT RELIES UPON SUBMARINE CABLES

Technology	Marine vessels	Anchors	Fishing	Seismic waves / Earthquakes [1]	Volcanic activity	Storms	Temperature	Temperature change	Salinity	Wave height (single wave)	Wave height (average value)	Ocean currents	Marine mammals	Subsurface imaging
	Useful for cable protection			*Useful for scientific monitoring/observation*										
Optical Interferometry	N	?	?	Y	Y	Y	N	N	N	?	?	Y	N	N
State of Polarisation	N	?	?	Y	Y	Y	N	N	N	?	?	Y	N	N
Distributed Acoustic Sensing	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y
SMART Cables	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N

Notes: 1) Earthquake-induced tsunamis are triggered by large vertical seafloor displacements, and most sensing modalities do not generally distinguish between horizontal and vertical axes (the exceptions being SMART cables and dedicated seafloor observatories).

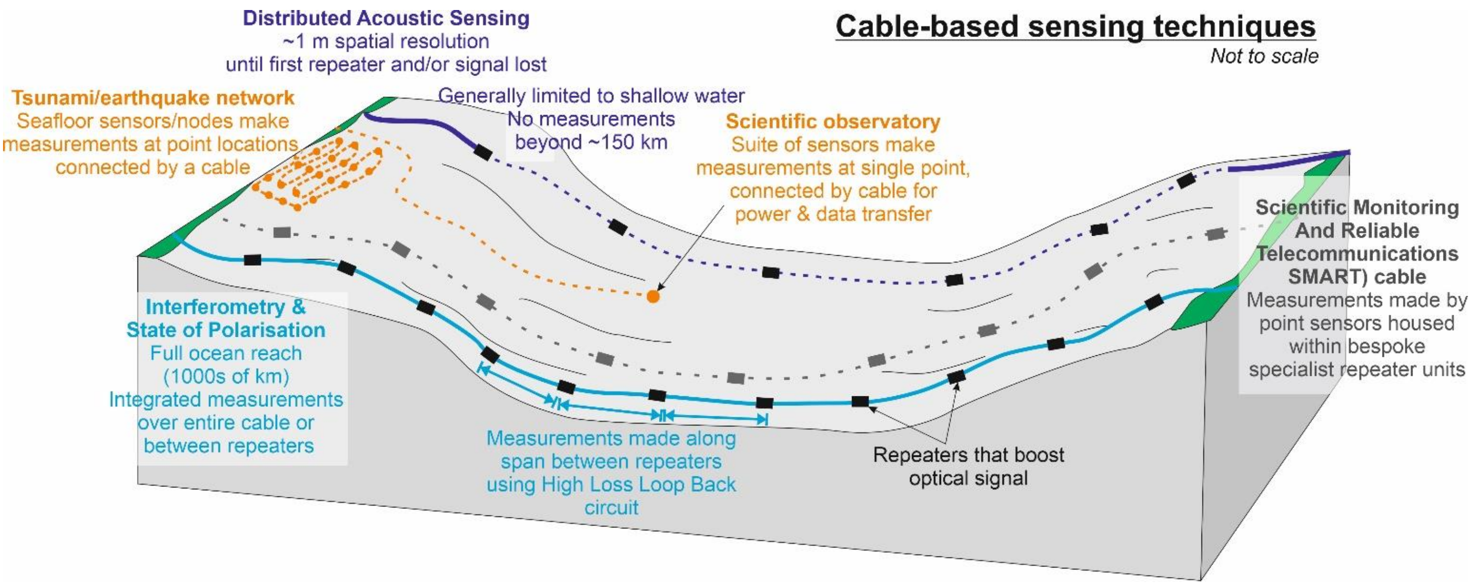
Technology	Range [km]	Spatial resolution	Compatible with data traffic on other channels	Monitoring application	Environmental sensitivity	Relative Capital Cost
Optical interferometry	1000s	10-100 km[1]	Yes	Global	High	$$
State of Polarisation	1000s	10-100 km[1]	Yes	Global	Medium	$$
Distributed Acoustic Sensing	<150	Metre-scale	Yes, if power reduced	Coastal	High	$
SMART Cables	1000s	10-100 km[2]	Yes[2]	Global	High	$$$$$
Cabled scientific observatories	1000s	Variable, depending on the number of nodes/ observatories	N/A – Uses bespoke cables for power and data transfer	Local/ Regional	High	$$$$$$

Notes: 1) Environmental changes recorded are integrated over the length of a cable between repeaters. 2) Environmental changes are recorded at a point by individual sensor packages that are integrated within a bespoke SMART repeater unit and monitoring does not use the optical fibre itself.

▲ **Table 1:** Applications of the different cable sensing techniques covered in this issue and SMART Cables.

◄ **Table 2:** Comparison of different fibre-optic sensing techniques and SMART Cables. Notes, modified from Marra et al. (2023) and presentation by Dean Veverka at the ICPC 2023 Plenary meeting.

DIFFERENT TYPES OF SENSING THAT RELIES UPON SUBMARINE CABLES



▲ **Figure 2:** Schematic illustrating the different types of sensing techniques that use cables. Blue colours refer to techniques that use the optical fibre and sense along the cable itself, including Distributed Acoustic Sensing, Interferometry and State of Polarisation. Also shown are techniques that rely upon cables, but that make point measurements at scientific nodes or sensors that are connected to cables (i.e. scientific observatories/networks in orange) or are integrated within a repeater (i.e. SMART Cables in grey) and hence require a bespoke design.

INTRODUCTION TO FIBRE-OPTIC SENSING TECHNOLOGIES

On the following pages, we provide an introduction to each of the available technologies, a general overview of how fibre-optic sensing technologies work, and about their relative advantages and limitations.

DISTRIBUTED ACOUSTIC SENSING (DAS)

- A light pulse is injected in the fibre and the reflected light (known as backscatter) is analysed using a method called Optical Time Domain Reflectometry.
- Backscattering is generated as a result of tiny changes in the density of the glass core of the optical fibres arising from small imperfections created during its manufacture. Environmental changes, such as temperature or ground movements, can cause changes to that backscatter, creating shifts in the phase of the backscattered light.
- As we know the time it takes for light to travel along and back through an optical fibre, this technique can be used to not only detect environmental changes from the backscatter response but also to locate where those changes occur along the cable to a precision of around 1 metre.
- This approach is used routinely for cable protection and is the most mature of these fibre-optic sensing technologies, having initially been developed for use in the oil and gas industry.
- Monitoring is typically performed on a so-called 'dark fibre,' which refers to a fibre that is not lit and does not carry data traffic. Modern telecommunications cables contain multiple fibres to provide the capacity needed for data transfer. It is now possible for Distributed Acoustic Sensing to be used on fibres carrying data traffic if the optical power is below a suitable threshold (i.e., avoiding gain imbalances in the optical repeaters); however, reducing the power will reduce the distance over which measurements can be made.
- Distributed Acoustic Sensing is limited to the distance at which the backscatter signal is too weak (i.e., due to optical losses) and/or the distance to the first repeater, unless a cable is

specifically designed with a fibre which does not pass through an amplifier within a repeater. This typically limits this technique's application beyond ~100-150 km from shore and will therefore typically be limited to coastal and shelf settings, except where continental shelves are narrow (e.g., active tectonic margins, volcanic islands etc.).

- In order to make measurements, an external unit known as an interrogator is required that is typically located at a cable landing station. The interrogator is connected to a fibre and can be added to any existing telecommunications cable.
- In addition to detecting different events or processes, Distributed Acoustic Sensing can can be used to image geological structures that lie beneath the seafloor. To do so requires a source of noise, which could like those used in typically offshore surveys (e.g., airgun or other controlled seismic source) or, as demonstrated by recent studies, it is possible to make use of ambient noises in the ocean, such as generated by earthquakes, weather events or even by whales (Lindsey and Martin, 2021).

DISTRIBUTED TEMPERATURE SENSING (DTS)

- Distributed Temperature Sensing is based on the understanding of how the intensity of light scattering within a fibre is affected by local changes in temperature, which cause slight changes to the fibre (Hartog et al., 2018).
- Unlike other fibre-optic sensing approaches, which detect relative changes in temperature, Distributed Temperature Sensing can provide an absolute measure of the temperature of the core of the fibre at the point at which the scattering occurs. This provides opportunities to monitor health status, particularly for power cables, but also provide potentially useful scientific information

about ocean bottom temperatures (e.g., to monitor the deep ocean's response to warming).

- This approach is now very well established, with many thousands of installations across applications ranging from fire detection in tunnels, through the dynamic thermal rating of energy cables, to the determination of the flow profile in hydrocarbon wells (Hartog, 2018).
- It is possible to use Distributed Temperature Sensing to measure over distances of tens of kilometres in length, at a spatial resolution of around 1 m, resolving temperature changes of less than 0.01°C.

OPTICAL INTERFEROMETRY

- Optical Interferometry requires an ultra-stable laser at one end of a cable. This laser source needs to be far more stable than that typically used in commercial systems but of a similar output power (~1 mW), and can be added to existing cable systems with no modification to underwater components of the system.
- A laser signal is injected into an optical fibre within a cable and the returned signal is compared to the one that went in. If there is no external perturbation to the fibre, the return signal will match the initial signal; however, environmental disturbances create small changes in the path of the light along the fibre leading to a delay in the return time of the light (known as a phase change).
- Phase changes can be related to disturbances caused by several processes, such as pressure variations induced by the passing of surface ocean waves or the effects of seafloor currents that cause the cable to move slightly.
- Optical Interferometric measurements are made with no impact on data traffic on other channels and have been shown to reach over thousands of kilometres.

- Initial trials demonstrated that ground shaking signals generated by earthquakes can be detected and characterised using this approach; however, those studies used the entire length of cable as a single integrated sensor (Marra et al., 2018).
- More recent advances have taken advantage of the Fibre Bragg Grating (FBG)-based High-Loss Loop Back (HLLB) circuit at each repeater, which is already used to provide a health check on the optical amplifiers. In addition to this update on cable health and using this same approach, it is now possible to localise phase changes to cable spans between individual repeaters; enabling span-wise detection of environmental signals (Marra et al., 2020).
- Monitoring can therefore be achieved across the full length of a cable system (thousands of kilometres), with a spatial resolution that is equivalent to the distance between repeaters (i.e. on the order of tens of kilometres).

STATE OF POLARISATION

- Polarised light is used to transmit data through telecommunications cables because the use of orthogonal polarisations doubles the capacity of each optical fibre. To extract a telecommunications signal, the receiver at a cable landing station continuously monitors the state of polarisation.
- It has been recognised that the state of the polarised light can also be affected by the surrounding environment, providing another tool to monitor cable health as well as detect natural processes in the ocean.
- As in the case of Optical Interferometry, the earliest State of Polarisation studies made measurements along the full length of a cable system, demonstrating that this technique can be used over

tens of thousands of kilometres (Zhan et al., 2021).

- More recent developments have shown that the High-Loss Loop Back circuit can also be used to locate signals to cable spans between individual repeaters, thus providing a spatial resolution on the order of tens of kilometres (Mertz et al., 2023).
- This approach does not require an ultra-stable laser and uses standard coherent transceivers without any need for modification to hardware.

EXAMPLE APPLICATIONS IN OCEAN AND EARTH MONITORING

How have these different techniques been used to better understand marine environments? Of the 150 peer-reviewed studies that demonstrate the application of fibre-optic sensing to environmental monitoring identified in the literature review, 82% included Distributed Acoustic Sensing, 15% Distributed

▼ **Table 3:** Comparison of injected optical signal types and laser source requirements for four sensing techniques from Marra et al. (2023).

Technology	Type of optical signal injected	Average optical power (typical)	Transceiver laser stability	Other comments
Optical Interferometry	Coherent Wave	1 mW	High	Requires High Loss Loop Back for spatial resolution and sensitivity
State of Polarisation	Coherent Wave or Modulated	1 mW	Low	Could use High Loss Loop Back for partial improvement of spatial resolution and sensitivity
Distributed Acoustic Sensing	Pulsed	mW-level (with reduced measurement range)	Medium	Limited range due to loss of signal strength or reaching a repeater unless a fibre is laid outside the repeater

Temperature Sensing, 8% Interferometry, and 3% State of Polarisation. This reflects the far more mature development of Distributed Acoustic Sensing, and the emerging nature of Interferometry and State of Polarisation.

MONITORING OF HUMAN ACTIVITIES

There are many more papers than those listed in the literature review that cover the use of Distributed Acoustic Sensing and Distributed Temperature Sensing to monitor the health of the cable itself; however, as the focus here is on the marine environment, those papers are not included in our review. Some of the highlights that demonstrate the ability to detect human activities include the following studies that are limited to Distributed Acoustic Sensing:

- Monitoring on a cable connecting Svalbard to mid-Norway via Uninett's research network over 44 days, detected and tracked ship traffic, in addition to whales, storms and earthquakes, demonstrating the multiple applications and benefits of Distributed Acoustic Sensing (Landrø et al., 2022).
- Distributed Acoustic Sensing during the COVID-19 pandemic recorded changes in human activity that could be related to lockdowns and their subsequent easing. Similar acoustic monitoring studies have been conducted in the ocean, to show the so-called COVID-quietening in the oceans (Lecocq et al., 2021).
- A 41.5 km long cable offshore Toulon, France, was used to track vessels, including a tanker cruising above the cable with monitoring successfully demonstrated from 85 m to 2000 m water depth. Spectral analysis enables identification of different vessels and analysis of the Doppler shift of the signals enable determination of their speeds (Rivet et al., 2021).
- Distributed Acoustic Sensing has been used to detect vibrations created by the discharge of

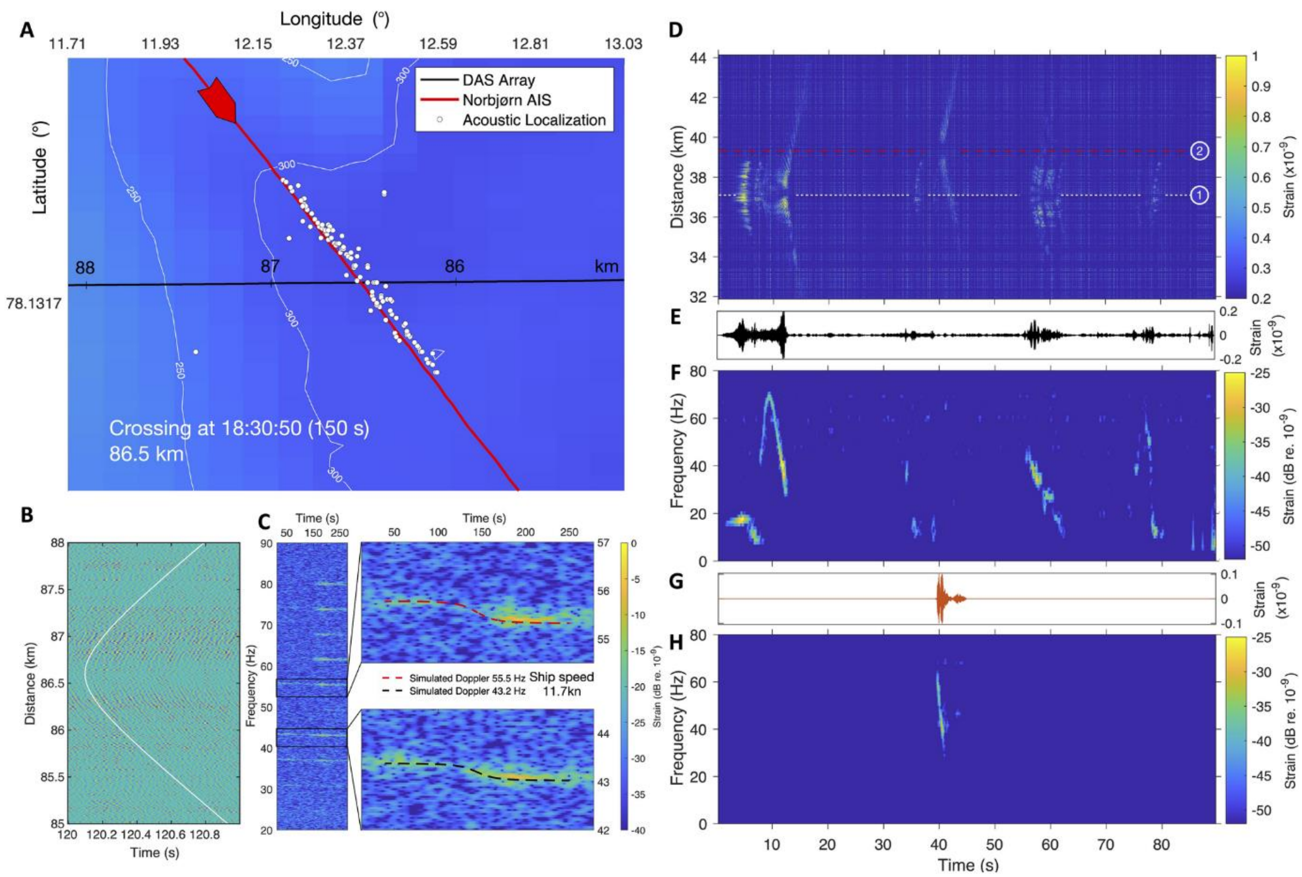
wastewater into rivers, which may increase the ability to monitor water quality in waterways and into the ocean (Chen et al., 2024).

EARTHQUAKES AND SEISMIC EVENTS

The greatest focus of scientific studies (a total of 67 papers) using fibre sensing was on earthquakes and seismic events and in this case there have been successful demonstrations of Distributed Acoustic Sensing, Interferometry and State of Polarisation.

- The arrival times of primary compressional (P) and secondary shear (S) waves generated by earthquakes

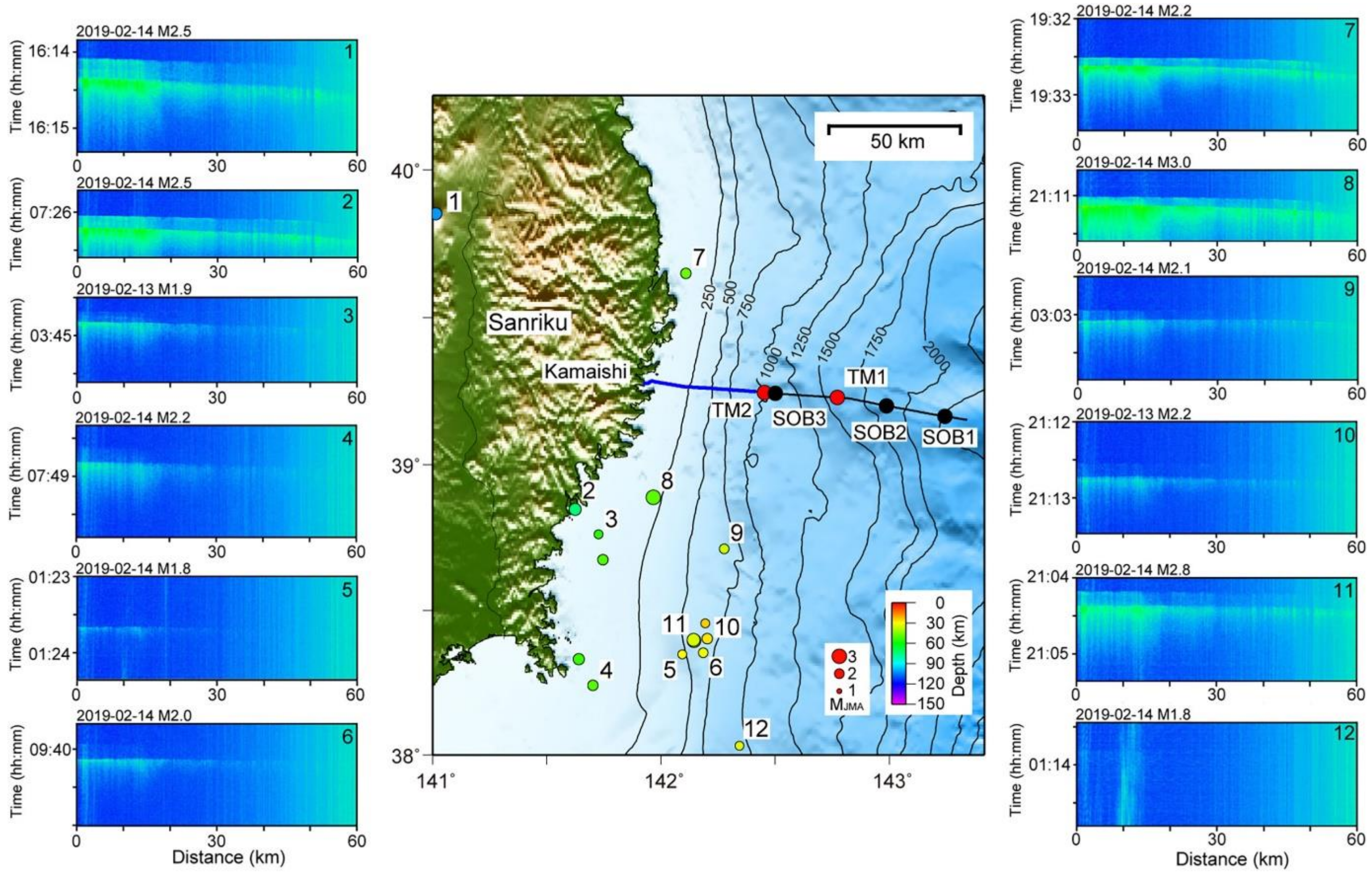
▼ **Figure 3:** Distributed Acoustic Sensing along Uninett's cable between Svalbard and Norway that shows the location of a ship detected along the cable (A), with its signals shown in B & C, and (D-H) calls from two types of whale (Fin and Blue Whale). Reproduced from Landrø et al. (2022) under a Creative Commons License.



have been detected for both earthquakes that occur close to a cable and also on the other side of the planet, demonstrating the utility of fibre-optic sensing. There is keen interest in using this capability to fill in gaps in the global seismic monitoring network, which is extremely sparse in the ocean and also in regions such as the South Pacific, despite the range of seismic hazards it experiences.

- Distributed Acoustic Sensing has the benefit of effectively transforming the cable into an array of thousands of

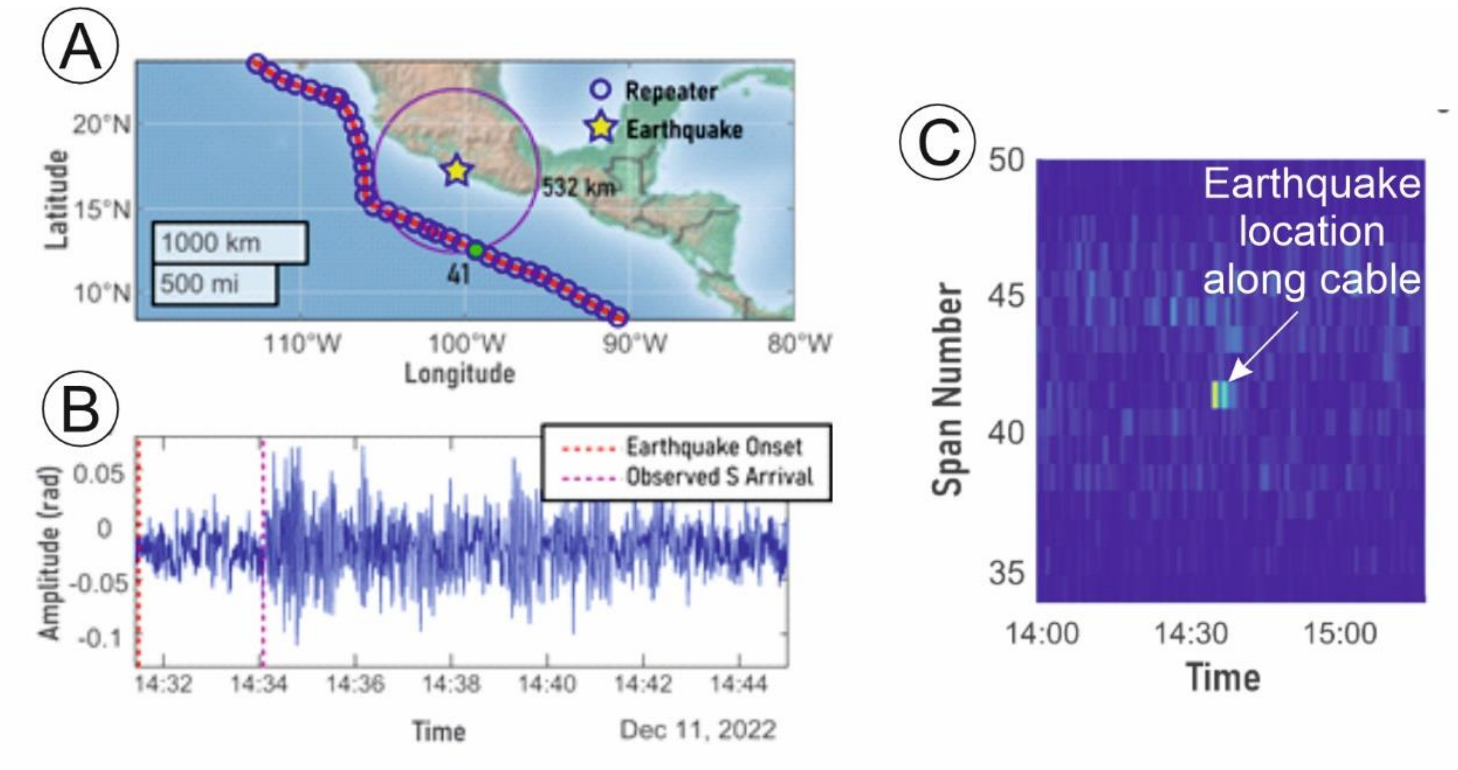
▲ **Figure 4:** Local earthquakes detected by Distributed Acoustic Sensing using the Sanriku cable system offshore Japan. Plots shown are for frequency band-extracted data that show the energy of strain rate between 10 and 20 Hz. The seafloor cable along which measurements were made is shown in blue and event numbers are labelled at their epicentres on the centre panel. Reproduced from Sinohara et al. (2022) under a Creative Commons Licence.



seismometers that can be used to not only characterise earthquake events, but also to locate their sources geographically (Lior et al., 2021).

- Distributed Acoustic Sensing can be used to map out earthquake-prone faults. A four-day DAS experiment on the Monterey Accelerated Research System cable identified a minor earthquake wavefield, which identified multiple previously unmapped submarine fault zones (Lindsey et al., 2019).

▼ **Figure 5:** State of Polarisation monitoring along a cable that connects between North and South America, used to detect a magnitude 6.0 earthquake that occurred in Mexico. This study made use of the High Loss Loop Back circuit to analyse signals detected between different repeaters (shown as circles in panel a). The time series along the 41st is shown in panel b, which clearly shows the onset of disturbance close in time to the earthquake start time as determined from onshore seismic monitoring. Panel c shows the signal power at each of the spans allowing the location of the earthquake to be pinpointed. Reproduced from Costa et al. (2023) under a Creative Commons Licence.



- Recent studies have shown how longer-reach, but coarser spatial resolution monitoring (State of Polarisation and Interferometry) can now be used to pin-point the location of earthquake signals along a cable to a resolution that is equivalent to the distance between repeaters (Marra et al., 2022; Zhan et al., 2021). Such monitoring can be performed over thousands of km, across the full length of a cable system, rather than DAS that is limited to approximately 100-150 km from shore.

TSUNAMI AND SURFACE WAVES

The ability to detect tsunami and storm surges ahead of them reaching a coastline provides a valuable opportunity to provide an early warning ahead to inform decision making and disaster response. Many parts of the global ocean are poorly monitored or are not monitored at all, hence there is considerable interest in the use of fibre optic sensing given the widespread coverage of cables across the global seafloor and the fact that they relay information in real-time (Wilcock, 2021). Seconds to minutes of additional warning time can make a fundamental difference to disaster response and evacuation strategies (Matias et al., 2021).

- Hydrostatic pressure changes created by travelling surface waves has been detected using Distributed Acoustic Sensing, that can now be used to track the passage of storm surges or tsunami waves over distances of tens of kilometres (Hartog et al., 2017).
- A seafloor seismic and tsunami monitoring cable system that uses Interferometry has been installed in the coastal waters at the Chinese State Oceanic Administration’s monitoring site in Hainan Province, China (Chang et al., 2020).
- Using a 10,000-kilometer-long submarine cable connecting Los Angeles, California, and Valparaiso, Chile, pressure

signals from ocean swells were recorded using State of Polarisation, in addition to multiple moderate-to-large earthquakes (Zhan et al., 2021).

- Ocean swells were detected on a cable crossing the North Atlantic using Interferometry (resolved to repeater spans) and calibrated against data from surface metocean buoys (Marra et al., 2022).
- There are plans to use various fibre-optic sensing techniques to complement the use of SMART repeater nodes in the planned Continent-Azores-Madeira (CAM) submarine cable to detect and provide early warning against tsunamis (Matias et al., 2021).

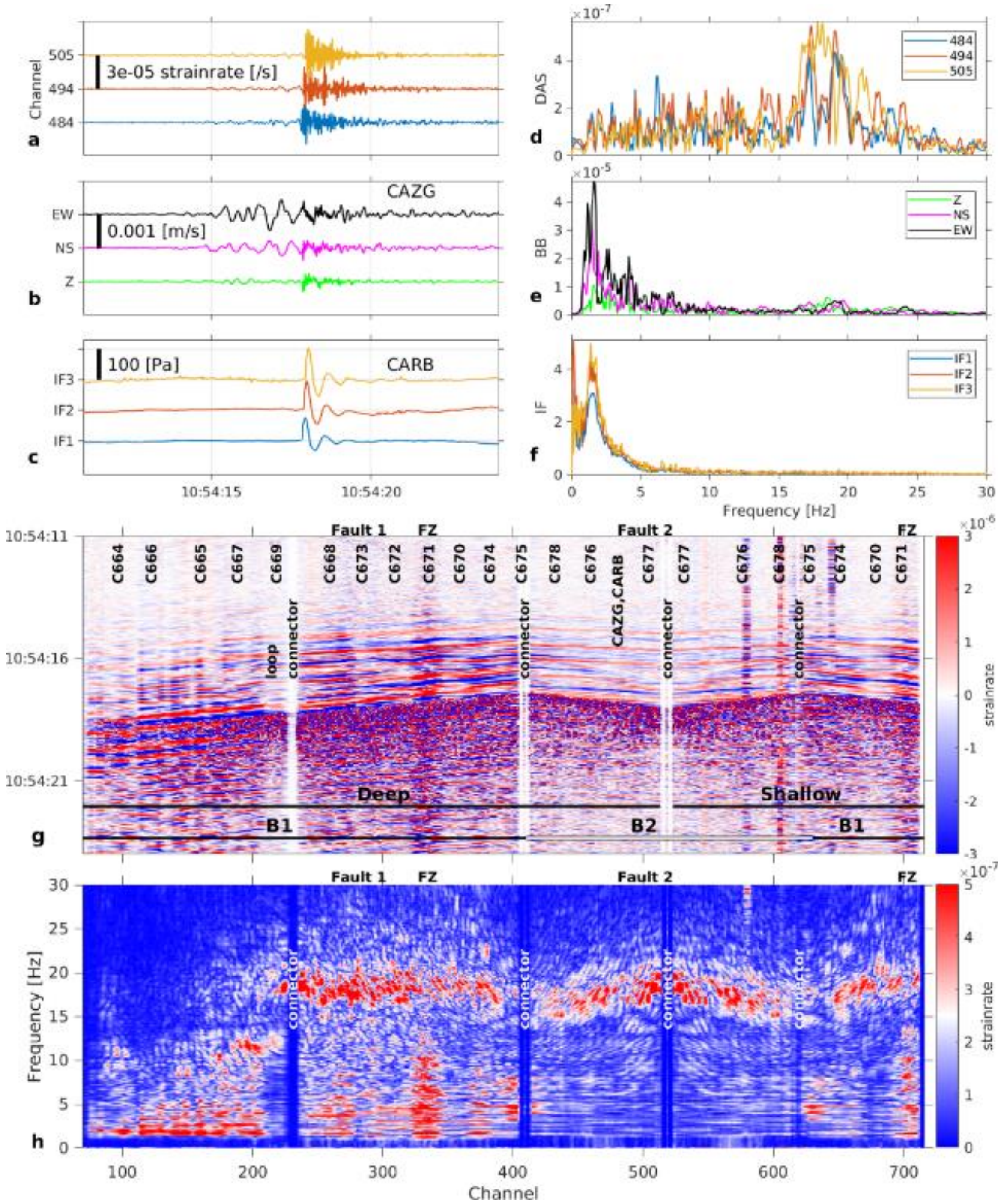
OTHER NATURAL HAZARDS INCLUDING VOLCANIC HAZARDS

Recent incidents such as the eruption of Hunga volcano offshore Tonga in 2022 and the 2018 collapse of Anak Krakatau, Indonesia, led to fatal tsunamis and a host of other socioeconomic impacts, but were not forewarned against due to a lack of monitoring infrastructure. There is thus a compelling need to strengthen global and local monitoring networks and fibre-optic sensing has the potential to add new monitoring capability in areas that are particularly vulnerable and provide critical early warning.

- The timing and location of volcanic earthquakes were characterised using Distributed Acoustic Sensing along a bespoke cable near to Azuma volcano, Japan (Nishimura et al., 2019). The source of these earthquakes was found to be shallow, beneath active volcanic areas. As Distributed Acoustic Sensing can be performed remotely and does not require maintenance of sensors, this observing approach may be highly suitable for monitoring other volcanoes with a reduced risk of system damage.
- Strain signals associated with volcanic explosions of Mount Etna were detected using

Distributed Acoustic Sensing along a bespoke cable and their origin was located (Jousset et al., 2022). This approach also detected very small volcanic events, related to fluid migration and degassing that show promise for the use of DAS as an early warning system to detect precursor events before large reruptions.

- Similarly, a terrestrial 3 km cable was used to detect spatial clusters of earthquakes at an active volcanic complex in British Columbia (Klaasen et al., 2021). Distributed Acoustic Sensing detected a broad range of unexpectedly intense, low-magnitude, local seismicity, with several tens to nearly 400 earthquakes per day. This shows that DAS has the potential to reveal previously undiscovered seismicity in challenging environments, where comparably dense arrays of conventional seismometers are difficult to install.
- A domestic subsea cable that was damaged by the 2022 eruption of Hunga volcano, was used to monitor earthquakes shortly after the catastrophic explosion, recording low magnitude seismic events, including one located beneath the volcano (Nakano et al., 2024). Given the sparse seismic monitoring network that exists offshore Tonga and in the South Pacific as a whole, the ability to use fibre-optic cables as earthquake and tsunami-detection tools has potential to fill key monitoring gaps and provide the much-needed, but missing early warning systems.



▼ **Figure 5:** Monitoring of volcanic explosions at Etna, Mediterranean using Distributed Acoustic Sensing along a fibre optic cable from Jousset et al. (2023). a) Strain rate from distributed acoustic sensing (DAS) records. b). Velocity seismograms from a nearby broadband seismometer. c) Pressure records from nearby infrasound sensors. d) Strain rate spectra. e) Ground velocity spectra. f) Pressure spectra. g) Strain rate record at the 710 DAS channels along the 1.3 km fibre around the explosion time. FZ: fault zone (~50 m width), at channels 315–340 (deep cable) and channels >700 (shallow cable). h) Strain rate-frequency distribution along the cable. Reproduced under a Creative Commons Licence from Jousset et al. (2022).

OCEANOGRAPHIC PROCESSES INCLUDING STORMS, CURRENTS AND TEMPERATURE FLUCTUATIONS

Ocean conditions can pose a hazard to cables due to strumming, scour and abrasion, but also to coastal infrastructure and shipping. Furthermore, understanding and monitoring ocean conditions is critical for understanding climate change. Ocean conditions, such as waves, storms, seafloor currents and internal waves all generate ambient noise in the ocean, which has been shown to be detectable using fibre-optic sensing.

- Ambient ocean noise was recorded via Distributed Acoustic Sensing on the Monterey Accelerated Research System cable, California, including observations of tidally-driven bores, storm-induced sediment transport, infragravity waves, breaking internal waves, and sea-state dynamics during a storm (Lindsey et al., 2019).
- Oscillations of a cable offshore southern France were recorded by DAS that were linked to a cable in free span (Mata Flores et al., 2023). Internal gravity waves and weak oceanic turbulence were detected. Estimates were provided for ocean currents speed at >2 km water depth and validated against a seafloor current meter.
- The use of Interferometry has been used to detect storms, seafloor currents that vary in intensity across tidal cycles, as calibrated against surface oceanographic buoys. These observations could be resolved to within repeater spans (Marra et al., 2021).
- State of Polarisation has been recently used to detect signals thought to be indicative of cable strumming due to deep-sea currents, although further work is needed to validate this hypothesis (Zhan, 2023).
- Legacy fibre-optic telecommunications cables were 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, similar short-term background variability in deep-sea temperature may be at the limits of detection using distributed optical fibre sensing systems (10–20 mK). However, longer-term (annual to decadal) changes in ocean temperature (in the order of 0.1–0.5°C rise per decade) are well within the measurement capabilities of Distributed Temperature Sensing (Hartog et al., 2017).

BIOLOGICAL ACTIVITY – WHALES AND DOLPHINS

The study of biological noise, generated by a wide range of animals that use sound to communicate, hunt and locate themselves, is a growing area of research. Perhaps the best-known organisms to use noise are cetaceans (whales and dolphins). A number of recent studies have shown that Distributed Acoustic Sensing along fibre-optic cables can be used to monitor cetacean activity.

- Two 260 km telecommunication cables were used to record low-frequency whale vocalizations offshore Svalbard, Norway (Landrø et al., 2022; Rørstadbotnen et al., 2023). This study pin-pointed the location of fin whales (to within 100 m) and recorded their songs, speed and heading to a distance of 95 km from the landing station.
- Baleen whales were detected along a 120 km cable with measurements made at a spatial resolution of 4 m (Bouffaut et al., 2022). This novel study not only identified the whale species, but also estimated their location, and used the noise generated by

the whales as a seismic source to image the sub-seafloor.

- Distributed Acoustic Sensing along two cables of the Ocean Observatories Initiative Regional Cabled Array (offshore Oregon) enabled detection of fin whale and Pacific blue whale calls, enabling differentiation of species and sex of the animals (Abadi et al., 2022; Wilcock et al., 2023).

POLAR AND GLACIAL PROCESSES

Monitoring polar regions is a critical component of understanding climate change and potential feedbacks that may exist. Such regions are remote and have limited monitoring in marine settings; hence, the ability to use subsea cables is of keen interest to researchers that study climate-ice-ocean interactions.

- During eight, one-week, seasonally-distributed periods across two years Distributed Acoustic Sensing was used to monitor the seasonal growth and thawing of sea ice on a 40 km long section of cable on the continental shelf of the Beaufort Sea, Alaska (Baker et al., 2021).
- Monitoring was performed using Distributed Acoustic Sensing along an array of bespoke cables to image changes in permafrost under a controlled melting experiment (Cheng et al., 2022).

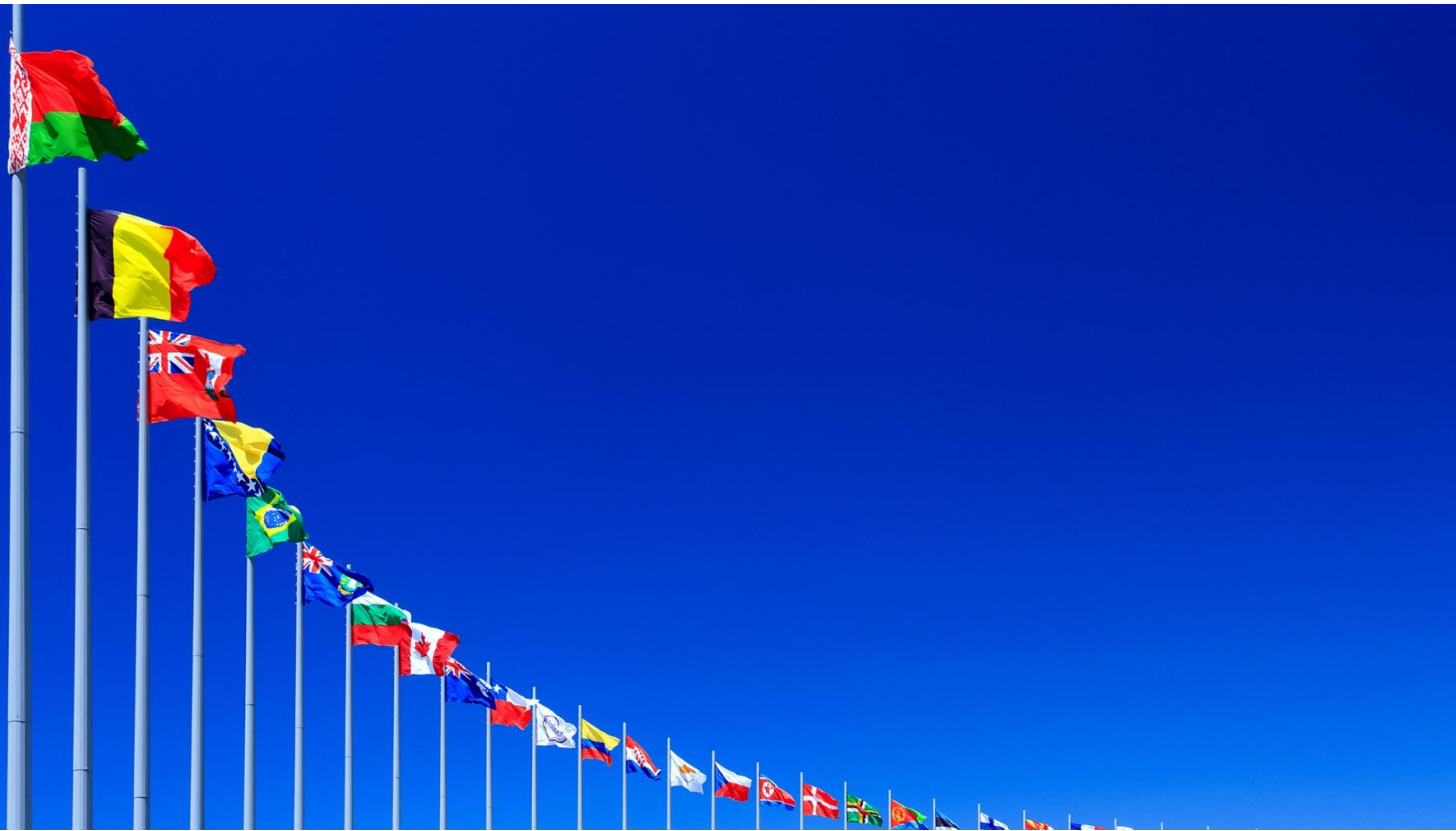
- Distributed Acoustic Sensing can also be deployed on cables that are installed vertically within a borehole (Booth et al., 2020). A bespoke cable was installed in a >1000 m deep borehole drilled in to the Store Glacier (a fast-flowing outlet of the Greenland Ice Sheet), and used to image the structure of the ice.
- Cables were temporarily installed vertically within boreholes drilled through the ice-shelf cavity on the Ross Ice Shelf, Antarctica (Tyler et al., 2013). Distributed Temperature Sensing (DTS) in fibre-optic cables was used to provide near-continuous observations of ice and ocean temperatures to a depth of almost 800 m beneath the ice-shelf surface. Data received document the presence of near-freezing water throughout the cavity from November through January, followed by an influx of warmer water reaching ~150 m beneath the ice-shelf base during February and March.
- Dynamic strain measurements along a 1 km terrestrial fibre-optic cable on an Alpine glacier made using Distributed Acoustic Sensing were used to produce high-quality seismograms related to glacier flow and nearby rock falls (Walter et al., 2020). The data enabled novel characterisation of the glacier movement.
- Snow avalanches were detected and characterised using bespoke fibre-optic cables at an onshore site in Switzerland (Paltz et al., 2023). These data showed that the signal of the snow avalanche was recorded long before it reached the cable, demonstrating that this approach may be used for early warning. Such flows are similar to turbidity currents in the ocean, so this shows promise for similar application in submarine settings.

WHAT DOES THE FUTURE HAVE IN STORE?

The steps forward in fibre-optic sensing technology, enabled by similar advances in analysis of large broadband datasets such as through use of Machine Learning, are seeing a revolution in ocean and earth monitoring. The rapid growth in studies that use this technology will continue to grow and the benefits for science and society are significant, but currently not fully realised. The scientific opportunities provided by fibre-optic sensing are seemingly endless; however, it is not yet possible to upscale this technology to create a global monitoring network. This is in part due to a number of outstanding challenges, several of which are the focus of a new working group on Cable Sensing established by the ICPC.

The data volumes that are generated by fibre-optic sensing, particularly Distributed Acoustic Sensing, are vast. Most studies have typically focused on short duration monitoring windows, that span no more than a few days or weeks, simply because of storage requirements. Many studies that have detected new processes or require careful consideration of precisely what is being detected. This emphasises a need for calibration of fibre optic-sensing data against measurements made by conventional sensors so that the data outputs can be converted into meaningful outputs. All of this is required such that data can be analysed robustly, but if early warning systems are to be developed, then new algorithms will be required such that the data stream can be interpreted in real time, with sufficient confidence that false alarms are not raised. Some challenges may relate to apparent security concerns, which may arise where cables connect between two different countries and cross their jurisdictional waters.

Under the United Nations Convention on the Law of the Sea (UNCLOS), all states have the freedom to lay submarine cables within the Exclusive Economic Zone of all Coastal States and in the High Seas beyond the continental shelf because of their important role in enabling global communications. UNCLOS places greater constraint on activities that involve Marine Scientific Research, which require special permits. If any cable-based monitoring was deemed to be focused on marine scientific research, then this could lead to jurisdictional creep with the requirement for additional permits, which could lengthen the timescales for any repairs required for cables or the installation of critical new infrastructure. It is therefore important to note that the fibre-optic sensing techniques summarised in this publication use unmodified telecommunications cables, hence the primary use of the cable remains the same (data and communications transfer). Fibre-optic sensing is first and foremost a cable monitoring tool, to understand the health of the system, identify any potential faults to aid repair, and support cable protection. The ICPC is actively supporting research into the benefits of technologies to improve cable protection. That this technology also has a scientific value is a mutually beneficial coincidence, and one that will hopefully continue to lead to a greater understanding of our global ocean and the planet as a whole.



Please visit w.iscpc.org for further information.

Sharing seabed and oceans in harmony

The International Cable Protection Committee (ICPC) was formed in 1958 and its primary goal is to promote the safeguarding of international submarine cables against human made and natural hazards. The organisation provides a forum for the exchange of technical, legal and environmental information about submarine cables and, with more than **215 MEMBERS** from over **70 NATIONS,** including cable operators, owners, manufacturers, industry service providers, and governments, it is the world's premier submarine cable organisation. The ICPC comprises of an 18 Member Executive Committee (EC)-led organisation voted in by its Full Members. In addition to the Marine Environmental Adviser (MEA), General Manager (GM) and Secretariat team, the ICPC also has an appointed International Cable Law Adviser (ICLA) as well as a United Nations Observer Representative (UNOR).

Prime Activities of the ICPC:

- Promote awareness of submarine cables as critical infrastructure to governments and other users of the seabed.
- Establish internationally agreed recommendations for cable installation, protection, and maintenance.
- Monitor the evolution of international treaties and national legislation and help to ensure that submarine cable interests are fully protected.
- Liaison with UN Bodies.

Recommendations:

- Taking into account the marine environment, the ICPC authors Recommendations which provides guidance to all seabed users ensuring best practices are in place.
- Educating the undersea community as well as defining the minimum recommendations for cable route planning, installation, operation, maintenance and protection as well as survey operations.
- Facilitating access to new cable technologies.

Advancing Regulatory Guidance:

- Promoting United Nations Convention for the Law of the Sea (UNCLOS) compliance.
- Championing uniform and practical local legislation and permitting
- Protecting cable systems and ships.
- Aiding education of government regulators and diplomats.

Working with Science:

- Supporting independent research into cables.
- Publishing reviews for governments and policy makers.
- Working with environmental organisations.
- Effective public education via various media.

To learn how to become of Member organisation of the ICPC, please click on join here.

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secured, the "Nexans Skagerrak" will start laying the cable towards Sicily.

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Authors	Year		Technique				Variables recorded																
		Review paper	Distributed Acoustic Sensing	Distributed Temperature Sensing	Interferometry	State of Polarization	Cetaceans	Temperature	Fishing	Storms and weather	Currents	Waves/ tsunami	Earthquakes and seismic events	Volcanic hazards	Rock falls/avalanches/ slope failures	Subsurface characterisation	Polar and glacial processes	Reservoir and aquifer characterisation	Vessels incl anchoring	Human activities	Asset integrity/ cable security	Comparison with conventional sensors
Ajo-Franklin et al.	2019		1										1			1						
Alahbab et al.	2005			1				1													1	
Baba et al.	2024		1										1									1
Baker and Abbott	2021		1														1					
Baker and Abbott	2022		1														1					
Becerril et al.	2024		1									1										
Bellefleur et al.	2020		1													1						
Biagioli et al.	2024		1										1	1								1
Bogris et al.	2022				1								1									
Booth et al.	2020		1														1					
Bouffaut et al.	2022		1				1															
Bowden et al.	2022		1	1									1									
Buisman et al.	2022		1													1						
Cantono et al.	2022	1	1		1	1																
Cao et al.	2023		1																1	1	1	1
Chang et al.	2020				1								1									
Chen et al.	2023		1										1									
Chen et al.	2024		1																	1		
Chen et al.	2023		1													1						
Cheng et al.	2021		1													1						

Authors	Year		Technique				Variables recorded																
		Review paper	Distributed Acoustic Sensing	Distributed Temperature Sensing	Interferometry	State of Polarization	Cetaceans	Temperature	Fishing	Storms and weather	Currents	Waves/ tsunami	Earthquakes and seismic events	Volcanic hazards	Rock falls/avalanches/ slope failures	Subsurface characterisation	Polar and glacial processes	Reservoir and aquifer characterisation	Vessels incl anchoring	Human activities	Asset integrity/ cable security	Comparison with conventional sensors
Cheng et al.	2022		1													1	1					
Correa et al.	2019		1													1		1				1
Costa et al.	2023					1							1									
Costa et al.	2023				1																	
Daley et al.	2013		1													1		1				
Dale et al.	2016		1													1						1
Dall'Osto	2023		1											1								
Dou et al.	2017		1																	1		
Douglass et al.	2023		1																			1
Escobar-Vera et al.	2023	1	1																			
Failleau et al.	2018			1				1													1	
Fang et al.	2020		1										1							1		
Farghal et al.	2022		1									1	1									
Fernández-Ruiz et al.	2022	1	1							1	1	1	1				1					
Fernández-Ruiz et all.	2020		1				1															
Fernández-Ruiz et al.	2020		1										1			1						
Fukushima et al.	2022		1										1			1						
Glover et al.	2023		1									1										
González-Herráez et al.	2024		1							1	1	1										
Gorshkov et al.	2022	1								1						1				1	1	

Authors	Year		Technique				Variables recorded															
		Review paper	Distributed Acoustic Sensing	Distributed Temperature Sensing	Interferometry	State of Polarization	Cetaceans	Temperature	Fishing	Storms and weather	Currents	Waves/ tsunami	Earthquakes and seismic events	Volcanic hazards	Rock falls/avalanches/ slope failures	Subsurface characterisation	Polar and glacial processes	Reservoir and aquifer characterisation	Vessels incl anchoring	Human activities	Asset integrity/ cable security	Comparison with conventional sensors
Gutscher et al.	2023				1								1									
Guo et al.	2023		1	1																		
Hara et al.	1999			1				1													1	
Hartog	1995			1				1													1	
Hartog	2002			1				1													1	
Hartog et al.	2018	1	1	1	1			1		1	1	1	1	1					1	1		
He et al.	2022			1				1										1			1	
Hernández et al.	2021		1										1									
Jousset	2019	1	1							1			1									
Jousset et al.	2022		1											1								
Jousset et al.	2018		1										1									1
Kennett	2022		1										1									
Klaasen et al.	2021		1										1	1								
Kumari et al.	2019	1		1				1														
Landrø et al.	2022		1				1			1			1						1			
Lauber et al.	2018			1				1													1	
Lecocq et al.	2020		1																	1		
Lentas et al.	2020		1										1									1
Lellouch et al.	2019		1													1		1				
Lellouch et al.	2023		1										1			1						

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		Review paper	Distributed Acoustic Sensing	Distributed Temperature Sensing	Interferometry	State of Polarization	Cetaceans	Temperature	Fishing	Storms and weather	Currents	Waves/ tsunami	Earthquakes and seismic events	Volcanic hazards	Rock falls/avalanches/ slope failures	Subsurface characterisation	Polar and glacial processes	Reservoir and aquifer characterisation	Vessels incl anchoring	Human activities	Asset integrity/ cable security	Comparison with conventional sensors
Li et al.	2023	1	1																			
Li et al.	2023		1										1									
Li et al.	2021		1										1									1
Li et al.	2021		1										1									
Lin et al.	2024		1							1	1	1										
Lina et al.	2023	1	1													1						
Lindsey and Martin	2021		1							1	1	1	1	1	1	1	1		1	1	1	
Lindsey et al.	2019		1							1		1	1			1						
Lindsey et al.	2017		1										1									
Lindsey et al.	2020		1																			
Lior et al.	2023		1									1	1									
Lior et al.	2021		1									1	1									
Lior et al.	2021		1										1									1
Luo et al.	2020		1										1			1						
Marra et al.	2018				1								1									
Marra et al.	2022				1					1	1	1	1									
Mata Flores et al.	2023		1								1										1	1
Mata Flores et al.	2023		1							1	1		1								1	
Maateeva et al..	2014		1															1				
Matias et al.	2021		1		1							1	1									

Authors	Year		Technique				Variables recorded																
		Review paper	Distributed Acoustic Sensing	Distributed Temperature Sensing	Interferometry	State of Polarization	Cetaceans	Temperature	Fishing	Storms and weather	Currents	Waves/ tsunami	Earthquakes and seismic events	Volcanic hazards	Rock falls/avalanches/ slope failures	Subsurface characterisation	Polar and glacial processes	Reservoir and aquifer characterisation	Vessels incl anchoring	Human activities	Asset integrity/ cable security	Comparison with conventional sensors
Matsumoto et al.	2021		1							1			1									1
Min et al.	2021	1	1		1			1		1		1	1								1	
Mjehovich et al.	2023		1										1									
Mo et al.	2023		1										1									1
Mondanos et al.	2015		1	1				1										1			1	
Nakano et al.	2024		1										1									
Nayak et al.	2021		1										1									
Nishimura et al.	2021		1										1	1								
Owen et al.	2012		1																		1	
Paitz et al.	2021		1																			1
Paitz et al.	2023		1												1		1					
Parker et al.	2014		1													1					1	
Pelaez Quiñones et al.	2023		1					1														1
Peña Castro et al.	2023		1														1					
Pevzner et al.	2020		1															1				
Rivet, D., Ampuero et al.	2022		1																			
Rivet et al.	2021		1																1			
Rodríguez Tribaldos. and Ajo-Franklin	2021		1															1				
Rørstadbotnen et al.	2023		1				1															

Authors	Year		Technique				Variables recorded															
		Review paper	Distributed Acoustic Sensing	Distributed Temperature Sensing	Interferometry	State of Polarization	Cetaceans	Temperature	Fishing	Storms and weather	Currents	Waves/ tsunami	Earthquakes and seismic events	Volcanic hazards	Rock falls/avalanches/ slope failures	Subsurface characterisation	Polar and glacial processes	Reservoir and aquifer characterisation	Vessels incl anchoring	Human activities	Asset integrity/ cable security	Comparison with conventional sensors
Rørstadbotnen et al.	2023		1												1							
Rosst et al.	2022		1													1						
Rui et al.	2019			1				1			1											
Seabrook et al.	2022			1				1										1			1	
Selker et al.	2006			1				1									1					
Shen and Wu	2024		1					1					1									
Shinohara et al.	2022		1										1			1						
Silva et al.	2022			1				1													1	
Sladen et al.	2019		1										1									
Smith et al.	2023		1														1					1
Sørensen et al.	2018		1	1				1		1	1										x	
Spica et al.	2023		1										1			1						
Spica et al.	2022		1													1						
Spica et al.	2020		1							1	1	1	1	1						1	1	
Spikes et al.	2019		1													1						1
Taweesintananon et al.	2021		1													1						1
Taweesintananon et al.	2022		1							1			1									
Taweesintananon et al.	2023		1							1						1						
Tonegawa et al.	2022		1										1									
Trabattoni et al.	2022		1										1									

			Technique				Variables recorded															
Authors	**Year**	**Review paper**	**Distributed Acoustic Sensing**	**Distributed Temperature Sensing**	**Interferometry**	**State of Polarization**	**Cetaceans**	**Temperature**	**Fishing**	**Storms and weather**	**Currents**	**Waves/ tsunami**	**Earthquakes and seismic events**	**Volcanic hazards**	**Rock falls/avalanches/ slope failures**	**Subsurface characterisation**	**Polar and glacial processes**	**Reservoir and aquifer characterisation**	**Vessels incl anchoring**	**Human activities**	**Asset integrity/ cable security**	**Comparison with conventional sensors**
Trafford et al.	2024		1													1						1
Tyler et al.	2013			1				1									1					
Ukil et al.	2011			1				1													1	
Van De Giesen et al.	2012			1				1													1	
van den Ende et al.	2021		1																			
van den Ende and Ampuero	2021		1										1									
Viens et al.	2022		1										1			1						
Viens et al.	2023		1													1						
Waagaard et al.	2022		1						1				1						1			
Walter et al.	2020		1												1		1					
Wang et al.	2018		1										1									1
Wilcock	2021	1				1							1									
Wilcock et al.	2023		1				1												1			
Williams et al.	2019		1										1									
Williams et al.	2023		1	1	1							1										
Williams et al.	2022		1	1				1		1	1	1										
Wu et al.	2017		1										1			1						
Xie et al.	2024		1										1				1					
Xie et al.	2022		1												1							

Authors	Year		Technique				Variables recorded																	
		Review paper	Distributed Acoustic Sensing	Distributed Temperature Sensing	Interferometry	State of Polarization	Cetaceans	Temperature	Fishing	Storms and weather	Currents	Waves/ tsunami	Earthquakes and seismic events	Volcanic hazards	Rock falls/avalanches/ slope failures	Subsurface characterisation	Polar and glacial processes	Reservoir and aquifer characterisation	Vessels incl anchoring	Human activities	Asset integrity/ cable security	Comparison with conventional sensors
Xiao et al.	2023		1										1									
Xiao et al.	2023		1																	1		
Xiao et al.	2023		1									1										
Yang et al.	2022		1										1			1						
Yetik et al.	2021		1																			
Yin et al.	2023		1										1									
Zhan	2020	1	1										1			1					1	
Zhan et al.	2021					1				1		1	1									
Zhang et al.	2006					1						1										
Zhu et al.	2022		1																		1	1
Zhu and Stensrud	2019		1							1												
Zhu et al.	2023		1										1									
Zumberge et al.	2018				1								1									

▼ **Table 3:** Summary of literature review of studies that use fibre-optic sensing to monitor the environment. Full reference list provided at the end of the main article.