

Technical Report: Multi-Modal Fiber Sensing for Subsea Infrastructure and Maritime Monitoring

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Executive Summary

Pilot Project: Multi-Modal Fiber Sensing for Offshore Monitoring

This report presents the findings of a research field trial conducted on the 118 km subsea fiber optic link between Egersund and the Yme offshore platform, executed by the Eindhoven University of Technology (TU/e) in collaboration with Adtran Networks SE and Tampnet AS. The primary purpose of this document is to provide the Norwegian Coastal Administration (Kystverket) with a comprehensive overview of the data gathered under the measurement permit granted for Norwegian coastal waters. The trial successfully validated the use of existing telecommunication infrastructure as a distributed sensor network, demonstrating how standard subsea cables can monitor both environmental dynamics and structural integrity.

During the monitoring period in June and August 2025, the consortium deployed a multi-modal sensing array combining Distributed Acoustic Sensing (DAS), State-of-Polarization (SOP), and Distributed Temperature and Strain Sensing (DTSS). This setup could be validated during storm "Floris" on 5 August 2025. The system delivered insights into seabed stability, specifically identifying a high-activity transition zone between 5 and 15 km offshore where ocean waves couple most strongly with the cable. While the storm induced significant static strain of approximately $180 \mu\epsilon$, subsequent analysis confirmed that this stress relaxed shortly after, indicating a temporary redistribution of cable slack rather than permanent structural damage.

In conclusion, this trial demonstrates that already existing subsea fiber infrastructure can be effectively dual-purposed for large-scale maritime surveillance. By providing real-time data on seabed dynamics and infrastructure resilience, this technology offers a scalable and cost-effective solution to enhance maritime safety and protect critical offshore assets. The project partners would like to thank the Norwegian Coastal Administration for the opportunity to conduct this research, which highlights the potential for future collaborative monitoring of the Norwegian coastline.

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List of Abbreviations

AIS	Automatic Identification System
BOTDR	Brillouin Optical Time Domain Reflectometry
C-OTDR	Coherent Optical Time Domain Reflectometry
DAS	Distributed Acoustic Sensing
DTSS	Distributed Temperature and Strain Sensing
PSD	Power Spectral Density
SOP	State-of-Polarization
SSMF	Standard Single-Mode Fiber
STD	Standard Deviation

1 Introduction & Technical Fundamentals

1.1 Project Context

The North Sea is a dynamic environment that poses significant challenges for protecting critical subsea infrastructure and monitoring environmental events. Traditionally, offshore monitoring has relied on discrete point sensors, such as oceanographic buoys or localized seismometers. However, these conventional methods are not only costly to deploy and maintain in deep waters, but they also leave vast spatial gaps in surveillance.

To address these limitations, this measurement campaign investigates the potential of Distributed Fiber Optic Sensing (DFOS). Instead of installing new, dedicated sensor hardware on the ocean floor, this project explores how existing submarine telecommunication cables can be repurposed into continuous, dense sensor arrays. By doing so, the campaign aims to demonstrate a cost-effective, real-time, and highly scalable solution for monitoring both natural phenomena (such as extreme weather) and anthropogenic threats (such as trawling or anchor drops) across large offshore distances.

1.2 Fundamental Principles of Fiber Sensing

To obtain a comprehensive picture of the subsea environment, this trial utilized three complementary optical sensing technologies. Each modality exploits a different property of light propagation inside the fiber core to detect environmental changes.

1.2.1 State-of-Polarization (SOP)

State-of-Polarization (SOP) monitoring leverages the polarization properties of light traveling through an optical fiber. Unlike Time-Domain Reflectometry methods, which rely on backscattered light for spatially resolved measurements, SOP sensing typically analyzes the transmitted light that arrives at the receiver end of the fiber link.

The fundamental principle behind SOP sensing is stress-induced birefringence. In a standard single-mode fiber (SSMF), light propagates in two perpendicular polarization directions. Under ideal, undisturbed conditions, these two parts of the light wave travel at the exact same speed. However, when the fiber is subjected to external mechanical stress, such as vibrations from ocean waves, seismic activity, or severe weather, the physical geometry and the refractive index of the glass core change slightly.

This mechanical deformation causes the two polarization directions to travel at slightly different speeds, altering their phase relationship. As a result, the light's overall polarization fluctuates rapidly. In our specific experimental setup, rather than using a full coherent receiver to calculate the absolute polarization state, we employ a polarization beam splitter. This allows us to measure the relative intensity variations of a projected polarization component.

It is important to note that SOP sensing is an integrated measurement. It captures the accumulated mechanical excitation over the entire length of the cable and cannot inherently pinpoint the exact location of an event. However, its major advantage is that it can be implemented over ultra-long distances using existing telecom transceivers, providing a continuous, real-time environmental monitor without the need for dedicated interrogation pulses.

1.2.2 Brillouin Optical Time-Domain Reflectometry (BOTDR)

Distributed Temperature and Strain Sensing (DTSS) uses a fiber-optic cable over its entire length as a continuous sensor for static mechanical strain and temperature changes. In long-haul scenarios, such as the monitoring of submarine telecom cables, DTSS is primarily realized through systems based on Brillouin scattering, such as Brillouin Optical Time-Domain Reflectometry (BOTDR).

The fundamental physical principle of DTSS relies on the interaction between the propagating optical wave and naturally occurring acoustic waves within the glass fiber. When the light launched into the fiber interacts with these acoustic waves, a small portion of it is backscattered. Due to this interaction, the backscattered light experiences a distinct change in its frequency, known as the Brillouin Frequency Shift.

The key characteristic of this effect is that the frequency shift is directly proportional to the local temperature and the mechanical strain of the fiber at that exact location. By measuring the time of flight of the light pulse and simultaneously performing a spectral analysis of the frequency shift, the DTSS system can generate a high-resolution, spatially distributed profile of the static loads along the entire fiber. While technologies such as SOP and DAS are better suited for detecting highly dynamic, short-lived events, such as vibrations from ship propellers or ocean wave frequencies, DTSS distinguishes itself by its ability to monitor static and quasi-static changes and can precisely quantify the stress states.

1.2.3 Distributed Acoustic Sensing (DAS)

Distributed Acoustic Sensing (DAS) transforms a standard fiber-optic cable into a continuous array of thousands of highly sensitive virtual microphones. In long-haul subsea monitoring, DAS is typically implemented using systems such as Coherent Optical Time-Domain Reflectometry (C-OTDR). The fundamental principle of DAS relies on Rayleigh scattering, which occurs when light interacts with microscopic natural impurities present in the glass. As a laser pulse travels through the fiber, a tiny fraction of the light naturally reflects back towards the source.

By evaluating the optical phase of the back-propagating signal, rather than its amplitude or polarization, DAS is extremely sensitive to dynamic vibrations and acoustic waves. When external pressure waves hit the cable, they cause microscopic stretching and compressing of the glass fiber. This rapid change in the fiber's physical length, which accounts for approximately 78% of the total induced phase shift¹, is fundamentally a mechanical strain. By evaluating these fast, oscillating phase variations, the DAS system can precisely determine the dynamic strain exerted on the cable. By measuring the exact time it takes for the altered light to return, the DAS system can precisely pinpoint the location of the disturbance along the entire fiber. While DTSS is used to monitor slow, static changes like temperature or permanent tension, DAS excels at capturing fast, dynamic events in real-time, making it the perfect tool for tracking moving vessels and identifying short-lived acoustic signatures.

1.3 Field Trial Setup and Interrogator Configuration

For this measurement campaign, the joint research team utilized a 118 km operational subsea fiber-optic cable connecting the terrestrial landing node in Egersund to the Yme

¹ A. Masoudi and T. P. Newson, "Analysis of distributed optical fibre acoustic sensors through numerical modeling," *Optics Express*, vol. 25, no. 25, pp. 32021-32040, Dec. 2017, doi: 10.1364/OE.25.032021.

offshore platform in the North Sea (see Figure 1). The sensing equipment was connected exclusively to “dark fibers”. These are spare, unlit optical fibers that carry no data transmission. This approach ensured that the active commercial data traffic running on different fibers in the same cable remained completely undisturbed.

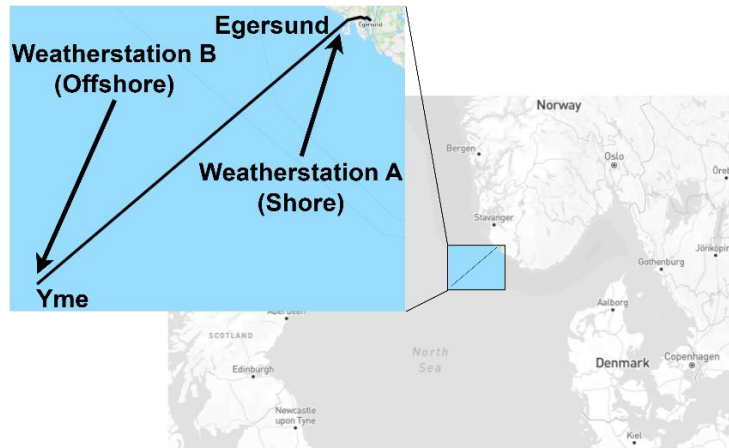


Figure 1: Map of the 118 km subsea cable route from the terrestrial landing node in Egersund to the Yme offshore platform in the North Sea.

The DAS and DTSS were integrated into a hybrid sensing system and connected to a single dark fiber. Meanwhile, the SOP monitoring was conducted on a separate, parallel dark fiber within the same cable.

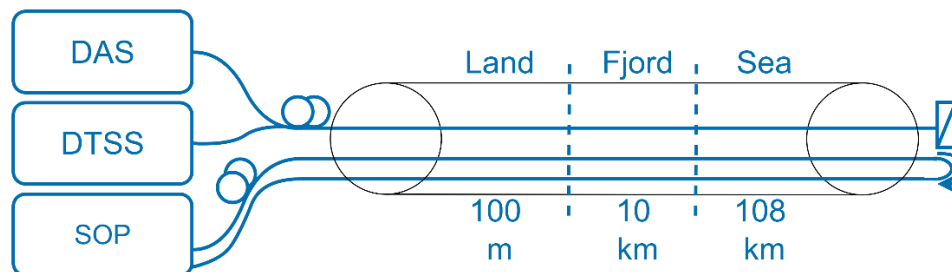


Figure 2: Schematic overview of the experimental multi-modal sensing setup co-located at the Egersund landing facility.

The cable's route provides an ideal testing ground, combining multiple environments, starting onshore at the landing facility, passing through a shallow coastal fjord, and extending into the deep offshore waters of the North Sea. This varying environment allowed the system to capture a wide spectrum of both anthropogenic and natural signatures.

The measurements were conducted continuously from 10 June to 26 August 2025. During this period, the multi-modal sensing setup comprising SOP, DTSS, and DAS interrogators was co-located at the Egersund network node.

To efficiently monitor the long subsea link, the DAS system pulse frequency was set to 600 Hz to capture acoustic events and vibrations of up to 300 Hz, while the spatial sampling interval was set to roughly 40.8 meters. This means, the interrogator effectively divides

the 118 km cable into thousands of continuous 40-meter-long virtual microphone segments.

2 Environmental Impact Analysis: Storm “Floris”

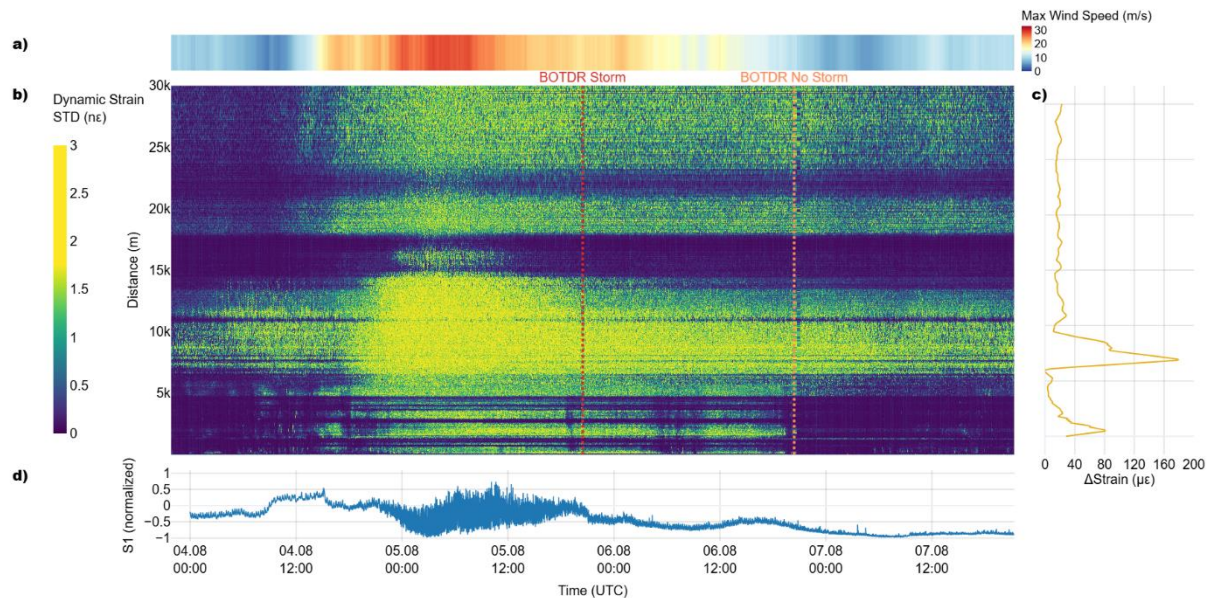


Figure 3: (a) Interpolated and averaged wind speed from two meteorological stations located near the two cable ends. (b) Down-sampled standard deviation of the DAS-measured relative phase change, highlighting increased activity during the storm. (c) Difference between the BFS profiles from two BOTDR measurements taken during and after the storm, revealing local strain increases. (d) SOP variation before, during, and after the storm.

Between 4 August and 6 August 2025, the setup successfully captured the environmental impact of storm "Floris" on the subsea infrastructure. The combined measurements from the different sensing modalities during this event are illustrated in Figure 3.

As seen in the recorded weather data (Fig. 3a), wind speeds steadily increased on the morning of 4 August, peaking at 29 m/s on 5 August, before calming again by noon on 6 August. During these peak conditions, the Distributed Acoustic Sensing (DAS) data (Fig. 3b) showed a significant increase in dynamic strain along the cable. The strongest dynamic responses were concentrated between 5 km and 15 km offshore. This specific zone marks the geographical transition from the protected fjord to the open sea. This proves that the DAS system can precisely localize the specific cable sections where ocean waves couple most strongly to the infrastructure.

Additionally, the DTSS provided crucial insights into the cable's structural health (Fig. 3c). Following the storm, the system registered measurable, localized increases in static strain. Specifically, increases of approximately 82 με at kilometer 0.75 within the fjord and a maximum of 180 με near the fjord's exit at kilometer 7 were measured. To contextualize these values, an increase of 180 με equates to a physical elongation of just 0.0018%, which is well within the typical elastic limit of optical fibers (up to ~10,000 με). Therefore, this poses absolutely no mechanical risk to the infrastructure. Rather than indicating permanent structural damage, this minor, reversible strain simply points to a temporary redistribution of cable slack on the seabed induced by the strong currents, which relaxed shortly after the storm.

Furthermore, the State-of-Polarization (SOP) measurements backed up the findings from the DAS data. The SOP data (Fig. 1d) showed strong polarization fluctuations that perfectly aligned with the time windows of the highest wind speeds.

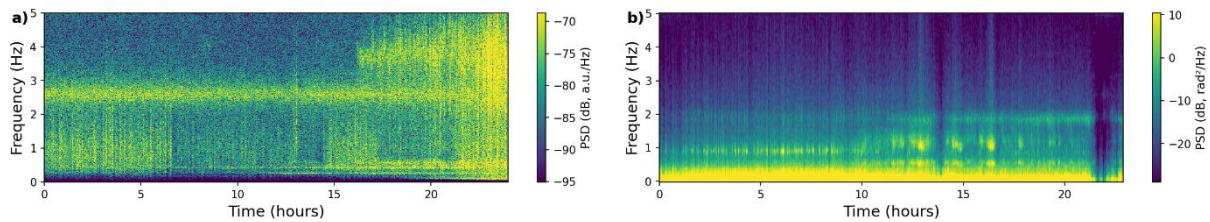


Figure 4: Power density spectrograms of (a) recorded SOP time data and (b) of the recorded DAS measurements at fiber segment 440 m around the storm period. Both show a narrowband component between 2 and 2.5 Hz, most prominent during the storm, illustrating the complementary sensitivity of the two sensing modalities.

To further investigate the frequency characteristics of these storm-induced fluctuations, a detailed power spectral density (PSD) analysis was performed for both measurement series SOP and DAS, as illustrated in Figure 2. The SOP spectrogram (Fig. 2a) reveals a distinct, narrowband frequency component between 2 and 2.5 Hz that emerged clearly during the storm peak. The power spectral density spectrogram from SOP data depicts the frequency information captured over the entire fiber sensor length. In order to analyze the frequency information at the most dominant fiber segments, the PSD spectrogram of the DAS data was calculated as an example for the fiber segment at 440 m (Fig. 4b).

The 2 Hz signal component was localized in the fjord and in the fiber segments between 10 km and 15 km. This component stems from strong and fast Scholte waves² caused by the higher wind speed. This strongly indicates that the severe weather conditions triggered specific standing-wave oscillations or localized resonances within the bay. By combining the global temporal monitoring of SOP with the spatial precision of DAS, the multi-modal setup successfully mapped both the occurrence and the exact location of these oceanographic dynamics.

²D. Gräff et al., "Calving-driven fjord dynamics resolved by seafloor fibre sensing," *Nature*, vol. 644, no. 8076, pp. 404–412, Aug. 2025, doi: 10.1038/s41586-025-09347-7.

3 Anthropogenic Signatures and Maritime Surveillance

In addition to analyzing Storm "Floris", the measurement campaign also investigated the system's ability to detect localized human-made activities. Leveraging the high spatial resolution of the Distributed Acoustic Sensing (DAS) system, we successfully identified and tracked distinct moving sources across different environments. In addition, it is worth noting that the temporal resolution in milliseconds provided the frequency resolution to detect the frequency components of the detected objects over one-second time frames, leading to an acoustic bandwidth of 300 Hz at a frequency resolution of 1 Hz.

The following sections detail these findings, focusing first on the monitoring of terrestrial railway infrastructure near the onshore landing node, followed by the detection and tracking of maritime vessel traffic in the open North Sea (Section 3.2).

3.1 Terrestrial Infrastructure

During the spectral analysis of the first fiber sections, specifically within the first 40 meters from the landing point, distinct signals were captured. Spectral analysis of these channels revealed recurring signal patterns with a dominant frequency component at exactly $16 \frac{2}{3}$ Hz.

This highly specific and persistent signature is a characteristic harmonic of the Norwegian electrified railway network infrastructure. While this 16.7 Hz component is continuously visible throughout the recording period in the onshore sections, its intensity fluctuates, appearing stronger or weaker over time.

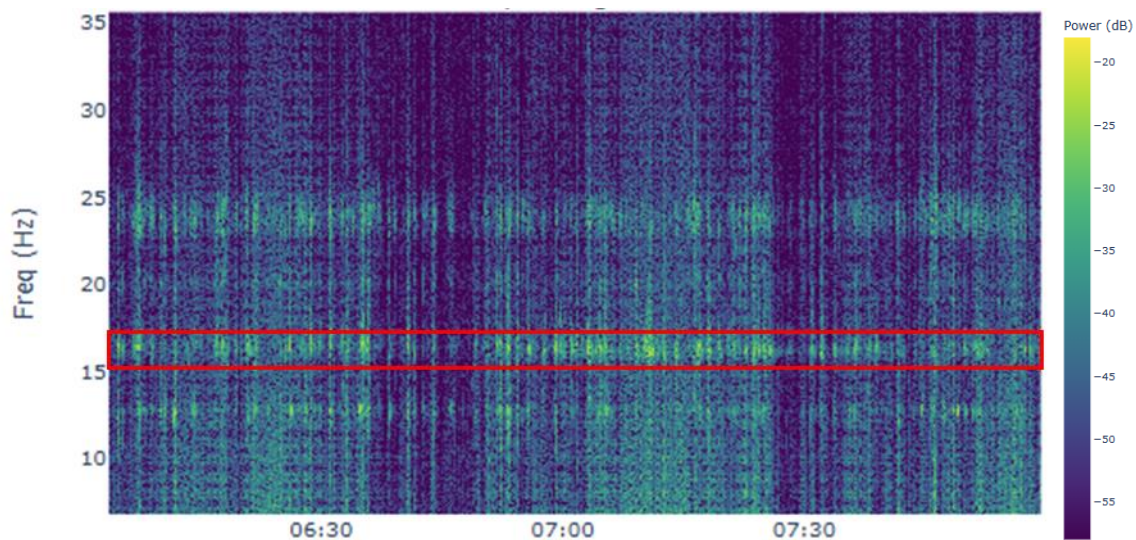


Figure 5: Spectrogram of the DAS data of the first 40 meters. The red rectangular-shaped box in the plot illustrates the continuous 16.7 Hz frequency component associated with the terrestrial railway network, which fluctuates in intensity but remains consistent over time.

When looking at the neighboring fiber section covering 40 to 80 meters, this infrastructure frequency completely vanishes. Given that the actual railway tracks are located further inland, this highly localized 16.7 Hz signal is likely induced by nearby electrical equipment, such as a generator or power supply unit located near the landing facility.

3.2 Maritime Surveillance

While standard commercial vessels, such as cargo ships and tankers, can be detected by the DAS system as they cross the fiber, they generally pose no direct physical threat since they do not interact with the seabed. A critical danger from these vessels only arises if they accidentally drag an anchor, which is expected to introduce distinct low-frequency acoustic signatures. Consequently, the primary focus of this chapter is on bottom trawling activities, where heavy fishing gear is dragged directly across the seabed, which represent one of the greatest physical risks to submarine telecommunication cables. To investigate the detectability of such high-risk events, the standard deviation (STD) of the optical phase was calculated along the offshore cable section and correlated with historical Automatic Identification System (AIS) vessel tracking data. Through this correlation, we successfully identified an active fishing trawler operating in the vicinity of the subsea cable.

The resulting STD waterfall plot visualizes the acoustic signal intensity over time and distance. In this representation, the trawler's movement becomes visible as a distinct, high-intensity track. The plot clearly captures the continuous trajectory of the vessel, mapping exactly how the object travels across a specific spatial section of the seabed over the observed time period.

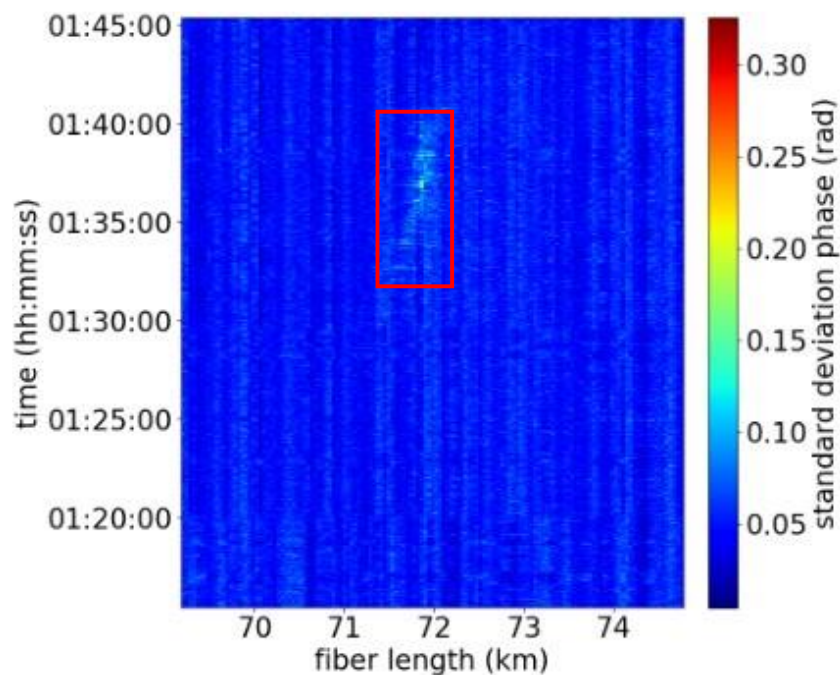


Figure 6: Standard deviation (STD) of the differential optical phase over time and distance, revealing the clear trajectory of a moving object. Subsequent correlation with AIS data confirmed this signature as an active fishing trawler.

To further analyze the specific acoustic footprint of this event, the PSD was analyzed. Unlike standard commercial cargo ships, which typically exhibit clear, sharp frequency peaks caused by the engine and propeller, the trawler's signature lacked a distinct single frequency.

Instead, the mechanical interaction of the heavy trawling gear scraping across the seafloor generated a broad acoustic response. This manifested as a prominent, low-frequency

"cloud" of energy concentrated between 3 and 5 Hz³. The peak at different times in those two plots, which were calculated at different locations on the cable also indicates a movement along the cable.

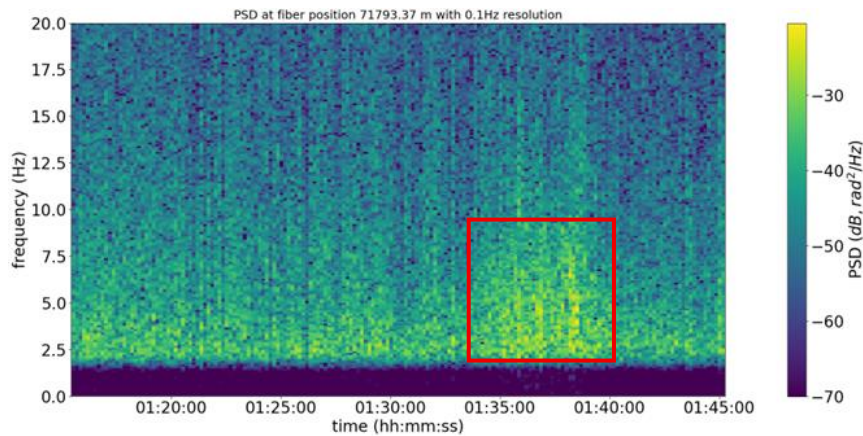


Figure 7: Power Spectral Density (PSD) spectrogram at two different locations along the cable. The spectrogram demonstrates the acoustic footprint of the moving vessel, highlighting the characteristic low-frequency energy cloud between 3 and 5 Hz caused by bottom trawling gear interacting with the seabed.

These observations demonstrate that existing optical infrastructure can be effectively dual-purposed as a real-time early warning system.

³ E. Daly and M. White, "Bottom trawling noise: Are fishing vessels polluting to deeper acoustic habitats?," *Marine Pollution Bulletin*, vol. 162, p. 111877, Jan. 2021, doi: 10.1016/j.marpolbul.2020.111877.

4 Conclusion

This field trial, conducted on the 118 km subsea fiber-optic link between Egersund and the Yme offshore platform, has demonstrated that existing telecommunication infrastructure can be effectively transformed into a sensing array. By combining DAS, SOP, and DTSS, the joint research team was able to monitor a vast offshore area with unprecedented spatial and temporal detail.

First, the analysis of storm "Floris" demonstrated that the system can quantify structural stress in real time. Detecting a temporary strain of $180 \mu\epsilon$ and confirming its subsequent relaxation provides an essential basis for long-term asset management and post-incident damage assessment. Second, the successful detection of terrestrial railway signatures at 16.7 Hz and grid-related frequencies highlights the system's extreme sensitivity to anthropogenic activities, enabling continuous monitoring of the sensitive transition zones between land and sea. Third, the identification of distinct bottom trawling signatures proves the technology's potential as a non-line-of-sight surveillance system for critical infrastructure. This offers a proactive solution for protecting critical subsea infrastructure from anchor drag or fishing-related damage.

In conclusion, fiber-optic sensing offers a scalable alternative to conventional point sensors, providing comprehensive insights into both the marine environment and the structural health of subsea infrastructure. While the primary focus remains on long-term environmental monitoring, the system's ability to identify anthropogenic activities adds an essential layer of security.