Enhancing Coastal Critical Infrastructure Protection with Distributed Acoustic Sensing (DAS)

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Technical Paper — Distributed Acoustic Sensing (DAS) enables real-time monitoring of subsea infrastructure by utilizing pre-installed optical fibers. This study demonstrates its application in offshore wind farms, detecting vessel movements, anchor drops, and diver activities. The findings indicate that DAS-based monitoring significantly improves situational awareness and threat detection in offshore environments, as well as its role in automated vessel tracking using machine learning techniques.

1 Introduction

Coastal and subsea infrastructure is vital to modern societies, underpinning energy supply, global communication, and economic stability. Key systems include subsea power cables connecting offshore wind farms to mainland grids, telecommunication networks responsible for over 95% of international data transmission, and pipelines transporting essential resources like oil and gas [1]. These infrastructures form the foundation of global economic systems and facilitate international cooperation by ensuring secure and reliable access to energy and communication. In addition to their operational significance, they represent strategic assets critical to national security and geopolitical stability [2]. Despite their importance, these infrastructures face an expanding array of threats that challenge their resilience. Natural hazards, such as seismic activity, underwater landslides, and extreme weather events, have the potential to cause significant damage to subsea cables and pipelines [3]. The resulting disruptions can lead to economic losses, interrupted energy supplies, and communication blackouts with cascading societal consequences. Human-induced threats, however, pose an even more pressing concern. Accidental damage, often caused by fishing activities or ship anchoring, accounts for nearly 70% of subsea cable faults worldwide. This type of disruption highlights the fragile nature of these systems, which are increasingly strained by growing maritime activity [1].

A particularly alarming subset of human-induced threats involve deliberate acts of sabotage and hybrid tactics designed to exploit vulnerabilities in critical infrastructure. Hybrid threats combine conventional and unconventional methods, such as cyberattacks, espionage, and physical sabotage, to create complex security challenges [2]. Recent incidents, including the suspected sabotage of the Nord Stream gas pipelines and increased naval activity near undersea cables in the Baltic Sea, exemplify the evolving nature of these threats [4], [5]. Intelligence reports have highlighted suspicious foreign vessel activity near key maritime assets, raising concerns over espionage and intentional damage to strategic infrastructure [6]. As the security of coastal and subsea systems become increasingly interconnected with global stability, addressing these risks has become a priority.

Traditional monitoring technologies, including hydrophones, sonar, and satellite-based systems, have long been employed to secure subsea infrastructure. While these systems provide valuable insights, they are often limited in their ability to offer real-time, high-resolution coverage across extensive areas. Environmental noise, operational constraints, and the inability to continuously monitor specific zones further hinder their effectiveness [7].

To overcome these limitations, Distributed Acoustic Sensing (DAS) has emerged as a transformative technology. DAS leverages existing optical fibers embedded within subsea infrastructure to create dense networks of acoustic sensors along their entire length. This technology uses coherent Rayleigh scattering to detect minute strain changes in the fiber caused by external disturbances, enabling precise monitoring of activities such as vessel movements, anchor drags, and environmental anomalies [3], [7], [8], [9]. By transforming pre-installed optical fibers into continuous sensing arrays, DAS offers unparalleled situational awareness, addressing critical gaps in existing monitoring capabilities.

In addition to its monitoring capabilities, DAS represents a cost-effective and scalable solution. It eliminates the need for additional sensor installations by utilizing already deployed optical fibers, minimizing complexity and reducing implementation costs. When integrated with complementary systems such as radar and sonar, DAS enhances the resilience of maritime security networks, creating multi-layered defenses capable of addressing a broad spectrum of threats [8].

As coastal and subsea infrastructure faces escalating risks from human-induced threats, innovative technologies like DAS are indispensable for ensuring the security and reliability of these critical systems. The following sections explore the practical applications of DAS in offshore wind farms, detailing its integration with additional sensing technologies and its potential to enhance the protection and operational efficiency of maritime infrastructure.

2 Methodology

The primary objective of this study was to demonstrate the capability of Distributed Acoustic Sensing (DAS) to detect specific threats to offshore wind farm infrastructure. By utilizing an existing subsea power cable, the study aimed to showcase how DAS can effectively monitor events such as an anchor drop and drag, vessel movements, and cable stress.

General Experimental Design

The study was conducted in an operational offshore wind farm, using a pre-installed subsea power cable as an acoustic sensor through DAS technology. Test scenarios were designed to simulate realistic events that pose risks to wind farm infrastructure, including:

- Vessel movements, allowing for the capture and analysis of acoustic signatures.
- Anchor drop and drag, conducted at a controlled distance from the cable.
- Induced mechanical disturbances to assess the system's ability to detect and localize strain events.

Data Acquisition and Processing Overview

The DAS system was configured to continuously monitor acoustic signals along the subsea cable during the test scenarios. The recorded data captured a range of events, such as the anchor drag, vessel movements, and induced mechanical stress. The data analysis is primarily focused on the acoustic energy within specific frequency bands. Spectral analysis techniques were applied to extract and distinguish event patterns relevant to operational scenarios.

Cable Configurations and DAS System Installation in Offshore Wind Farms

Offshore wind farms rely on a robust infrastructure to transmit the energy generated by individual turbines to onshore facilities. This is achieved through export cables that typically collect the electrical output at a central inverter station before routing it to the mainland. These export cables generally consist of three power-conducting cores, each surrounded by a polymeric insulation layer. Embedded within this insulation are optical fibers, which are predominantly used for data communication. However, these fibers can also be repurposed as sensor fibers for Distributed Acoustic Sensing (DAS).

DAS operates by converting existing optical fibers into highly sensitive acoustic sensors. Using the principle of Rayleigh backscattering, a DAS interrogator unit sends laser pulses through the optical fiber. Any acoustic disturbances along the cable—such as vibrations caused by ship movements, anchor drops, or seabed activity—result in changes in the scattered light, allowing for real-time detection and localization of events. This setup enables comprehensive monitoring of the cable and its surrounding environment without the need for additional specialized sensor installations.

The installation of DAS systems is straightforward and highly adaptable to existing infrastructures. In a typical setup, the DAS interrogator unit is housed at the cable termination point onshore. The system interfaces with one of the unused optical fibers embedded in the export cable, leveraging its entire length as a distributed acoustic sensor. The technology requires no modifications to the cable itself, making it a cost-effective solution for enhancing maritime surveillance and infrastructure protection.

In areas of shallow water, where the deployment of a single export cable may be impractical, the three power-conducting cores can be installed as separate cables. In such configurations, the optical fibers are placed in a dedicated auxiliary cable that is routed alongside the power cables. Regardless of the cable configuration, DAS technology can seamlessly integrate into the system, providing continuous monitoring across large distances. A typical installation of these configurations is illustrated in figure 1.

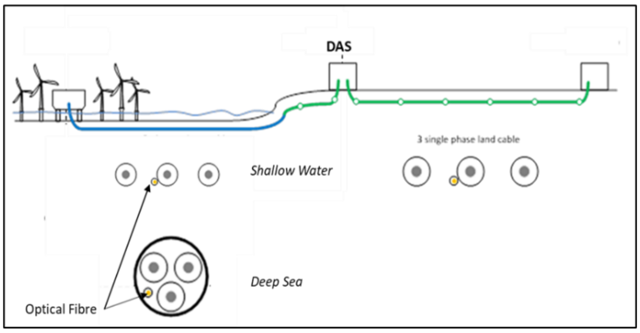

Fig. 1: Schematic representation of cable configurations in offshore wind farms. Left: Three power-conducting cores in a single cable with integrated optical fibers. Right: Three separate power cables with an additional optical fiber cable for DAS.

By leveraging existing optical fibers, DAS transforms subsea export cables into an extensive acoustic sensing network, enabling real-time detection of potential threats and environmental changes. This capability is critical for the operational security and efficiency of offshore wind farms.

3 Principle of Distributed Acoustic Sensing (DAS)

Distributed Acoustic Sensing (DAS) is an innovative technology that transforms standard single-mode optical fibers into distributed acoustic sensors. The system operates based on the coherent Rayleigh scattering effect, where laser pulses injected into the fiber interact with microscopic variations in the fiber's refractive index. These scattering centers are distributed along the entire length of the fiber, creating a network capable of sensing acoustic and mechanical disturbances (see figure 2).

When an acoustic wave or vibration interacts with the fiber, it induces minute shifts in the relative positions of these scattering centers. This alters the intensity and phase of the backscattered light, which is then detected by the DAS interrogator. By analyzing these variations, the system can capture detailed information about the nature and origin of the disturbance [10], [11], [12].

However, standard telecommunication fibers are optimized for low attenuation and minimal scattering, as their primary function is efficient light propagation rather than backscattering. Consequently, such fibers contain relatively few scattering centers, which limits the amount of backscattered light available for sensing. To improve the signal-to-noise ratio (SNR) and extend the sensing range, specialized fibers with an increased density of scattering centers have been developed. These fibers generate a higher level of backscatter, enhancing the detection capabilities of DAS systems. The choice of fiber represents a trade-off between cost and performance, as specialized sensing fibers are significantly more expensive than standard telecommunication fibers.

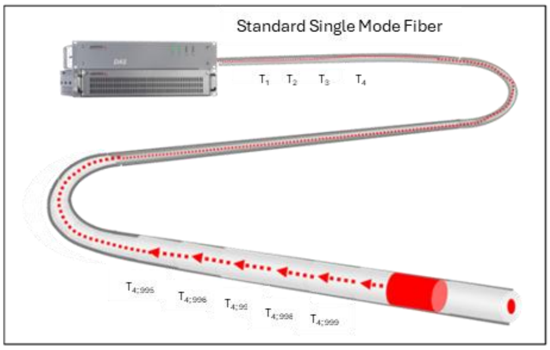

Fig. 2. The principle of Distributed Acoustic Sensing (DAS). Laser pulses sent through the optical fiber interact with acoustic waves in the environment, modifying the backscatter signal. These interactions enable the precise detection and localization of acoustic events along the fiber:

One approach to balancing cost and performance involves splicing a section of highly scattering fiber to the end of a standard telecommunication fiber, thereby extending the DAS sensing range without requiring optical amplification. This method has been successfully demonstrated, achieving a sensing distance of up to 125 km using a hybrid fiber configuration [13].

To extend the sensing range of standard DAS systems using standard telecommunication fibers, optical amplification techniques such as Raman amplifiers [14] and bidirectional EDFAs can be employed. Raman amplification is particularly advantageous for submarine cable monitoring, as the amplifier can be installed on land alongside the DAS interrogator, eliminating the need for any modifications or access to the sensor cable on the seafloor. Additionally, a second DAS interrogator and Raman amplifier can be deployed at the opposite end of the cable, enabling bidirectional monitoring [15]. This setup effectively doubles the monitored length and ensures greater coverage, improved redundancy, and enhanced detection reliability across the entire cable infrastructure.

For even greater coverage, bidirectional EDFAs can be deployed along the sensor cable, amplifying both the outgoing measurement pulse and the returning backscattered signal. This method has been shown to achieve a sensing range of up to 300 km [16]. However, unlike Raman amplification, this approach requires physical access to the submarine cable to install optical amplifiers along its length. These amplification techniques significantly enhance the capabilities of DAS for large-scale subsea monitoring applications but may not always be feasible due to the complexity and cost of subsea infrastructure modifications.

One of the key concepts underpinning DAS is the idea of virtual microphones. Each segment of the optical fiber, corresponding to the system's spatial resolution (as fine as ±5 meters), acts as an independent acoustic sensor. When an acoustic wave, such as the vibration from a ship's engine or a mechanical disturbance on the seabed, reaches the fiber, it modulates the scattering centers within that segment. This modulation results in measurable changes to the backscatter signal, effectively converting the fiber into a continuous array of microphones distributed along its length. Unlike traditional point sensors, such as hydrophones, DAS enables spatially distributed sensing without the need for additional physical sensors along the cable. This capability allows DAS to monitor extended infrastructures, such as subsea cables in offshore wind farms, with unprecedented precision and coverage. To precisely locate a disturbance, the DAS system utilizes time-of-flight measurements. By calculating the time delay between the emission of a laser pulse and the return of the backscattered signal, the system determines the distance to the point of disturbance. This process, combined with the virtual microphone array, enables the DAS system to produce a spatially resolved "acoustic map" of the monitored area. This real-time localization capability is critical for detecting and characterizing events such as ship movements, anchor drops, or other mechanical impacts on subsea cables.

4 Vessel Movement Detection

The purpose of this experiment was to demonstrate that the DAS system can detect and monitoring ship movements near a subsea power cable equipped with integrated optical fibers. The demonstration aimed to validate the technology’s ability to capture acoustic signals generated by passing vessels and to provide insights into its practical application for monitoring offshore wind farm infrastructure.

Experimental Setup:

The DAS system used in the following tests was an AP Sensing N52 series DAS (see figure 2). The system was installed on Lilla Båtskär and continuously monitored the sensor cable (see figure 3). The sensor cable runs alongside the power cable, as depicted in figure 1, in a shallow water configuration. The total length of the cable is approximately 17 km. This setup replicates a typical offshore wind farm configuration, ensuring that the results reflect real-world conditions.

To evaluate the system’s performance, various vessels—including large ferries and smaller watercraft such as jet skis—were instructed to traverse predefined paths over or near the cable. The optical fiber served as the sensing element for the DAS system. The DAS interrogator continuously recorded acoustic signals along the cable, capturing vibrations generated by the vessels’ engines and propellers. The primary objective of the experiment was to demonstrate that these acoustic signatures could be reliably detected and localized using DAS.

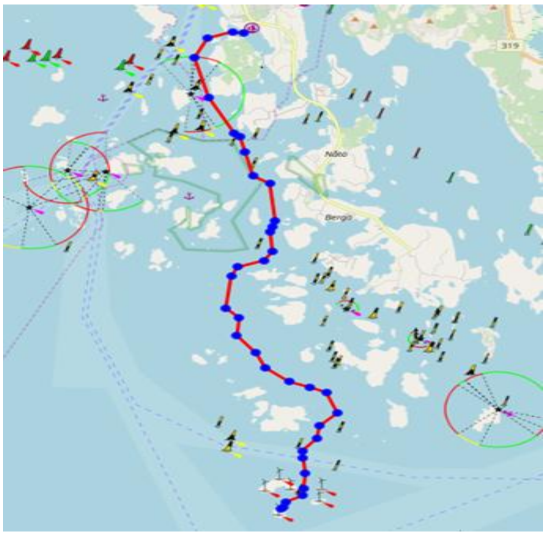

Fig. 3: Sensor cable layout and test locations near Lilla Båtskär. The sensor cable runs parallel to the power cable in a shallow water configuration. The DAS system was installed on Lilla Båtskär to monitor vessel activity. Sea map provided by OpenSeaMap.

Observations and Results

The DAS system successfully detected and visualized acoustic events associated with all vessel types tested. The key observations are illustrated in figure 4 and described below. The acoustic signals from both ships were clearly visible in the recorded data. The distinct green traces in the spectrogram represent the acoustic energy emitted by the vessels as they crossed the cable. The plot in figure 4 shows the intensity of the acoustic signals over time, with brighter colors indicating stronger signals. The acoustic energy plot provides a comprehensive visualization of the spatial and temporal distribution of the vessel's acoustic emissions along the cable.

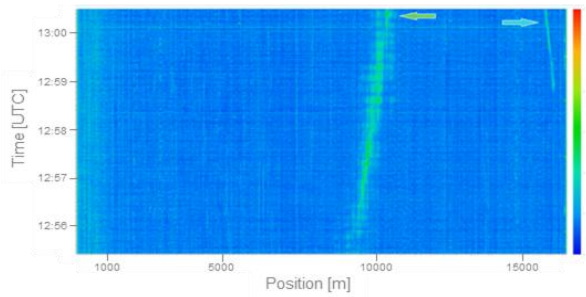

Fig. 4: Intensity of the acoustic signals of two different vessels in the vicinity of the cable. The Subsea VII (green arrow) on the left-hand side of the plot and the smaller vessel Savante G (blue arrow) moving in opposite directions.

The data show the movement over time which leads to an estimation of the vessels speed. A rough estimation results in 5 kn for the Subsea VII and -7 kn for the Savante G, respectively. The negative sign indicates that the vessel is moving towards the interrogator's place. It should be mentioned that the exact vessel speed can be calculated either the vessel is moving parallel to the cable or the angle to the cable is known. It is also worth to mention that additionally to the speed, the acoustic size of the vessel – which is not the LOA - can be derived from the data. Furthermore, variations in acoustic energy intensity correlate with changes in the vessel's operational state, such as alterations in speed, heading, or proximity to the cable. These spatial energy variations offer critical insights into the dynamic interactions between the vessel and its surrounding environment. The two distinct traces in the spectrogram correspond to the vessels Subsea VII and Savante G, moving in opposite directions along the cable. The DAS system successfully captured their continuous paths, providing a clear visualization of their trajectories and movement patterns. The varying signal intensities highlight differences in the acoustic emissions of the vessels, potentially linked to their size, speed, or proximity to the cable. This capability demonstrates DAS's ability to distinguish and monitor multiple vessels simultaneously, even in dynamic and high-traffic maritime environments. The high spatial and temporal resolution of DAS ensures precise tracking of vessel movements over extended distances, with each section of the cable acting as an individual sensor. This feature is particularly critical for monitoring shipping lanes and safeguarding critical subsea infrastructure.

In addition to detecting large vessels like ferries, the DAS system also demonstrated its sensitivity to smaller watercraft, such as jet skis (see figure 5).

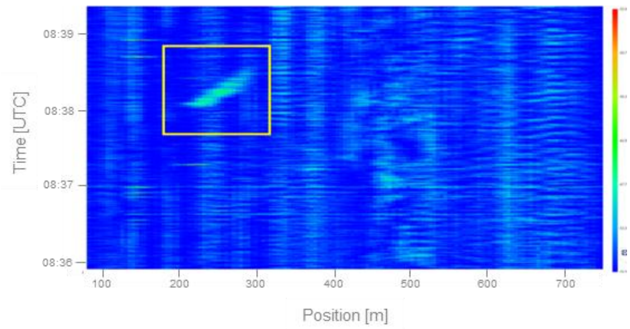

Fig. 5: Acoustic energy plot illustrating the spatial and temporal distribution of a jet ski's acoustic emissions along the subsea cable (yellow rectangle). The high-intensity regions in the plot correspond to the jet ski's trajectory, highlighting its dynamic activity.

The distinct high-intensity regions in the plot highlight the jet ski's trajectory and dynamic activity, emphasizing DAS's capability to monitor diverse vessel types and sizes within the same environment. Despite their smaller size, jet skis may generate significant acoustic energy due to their high-revving engines and rapid propeller rotations, particularly in the high-frequency range. The system successfully resolved and tracked their movements, as depicted in figure 5, which sows the acoustic energy distribution along the cable during a jet ski crossing.

5 Anchor Drag Experiment

To evaluate the DAS system's ability to detect mechanical interactions with the seabed, a controlled anchor drag experiment was conducted. The setup involved a vessel positioned approximately at 360 m along the cable, with its anchor lowered and dragged across the seabed using the ship's winch. For safety reasons, the experiment was conducted at approximately 100 m from the cable to avoid any potential damage to the infrastructure. The acoustic energy plot in figure 6 visualizes the distinct signals generated by the vessel and the dragged anchor. The vessel's minimal movement is apparent in the consistent energy observed at the 360 m position, while the dragged anchor produces a dynamic, high-energy signature as it interacts with the seabed.

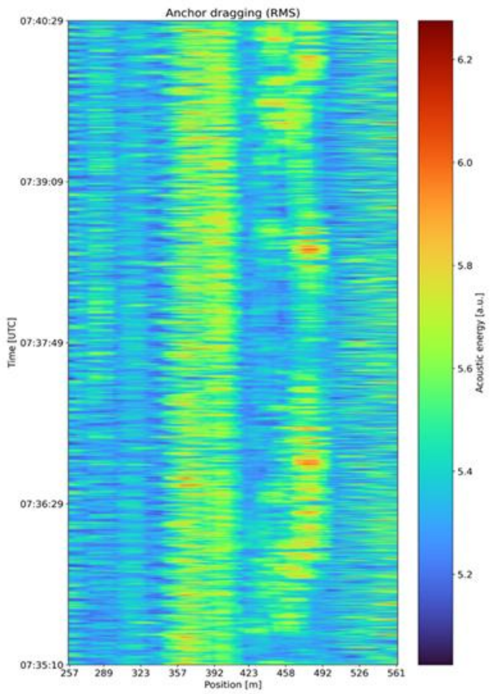

Fig. 6: Acoustic energy plot of the anchor drag experiment, showing the vessel at approximately 360 m and the dynamic signature of the anchor being dragged across the seabed.

The results highlight DAS's sensitivity to mechanical disturbances and its capability to monitor potential threats to subsea infrastructure, such as anchor drags or other physical impacts. The clear visualization of the anchor's movement in the acoustic energy plot underscores the effectiveness of DAS in detecting and localizing such events with high spatial resolution.

6 Diver Detection and Tracking

To evaluate the DAS system's ability to detect and monitor underwater activities, a controlled experiment was conducted involving a Dive X scooter (see figure 7). The scooter, a compact underwater propulsion device, was used to simulate dynamic acoustic disturbances near a subsea cable. The diver followed a predefined trajectory along the cable, moving back and forth between positions at 200 m and 400 m. Over the course of three passes, the diver deliberately interacted with the cable by tapping on it

Fig. 7: The Dive X underwater propulsion scooter used during the experiment.

at specific locations, generating localized acoustic signals to test the system’s sensitivity (see figure 8).

The DAS system successfully recorded the diver’s movements and interactions. Tapping events, occurring at positions near 200 m and 400 m, were visible in the

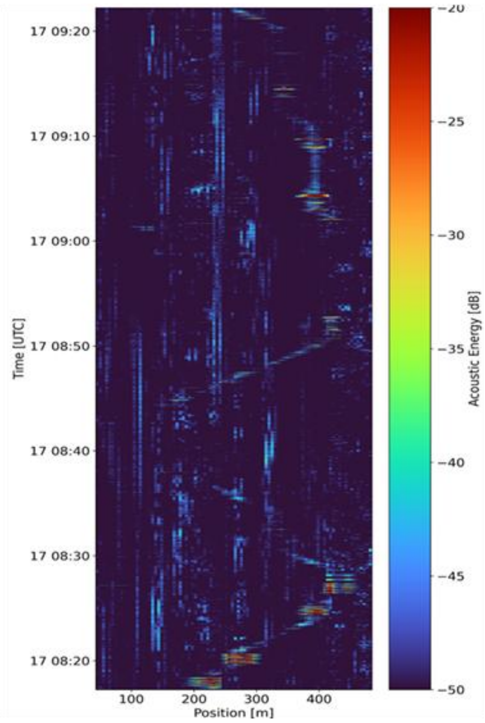

Fig. 8: The acoustic energy plot showing the diver’s movements and cable interactions, including distinct tapping events near the 200 m and 400 m positions.

acoustic energy plot (figure 8).

These events were represented by distinct intensity peaks in the recorded data, demonstrating the system's ability to detect direct mechanical interactions with the cable. The acoustic signature of the scooter, produced by its propulsion system, was also consistently detectable throughout the experiment. This continuous signal provided a clear trace of the diver's movements along the cable, enabling accurate trajectory reconstruction. The frequency spectrum of the scooter’s acoustic emissions (figure 9) reveals distinct peaks at approximately 32 Hz and 64 Hz, corresponding to the motor and propeller dynamics of the device. These frequencies highlight the scooter's characteristic acoustic signature, which was readily captured by the DAS system. The ability to isolate and analyze such specific frequency components underscores the system's sensitivity to dynamic underwater activities and demonstrates its capability to distinguish the scooter's emissions from background noise or other underwater sources.

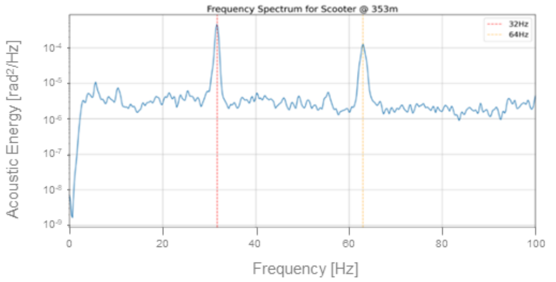

Fig. 9: Frequency spectrum of the Dive X scooter recorded at 353 m, showing distinct peaks at 32 Hz and 64 Hz, which correspond to the propulsion system's acoustic emissions.

No other moving underwater targets were detected during this experiment, as the test was conducted in calm water conditions without ship traffic or additional underwater activity near the cable. However, previous sections of this study demonstrate that DAS effectively detects and tracks vessel movements in busy maritime environments. The results of this controlled experiment further confirm that the system is capable of distinguishing underwater targets from background noise with high spatial resolution. The analysis of the DAS data involved processing the backscattered optical signals to identify variations in acoustic energy along the cable. These variations were correlated with the diver's predefined trajectory, allowing the system to map the diver's movements with high spatial accuracy along the length of the cable. Although the exact lateral distance of the diver from the cable could not be determined, the DAS system provided precise localization of the diver's position relative to the cable's layout. The experiment concluded with the diver stopping at the 400 m position, as evident from the final acoustic traces in the energy plot.

This demonstration highlights DAS's ability to monitor underwater activities with high spatial and temporal resolution. By detecting both localized events, such as the tapping on the cable, and continuous movements, such as those generated by the scooter, the system proves to be an effective tool for subsea infrastructure monitoring. The integration of the frequency spectrum further validates the ability of DAS to capture and analyze the characteristic acoustic emissions of small, fast-moving underwater objects, providing valuable insights for the protection of critical subsea assets.

7 Analysis of Underwater Activities: Virtual Listening with DAS

To further explore the capabilities of DAS for monitoring underwater activities, a series of controlled experiments were conducted involving various actions near the cable. These activities, visualized in both the acoustic energy plot and the corresponding phase-time series (figure 10), highlight DAS's ability to capture and analyze strain and stress variations along the cable caused by acoustic waves.

Each arrow in the acoustic energy plot (figure 10) corresponds to a specific type of activity performed near the cable (see Table 1).

Table 1: Diver activities along the cable

Arrow colour	Start time	Description
Orange	9:25:00	Scratching (~7 seconds ON / ~10 seconds OFF, repeated 5 times). The continuous yet irregular signal traces produced during scratching are distinguishable from tapping events
Green	9:25:50	Weight drops (1 kg, repeated 5 times). These short, high-energy bursts represent the impact of the weight hitting the seabed near the cable
Blue	9:26:35	Digging near the cable (~7 seconds ON / ~10 seconds OFF, repeated 5 times). This activity produced sustained acoustic energy over a longer period, with unique temporal and spatial characteristics.

The combination of the acoustic energy and the phase-time series provides a comprehensive representation of these activities. The acoustic energy plot illustrates the spatial and temporal distribution of acoustic energy, while the phase-time series captures the time-domain response of the cable to these disturbances, directly representing the strain and stress variations caused by acoustic waves. This dual representation allows for a detailed characterization of each activity and its dynamics.

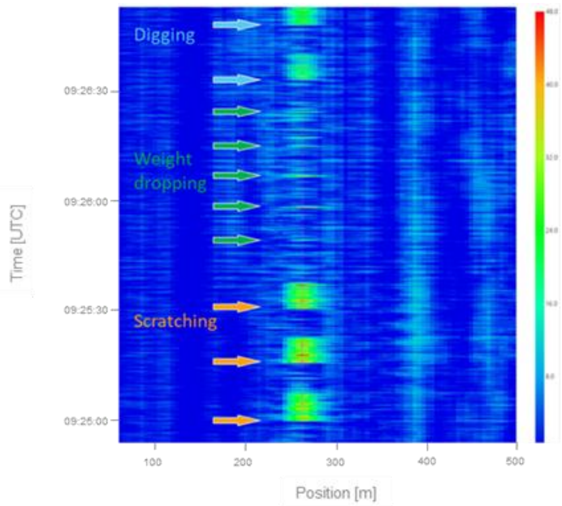

Fig. 10: Acoustic energy plot showing various underwater activities near the cable. Each arrow color corresponds to a specific activity: Red (tapping), Orange (scratching), Green (weight drops), and Blue (digging).

By leveraging DAS technology, the optical fiber within the cable can be treated as a dense array of virtual microphones, capable of capturing acoustic signals at specific positions along the cable. While the fidelity of the recorded audio is limited, particularly at higher frequencies, this approach enables precise localization and detailed analysis of underwater acoustic events. Operators can virtually 'position themselves' along the cable and listen to the signals detected at specific locations, offering new possibilities for targeted investigations. In figure 11 the phase time series is shown.

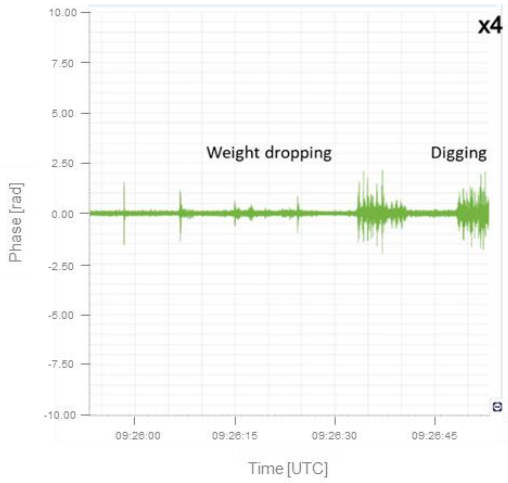

Fig. 11: Phase-time series showing the phase data versus time for various underwater activities near the cable.

The phase signal represents the strain and stress at a certain point along the fiber over time. In case of a sound wave impinging on the fiber, the phase time series represents the sound detected by the DAS.

8 Automated Vessel Tracking Using Machine Learning

To enhance the DAS system's capability for real-time vessel monitoring, a Machine Learning based algorithm was developed and applied for automatic vessel detection. The detection and tracking of the were achieved using a Machine Learning algorithm integrated into the DAS system. The algorithm, primarily based on outlier detection techniques, leverages the distinct and consistent acoustic signatures generated by vessels to differentiate them from background noise. By training the model on baseline noise and typical environmental signals, deviations in the acoustic data—such as those caused by vessel movements—are identified as anomalies and classified as ship signals.

Outlier-detection algorithms are specifically designed to identify anomalies in datasets without requiring extensive training data. They recognize normal patterns and classify significant deviations as outliers. The literature highlights that such algorithms can operate effectively even with limited or unlabeled data [17]; [18]. Given the high volume of vessel traffic crossing subsea cables in areas such as the North Sea or major port approaches, these methods are well suited for ship detection. The algorithm can reliably distinguish ships from background noise, even in complex acoustic environments with overlapping signals.

However, while AIS data provides a reliable ground truth for surface vessel classification, the identification of underwater targets remains challenging. Autonomous underwater vehicles (AUVs) do not transmit AIS signals, making validation more difficult. Furthermore, a vessel's acoustic signature varies depending on factors such as

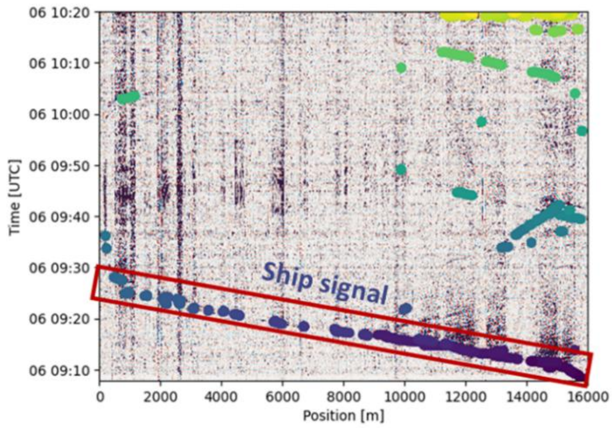

Fig. 12: Automated detection of a SAR boat traveling along the subsea cable. The red box highlights the acoustic signals classified as the SAR boat, with other acoustic events outside the box excluded from the trajectory reconstruction

speed, load, and environmental conditions, meaning that multiple observations are necessary to recognize specific vessels consistently. This approach was tested on a scenario involving a SAR boat traveling along a subsea cable. The results, visualized in figure 12, demonstrate the effectiveness of combining DAS data with automated analysis methods.

The acoustic emissions of the SAR boat were successfully detected and tracked along the cable by the ML algorithm. As shown in Figure 11, the red box highlights the signals classified as the SAR boat, clearly illustrating its trajectory along the cable. The continuous trace within the red box represents the vessel's movement over time, providing a clear and consistent visualization of its path. In contrast, other acoustic events outside the red box, while recorded by the DAS system, were not identified as ship signals by the algorithm. These signals were excluded from the trajectory reconstruction, demonstrating the algorithm's capability to filter out irrelevant or non-ship acoustic events. This selective classification enhances the reliability and accuracy of the monitoring process, particularly in environments with overlapping acoustic activities.

The continuous trace represents the vessel's movement over time, clearly following its path along the cable. Using DAS, it is possible to represent the position of the vessel along the length of the cable with high spatial accuracy. This enables the system to automatically plot the vessel's path on a monitor with an overlaid nautical chart, providing a real-time, intuitive visualization of the ship's trajectory in relation to the cable and surrounding infrastructure.

However, while the system can accurately track the vessel along the cable, it is currently not capable of determining the vessel's exact distance from the cable or its orientation, such as whether it is to the left or right of the cable. This limitation arises from the nature of DAS technology, which measures spatial resolution along the cable but does not directly capture lateral positioning.

The integration of Machine Learning into the DAS system provides several key benefits. First, the algorithm's ability to distinguish ship signals from other acoustic noise ensures accurate and focused monitoring. The example of the SAR boat highlights the system's capability to not only detect vessels but also reconstruct their trajectories automatically, offering a scalable and efficient solution for real-time maritime surveillance. By rejecting non-relevant signals, the system also minimizes false positives, ensuring robust performance even in high-traffic maritime zones.

9 Integration of DAS into Multi-Layered Sensor Platforms

During the tests conducted in Åland (see figure 12), the potential of DAS as part of a maritime protection concept was demonstrated. The system utilized an existing fibre optic cable to detect vessel activities in real time. While only DAS data was analysed in this study, the results highlight the feasibility of integrating DAS into a broader multi-sensor security architecture. Sensor fusion—combining DAS with complementary technologies such as radar and sonar—could further enhance detection capabilities and provide a more comprehensive maritime situational awareness framework.

Fig. 13: Control room where data from DAS, radar, and multiple sonar nodes deployed on the seabed were centralized. These sensors recorded identical scenarios, offering a comprehensive view of surface and underwater activities.

Multi-sensor integration offers significant advantages for maritime security and infrastructure protection. By integrating these diverse data streams, operators gain a holistic understanding of the monitored area, allowing for improved situational awareness and rapid decision-making. Such integration enables the correlation of information, such as radar-detected vessel positions, sonar-generated underwater maps, and DAS-recorded acoustic signals, enhancing the detection and classification of events. The synergy between these sensors offers several advantages. The fusion of data streams from different modalities reduces the limitations of individual sensors, such as the range constraints of radar or the directional sensitivity of sonar. By combining their outputs, the system achieves greater reliability, accuracy, and robustness, minimizing blind spots and reducing false positives. This collaborative approach not only improves operational efficiency but also ensures a higher level of maritime security.

While FIBERMARS was not part of the Åland deployment, its principles align with the findings from these tests. FIBERMARS data collection platform figure 13 is designed to extend the capabilities of multi-sensor maritime surveillance by integrating data from diverse sensor sources into a layered detection, classification, and response system.

The FIBERMARS platform, which has been applied in other maritime security contexts, follows a multi-layered processing approach:

- Layer 1: Centralized sensor data collection.
- Layer 2: Pre-processing and classification of relevant signals.
- Layer 3: Detection, tracking, and classification using machine learning.
- Layer 4: Cross-validation between different sensor types to improve reliability.

This architecture has proven effective in various operational environments. In offshore wind farm security, FIBERMARS integrates DAS data from pre-installed subsea cables with radar and sonar, enabling early detection of vessel activities, unauthorized access, or anchor drop events. In naval base and port surveillance, the system supports perimeter monitoring and underwater threat detection by leveraging DAS alongside traditional security sensors

FIBERMARS successfully integrates DAS as part of a real-time detection system by continuously processing DAS data and correlating it with radar, sonar, and other sensor inputs. The system transforms acoustic signals into actionable information, automatically classifying detected anomalies and vessel activities. To support operator analysis and Command & Control, DAS-derived data is visualized in a real-time operational interface. The integration of automated analysis tools and an intuitive visualization interface ensures that operators receive clear, actionable intelligence, facilitating rapid decision-making in maritime security scenarios.

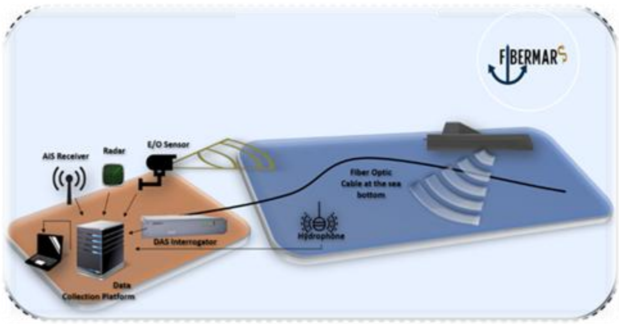

Fig.14; Architecture of the FIBERMARS data collection platform. The platform integrates DAS, radar, AIS, electro-optical (E/O) sensors, and hydrophones to enhance real-time detection and tracking. Sensor fusion follows a multi-layered processing approach, improving situational awareness, automated vessel classification, and training of detection algorithms.

The Åland tests demonstrated that effective maritime protection is feasible using DAS-based monitoring. The insights gained reinforce the importance of multi-sensor fusion and confirm that DAS-based detection can be a key component of layered security architectures. These findings align with the core principles of FIBERMARS, supporting its further development as a scalable and cost-effective maritime security solution.

10 Conclusion

This study highlights the transformative potential of Distributed Acoustic Sensing (DAS) technology for protecting and monitoring critical coastal and subsea infrastructure. By leveraging pre-installed optical fibers, DAS offers a cost-effective and scalable solution for real-time, comprehensive monitoring. The key insights derived from the experiments are summarized as follows:

Comprehensive Monitoring: DAS effectively detects a wide range of events, such as vessel movements, anchor drags, and underwater activities, with high spatial and temporal resolution.

Enhanced Protection: The technology strengthens the security of vital infrastructure, such as offshore wind farms and telecommunication cables, against natural and human-induced threats.

Seamless Integration: While this study focused solely on DAS, the findings support its integration into multi-sensor platforms. DAS complements radar, sonar, and other surveillance systems, creating a robust, multi-layered monitoring network that minimizes blind spots and enhances detection accuracy.

Real-Time Detection and Decision Support: FIBREMARS successfully integrates DAS into a real-time detection framework, correlating acoustic signals with radar and sonar data. This enables automated classification of vessel activities and provides operators with intuitive visual representations for Command & Control applications.

Proactive Detection: DAS enables early warning capabilities, allowing operators to detect potential threats before they escalate. This facilitates rapid response and risk mitigation, protecting critical assets.

Efficiency and Scalability: By utilizing existing fibre optic infrastructure, DAS eliminates the need for additional sensors, making it a practical solution for large-scale deployments.

Advanced Analytics: Machine learning enhances DAS's ability to automatically detect, classify, and track events, improving operational efficiency and reducing false alarms.

These findings establish DAS as a cornerstone technology for securing coastal and subsea infrastructures. Its ability to address the limitations of traditional monitoring systems and its seamless integration into multi-sensor platforms underscore its potential as a next-generation maritime security solution.

Future work should focus on refining the multi-sensor integration of DAS, expanding its classification capabilities through advanced data fusion techniques and machine learning algorithms. Addressing limitations such as lateral positioning of detected activities will further enhance its applicability. Additionally, further validation of real-time operational interfaces within platforms like FIBERMARS will be crucial for optimizing its use in maritime security. With these advancements, DAS is poised to become an indispensable tool for ensuring the resilience and security of critical maritime infrastructure.

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