Ultra-Low-Noise Precision-Engineered DAS Hydrophone Arrays for Littoral and Offshore Surveillance

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Abstract — Distributed Acoustic Sensing (DAS) utilizes Rayleigh backscatter along standard single-mode fibre. However, more recently, a precision-engineered fibre, (Constellation™ fibre) with brighter low-loss scatter centers and an advanced Carina® optoelectronic interrogator system offer a step-change in DAS performance, with 20 dB (100x) lower noise floor compared to that achieved with the standard fibre. Coiled Fibre Optic Mandrel Hydrophone (CFMH) arrays were manufactured using continuous lengths of Constellation fibre. A noise floor at sea-state zero has been demonstrated in an earlier sea trial led by the Swedish Defence Materiel Administration (FMV) in collaboration with Akitemos Solutions AB, Subvision AB, and Silixa LLC. Advanced signal processing techniques, such as beamforming, were used for precise detection, localization and tracking of acoustic signals. The Constellation fibre offers significant advantages in manufacturing a long, continuously distributed hydrophone array for rapid underwater deployment with a broad frequency response from mHz to several kHz. Key advancements discussed include omnidirectional sensitivity, the dual capability to detect signals through both earth and water, and validation of advanced processing techniques through sea trials.

1 Introduction

Acoustic sensing plays a critical role in maritime security, infrastructure monitoring, environmental research, and underwater resource exploration. However, traditional hydrophones, designed as point sensors, face significant limitations in scalability and adaptability to complex subsea environments. Distributed Acoustic Sensing (DAS) addresses these challenges by utilizing optical fibres to detect and analyze acoustic signals with remarkable precision and flexibility. By measuring minute changes in Rayleigh or enhanced scattering induced by acoustic waves, DAS systems can pinpoint sound sources over long distances, providing real-time, high-resolution monitoring.

DAS arrays present unique advantages over traditional hydrophone systems: (1) No requirement for distributed power systems, improving reliability and reducing complexity; (2) Long-range capabilities, enabling coverage of vast areas with fewer deployment challenges; (3) A high number of sensing elements, simplified system architecture, and improved robustness; These benefits make DAS an adaptable and efficient solution for diverse underwater monitoring needs.

Since its inception, DAS technology has advanced significantly, transitioning from telecommunications and infrastructure monitoring to demanding subsea and terrestrial applications. Recent progress in fibre technology, signal processing, and computational power has unlocked the system's potential for modern acoustic monitoring challenges.

The efforts described in this paper were led by the Swedish Defence Materiel Administration (FMV), in collaboration with Subvision AB, Akitemos Solutions AB, and Silixa LLC. Subvision's innovations in Coiled Fibre Mandrel Hydrophone (CFMH) arrays, Akitemos Solutions

AB's engineering expertise, and Silixa's advancements in DAS systems and signal processing have been instrumental in creating robust and adaptable solutions for diverse monitoring applications.

Figure 1 illustrates DAS's operational principles, featuring acoustic signal detection along a fibre optic cable with CFMH arrays and a real-time data display. The system's ability to detect various underwater threats, including submarines, divers, autonomous underwater vehicles (AUVs), and marine mammals, demonstrates its versatility in real-world applications.

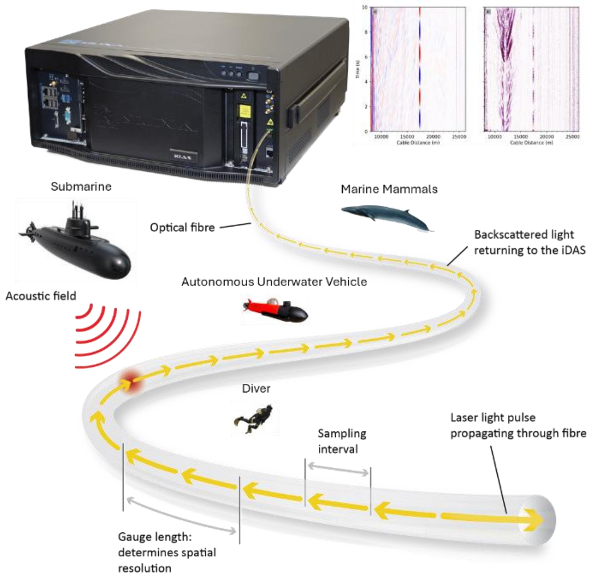

Fig. 1. DAS sensing system, including CFMHs, demonstrating acoustic detection along a fibre optic cable with a waterfall plot and examples of underwater threats such as submarines, divers, AUVs, and marine mammals.

This paper examines the technical advancements and methodologies integral to DAS implementation, including system design, field setup, and acoustic testing. Emphasis is placed on demonstrating the system's omnidirectional sensitivity, ability to detect both seismic and acoustic signals, and its validation through beamforming techniques during sea trials. By focusing on these technical aspects, the paper highlights DAS's transformative potential for reshaping acoustic monitoring across defence, environmental, and industrial sectors.

2 Technical approach

2.1. System design and configuration

Distributed fibre optic sensing, where the fibre is permanently installed, offers many advantages for subsurface monitoring. The DAS utilises Rayleigh backscatter light and allows acoustic data to be acquired along a continuous length of fibre, providing a high-definition acoustic measurement along the entire length of fibre [2].

In addition, advances in precision-engineered fibre (Constellation™ fibre) with brighter scatter centres and a new Carina® optoelectronic interrogator system offer a step-change in DAS performance, with 20dB (100x) lower noise floor compared to that achieved with standard fibre [3,4]. The Carina System, paired with Constellation fibres, represents the pinnacle of advanced DAS technology. This system enables software-selectable gauge lengths from 25 cm to 30 m, providing unmatched flexibility for a wide range of applications. The system achieves an extended sensing range exceeding 100 km in range-extending configurations, making it suitable for large-scale acoustic monitoring. The system supports a dynamic range of up to 130 dB while balancing high sensitivity across a broad frequency spectrum of 0.001 Hz to 50 kHz.

Configurations utilize both straight and coiled fibres to optimize performance. Straight fibres are ideal for wide-area monitoring, leveraging their linear design for detecting distant signals. Conversely, coiled fibres enhance localized acoustic detection by amplifying pressure-induced strain sensitivity, a key feature for high-resolution analysis in focused areas. Sampling rates up to 8 kHz enable the system to capture low-frequency seismic signals while maintaining the precision required for high-frequency sound localization and mapping.

Subvision's CFMHs were integrated into the system using single-mode fibres (SMFs) and Constellation fibres for benchmarking. These hydrophones utilize robust coiled mandrel designs, amplifying strain sensitivity while ensuring durability under field conditions. This integration provided a baseline to evaluate acoustic signal propagation and detection capabilities under diverse operational scenarios.

Silixa's Carina Sensing System, combined with Subvision's CFMHs and its capability to support long-distance, high-density sensing arrays, offers a robust solution for real-world applications. Its exceptional dynamic range and adaptability make it uniquely suited to tackle the challenges of underwater security.

2.2. Field setup

The trials took place at FMV's test site in Sweden, utilizing a 12-meter underwater beam deployed at a depth of 25 meters. Constructed with reinforced fibreglass and wood, the beam provided a stable platform for sensor mounting. The arrangement included straight and coiled SMFs, Constellation fibres, and traditional piezoelectric Reson 4032 hydrophones, allowing direct comparison of their respective sensitivities, noise thresholds, and spatial resolutions.

Acoustic sources were strategically placed at varied distances and angles to simulate realistic underwater acoustic environments. Signals were emitted in a controlled manner to facilitate consistent data collection. Calibration ensured uniformity in signal propagation across test scenarios.

Real-time data acquisition was supported by the Carina Sensing System, which connected to the various fibre arrays to capture high-fidelity signals. Sampling frequencies were chosen to accommodate a broad spectrum of acoustic signals, and advanced synchronization ensured precise alignment of emitted and received signals. These controlled conditions allowed for systematically evaluating DAS configurations under diverse environmental and operational settings.

2.3. Acoustic testing

Acoustic testing was performed to assess the DAS sensing system's ability to detect, localize, and analyze sound waves under diverse conditions. Controlled signals—including continuous tones, chirps, sonar pings, and transient pulses—were transmitted at defined frequencies ranging from 200 Hz to 10 kHz. These signals were systematically varied in distance and orientation relative to the sensor arrays to evaluate performance across a wide range of acoustic scenarios, including sensitivity to angle of arrival.

The captured acoustic data enabled advanced signal processing, such as beamforming, to analyze the system’s localization capabilities. Both straight and CFMHs were employed in the tests, with the coiled configurations amplifying pressure and strain sensitivity for detecting subtle acoustic variations. Source amplitudes were measured to determine the transfer function of the array and assess its frequency and amplitude response.

Traditional hydrophones were included as reference devices to benchmark performance under identical conditions. Data captured by the DAS array was calibrated against these hydrophones to convert native strain-rate measurements into sound pressure levels, providing standard acoustic units for analysis. This systematic calibration ensured accurate comparisons and validated DAS performance across key acoustic metrics. The approach demonstrated the system's capability to handle complex field conditions while maintaining consistent and precise results.

3 Results and discussion

3.1. Omnidirectional sensitivity

The field data emphasizes the omnidirectional response of the DAS-CFMH system, which consistently detects acoustic signals with uniform sensitivity regardless of the source's angle of incidence. As depicted in figure 2, the polar response plots at 420 Hz (top) and 2200 Hz (bottom) highlight this omnidirectional sensitivity. The uniformity of the system's response is critical for applications in dynamic environments where sound sources, such as vessels or marine life, are unpredictable in orientation or movement.

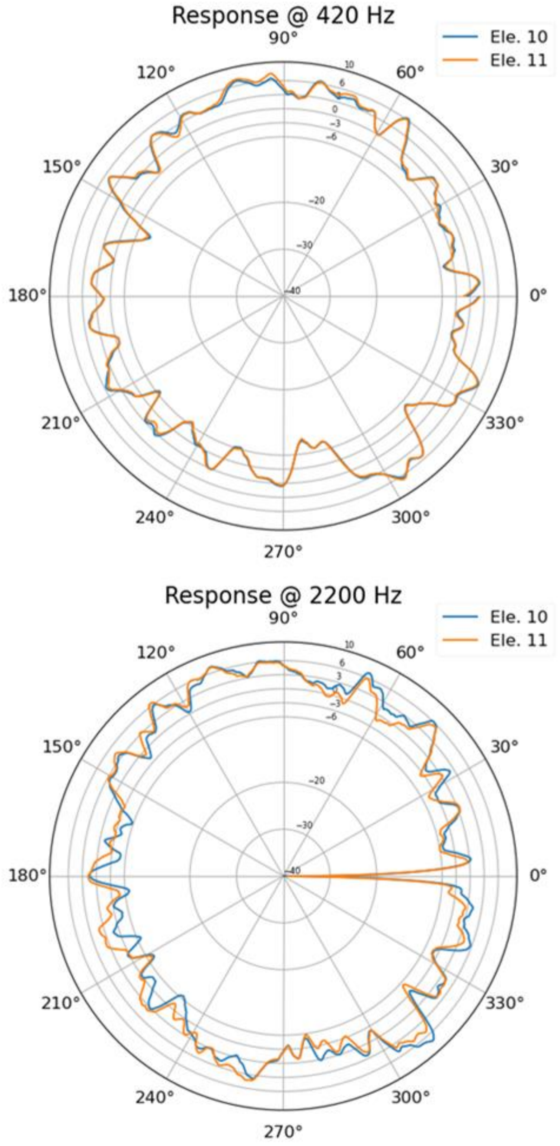

Fig. 2. DAS-CFMH directional response at 420 Hz and 2200 Hz, effectively demonstrating omnidirectional frequency sensitivity. Measurements were conducted at approximately 75 meters from the source.

The response demonstrates a flat amplitude across angles, with some variations in the plots attributed to the complexities of the experimental setup and environmental conditions. The positioning of the reference hydrophone relative to the DAS array was not optimized for precise beampattern comparisons, and the open-water testing environment introduced natural multipath effects. In contrast, published beam plots for traditional piezoelectric hydrophones are often obtained under tightly controlled laboratory conditions, which inherently minimize such environmental influences.

The system's omnidirectional performance is essential for applications in maritime monitoring, where sound sources can originate from any direction, ensuring effective large-area coverage without complex directional adjustments. This capability increases operational efficiency and minimizes the risk of missed detections in real-world scenarios.

The scalability of the DAS system further enhances its versatility. The system achieves exceptional spatial resolution and extensive coverage with potential configurations allowing up to 10,000 sensors per 20 km of fibre using a 2-meter gauge length. This scalability positions the DAS hydrophone array as a robust solution for subsea defence, geophysical surveys, and environmental monitoring. At the same time, its omnidirectional sensitivity ensures its functional equivalence to traditional hydrophones in dynamic and unpredictable environments.

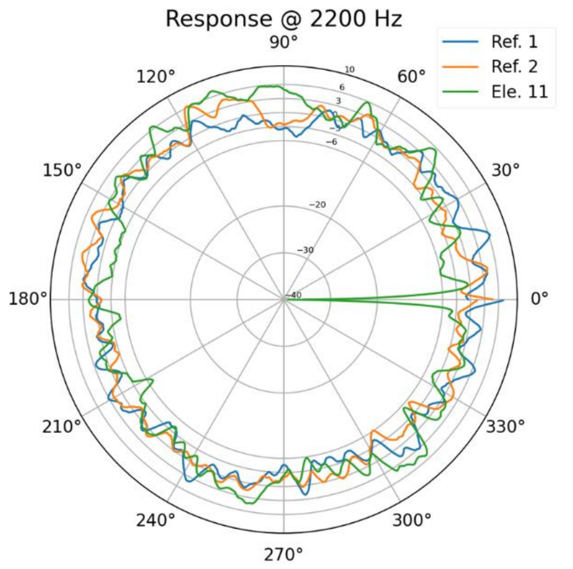

Fig. 3. DAS-CFMH directional response shows comparable sensitivity and directionality to Reson 4032-built hydrophones. Ref. 1 and Ref. 2 illustrate the amplitude response of reference hydrophones, while Ele. 11 represents the response of a DAS-CFMH located at the midpoint between the two reference hydrophones.

3.2. Hydrophone comparison

The comparative analysis between the DAS-CFMH system and traditional Reson 4032-built hydrophones highlights the advanced performance capabilities of DAS. Figure 3 demonstrates the directional response of DAS-CFMH element 11 compared to two Reson 4032 reference hydrophones (Ref. 1 and Ref. 2) at 2200 Hz. The results show that the DAS hydrophone achieves comparable sensitivity and directional amplitude response, even under controlled low-noise conditions.

Figure 4 further emphasizes this equivalence by presenting frequency-domain comparisons. Panels (a) and (b) display spectrograms of logarithmic chirps (200-2000 Hz) captured by the DAS and reference hydrophones, respectively, while panel (c) compares their frequency responses. The DAS-CFMH exhibits sensitivity nearly identical to the reference hydrophone across the 200-2000 Hz range, with minor deviations in the lower frequencies below 200 Hz. This demonstrates that the DAS hydrophone offers a frequency response function closely aligned with reference hydrophone sensors.

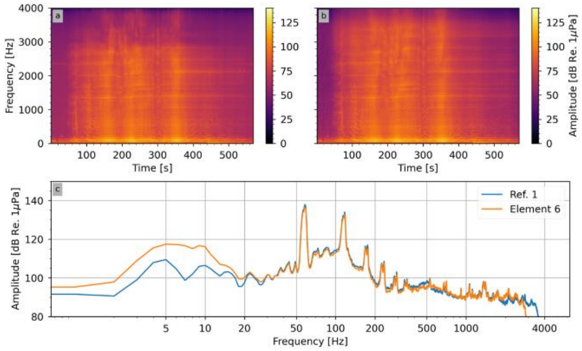

Fig. 4 Frequency sensitivity comparison between CFMHs and reference hydrophones: (a) DAS spectrogram (200-2000 Hz), (b) Reson 4032 hydrophone spectrogram, and (c) frequency response showing near-equivalent sensitivity across 200-2000 Hz.

Achieving such parity in performance represents a significant milestone for DAS technology, validating its potential as a viable alternative or complement to traditional hydrophone arrays in critical subsea applications. The DAS system's superior noise floor ensures reliable performance in low-noise environments, such as 'Sea State 0,' where traditional hydrophones may struggle to detect subtle acoustic variations. Furthermore, the DAS-CFMH robustness and adaptability across diverse acoustic scenarios—coupled with its capacity to integrate thousands of sensing elements within linear fibre arrays—enable scalable, long-range monitoring. This approach reduces logistical and maintenance challenges compared to traditional hydrophone systems while expanding operational capabilities.

3.3. Detection through earth and water

One of the most significant advancements demonstrated by the DAS-CFMH system is its ability to detect acoustic signals propagating through both underwater and terrestrial environments, emphasizing its versatility for diverse applications. While this testing occurred over a relatively short distance, the results underscore the system's effectiveness in capturing sound propagation in complex environments. As shown in figure 5, the DAS-CFMH response illustrates amplitude loss consistent with spherical spreading, with higher observed amplitudes attributed to the reverberant test environment.

Since the SMFs used in the deployment were not perfectly straight, it remains uncertain whether the measurements reflect "stretching" effects from bottom sediments or pressure signals. In shallow water conditions, low-frequency sound waves propagate through both the seabed and the water column, further complicating the interpretation of the signal's origin. This dual-path propagation highlights the importance of understanding environmental conditions and system placement to ensure accurate detection.

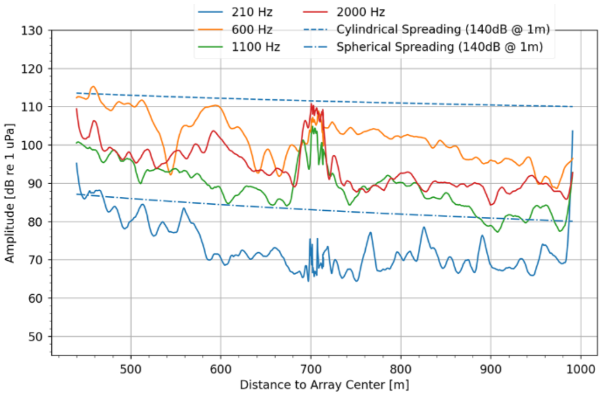

Fig. 5. DAS-CFMH response as the source moves away from the array shows amplitude loss consistent with spherical spreading, with higher amplitudes due to the reverberant test environment.

Despite these complexities, the ability to detect amplitude decay and maintain signal fidelity underscores the DAS system's robustness across varying mediums. Its dual detection capability enables monitoring scenarios spanning aquatic and terrestrial domains, simplifying system architecture and reducing operational complexity. For instance, in geological contexts, DAS can monitor seismic activity and subsurface infrastructure while simultaneously detecting underwater activity in nearby water bodies.

The performance in reverberant conditions is particularly significant for real-world deployments, where ideal acoustic environments are rare. The system's ability to maintain reliable detection in such scenarios provides confidence in its applicability for coastal defence. These findings further reinforce the need for advanced signal processing algorithms to differentiate reverberant noise from primary signal paths, ensuring the accurate detection and localization necessary for operational success.

3.4. Advanced signal processing

The sea trials showcased the DAS-CFMH system's ability to leverage advanced signal processing techniques, such as beamforming, for precise localization of acoustic sources over substantial distances. Beamforming takes advantage of the hydrophone array's coherence, as demonstrated in figure 6, to improve directional resolution and reduce spatial noise, which is vital for applications in maritime surveillance and environmental monitoring [1].

Figure 6 highlights the system's capacity to track a boat's angle of arrival as it circled the array. Although the linear geometry of the array introduces phase ambiguity, evident in the symmetrical patterns of the polar plots, this geometry achieves commendable results. Future exploration of non-linear array designs, such as circular or triangular configurations, could further enhance directional resolution and address these ambiguities. The results also suggest that advanced processing techniques, including 3D beamforming and localization, could unlock additional insights in more complex array configurations.

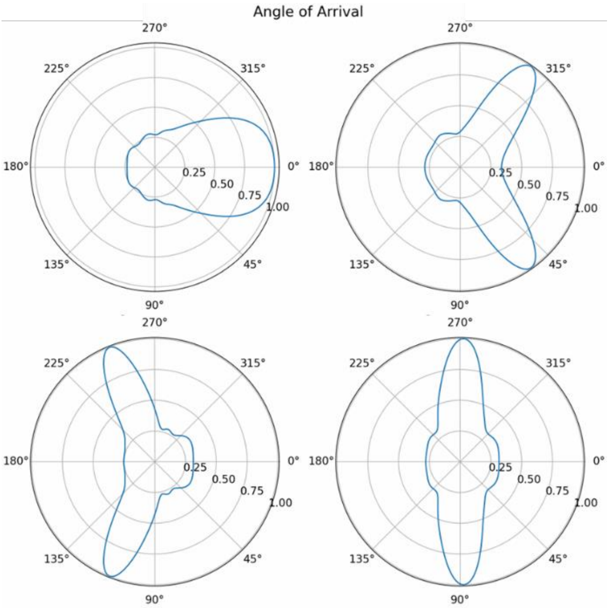

Fig. 6. The DAS-CFMH array demonstrates coherence for beamforming, with polar plots tracking a boat as it circled the array. Phase ambiguity from the linear geometry highlights opportunities for optimizing array configurations.

Beamforming's ability to suppress noise and isolate sound sources underscores its critical role in high-resolution monitoring within dynamic and noisy environments. These capabilities ensure robust performance in applications such as underwater navigation, seismic surveys, and maritime security.

Furthermore, the high-quality datasets generated by DAS arrays align seamlessly with ML applications. ML algorithms can classify acoustic patterns, detect anomalies, and automate data interpretation. With thousands of sensors integrated along a single fibre, the scalability of DAS technology facilitates real-time analytics, reducing manual intervention and enhancing operational efficiency.

4 Future work

A comprehensive long-term sea trial is planned to evaluate the performance, reliability, and scalability of DAS technology in real-world conditions. This deployment will integrate advanced CFMHs, shorter gauge-length fibres, over long distances, and an intuitive graphical user interface (GUI). The GUI will streamline operations with features such as real-time beamforming visualization, automated anomaly detection, and customizable monitoring parameters, significantly reducing operational complexity. The trial will also test system robustness across varying sea states, focusing on acoustic sensitivity, hydrophone durability, and long-term operational stability.

Additionally, the trial will explore non-linear array geometries, such as circular or triangular designs, to mitigate phase ambiguities and enhance directional resolution, offering greater flexibility for deployment. Insights from these efforts will shape future advancements, including the integration of ML algorithms for automated signal classification and real-time decision-making. These innovations will enable scalable, continuous monitoring and further establish DAS as a transformative technology for maritime security.

5 Conclusions

This study underscores the significant technical advancements and capabilities of DAS technology for acoustic monitoring in diverse and challenging environments. By integrating CFMHs with advanced signal processing techniques like beamforming, DAS systems demonstrated performance comparable to traditional Reson 4032 hydrophones while achieving superior scalability and adaptability. The system's ability to detect acoustic signals across both underwater and terrestrial domains highlights its versatility for applications ranging from maritime security to environmental monitoring.

Field trials validated DAS's capability to precisely localize sound sources, effectively suppress spatial noise, and maintain high sensitivity across a broad frequency range. The linear array configuration exhibited robust performance in capturing acoustic signals, with minor limitations that could be addressed through non-linear geometries to optimize directional resolution. Additionally, the scalability of DAS, which supports thousands of sensors along a single fibre, enables cost-effective and robust long-range monitoring while minimizing logistical complexity, firmly positioning it as a transformative solution for contemporary acoustic sensing challenges.

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Author/speaker biographies

Dr. Bryce Davis has over 20 years of experience in defence technology, with current focus on fibre optic sensing solutions like DAS for subsea monitoring. He manages projects, collaborates with government agencies and defence contractors, and drives innovation in sensing technologies to enhance security and monitoring within the defence sector.

Rune Tenghamn, engineering adviser at Akitemos Solutions AB, brings extensive expertise in advanced acoustic sensing technologies. Based in, Sweden, he leads Akitemos Solutions AB in developing innovative solutions for maritime security and environmental monitoring. Rune specializes in integrating cutting-edge systems, fostering collaboration, and advancing research to address complex challenges in underwater sensing and monitoring.