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REVIEW

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Distributed acoustic sensing technology in marine geosciences

Jiayi Wei[1†], Wende Gong[3†], Junhui Xing[1,2*] and Haowei Xu[1]

Abstract

Distributed acoustic sensing (DAS) is an emerging vibration signal acquisition technology that transforms existing fiber-optic communication infrastructure into an array of thousands of seismic sensors. Due to its advantages of low cost, easy deployment, continuous measurement, and long-distance measurement, DAS has rapidly developed applications in the field of marine geophysics. This paper systematically summarizes the status of DAS technology applications in marine seismic monitoring, tsunami and ocean-current monitoring, ocean thermometry, marine target monitoring, and ocean-bottom imaging; analyzes the problems faced during its development; and discusses prospects for further applications in marine geoscience and future research directions.

Keywords Distributed acoustic sensing, Marine geoscience, Seafloor sounding, Marine microseismicity

1 Introduction

As human exploration of the Earth's deep-sea environment continues, the demand for efficient and reliable marine geoscience data acquisition and analysis technologies is increasing. As an innovative monitoring and detection method, distributed acoustic sensing (DAS) technology has gradually become one of the key technologies to address this challenge.

DAS originated in the 1970s as a novel vibration signal acquisition technology, using optical fiber as a sensing and transmission medium. It is based on phase-sensitive optical time-domain reflectometry, achieving continuous distributed detection of acoustic signals through the interference effect of backscattered Rayleigh light in the optical fiber (Hartog 2017). DAS enables continuous

spatial sampling of seismic wavefields with meter-level precision. This technology, initially used in military defense and engineering structure monitoring, inherits the advantages of conventional optical fiber sensing technologies, such as resistance to electromagnetic interference, good concealment, corrosion resistance, insulation, and low deployment costs (Wang et al. 2019). Thanks to the sensitivity of phase to propagation distance in optical transmission, DAS technology can sense a wide frequency range of vibration signals. As a new measurement method in geophysics, it can transform existing fiber-optic communication infrastructure into an array of thousands of seismic sensors. Over the past decade, the gradual development of DAS technology has been increasingly useful in fields such as oil and gas exploration, downhole vertical seismic profiling (VSP), and traffic monitoring (Parker et al. 2012; Daley et al. 2013; Madsen et al. 2013; Hartog et al. 2014; Mateeva et al. 2014; Jiang et al. 2016).

In marine geophysical research, the application of underwater seismic sensors such as ocean-bottom seismometers (OBS) has matured. The data collected from deployed OBS can be used for volcano structure detection, earthquake detection, and seabed structure exploration. However, the deployment cost of OBS is extremely

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high for observing larger areas. In contrast, DAS systems are simple in structure, have modest maintenance costs, feature real-time data transmission capabilities, are easy to deploy, allow for continuous measurement, and can measure over long distances. Because DAS is sensitive to optical fiber deformations, it can be directly applied to existing communication cables. Currently, millions of kilometers of optical fiber cables have been laid worldwide, with a sizable proportion in the ocean as communication fibers or dark fibers. DAS technology can leverage these fibers to establish a large-scale seabed observation network for marine geophysics applications (Marra et al. 2018; Lindsey et al. 2019). To provide readers with a clearer understanding of the marine geoscience applications of this technology, this work explains the status of DAS equipment and parameters. It also details the application of DAS in marine seismic monitoring, seabed imaging, tsunami and typhoon monitoring, sea water temperature monitoring, and marine target monitoring. Based on this, it outlines prospects for the future development and application of DAS technology.

2　Equipment parameters

The distributed fiber-optic sensing system consists of the DAS demodulation and the sensing fiber. There are many options for distributed acoustic sensing demodulations, such as the iDAS from Silixa in the UK (https://silixa.com), the FEBUS A1-R from FEBUS Optics in France (https://www.febus-optics.com), the DAS N51/N52 series from AP Sensing in Germany (https://www.apsensing.com), the QuantX DAS from OptaSense in the US (https://www.optasense.com), the USTC ZD-DAS developed by the University of Science and Technology of China (https://36kr.com/p/2410165669176072), or the DITEST DAS series from Omnisens in Switzerland (http://www.omnisens.com.cn/) (Fig. 1). The parameters of these devices are listed in Table 1.

The DAS devices developed by various companies exhibit many common features, but each has unique advantages. DAS devices have a wide frequency-response range, high spatial resolution, and long measurement distances. For example, Silixa's iDAS and AP Sensing's DAS devices both have a frequency-response capability of up to 20 kHz or more, suitable for capturing high-frequency vibration and acoustic signals. The measurement distances of DAS devices typically reach or exceed 50 km. Silixa's iDAS and the USTC DAS developed by the University of Science and Technology of China provide long-distance measurements over 50 km while offering sub-meter spatial resolution, allowing these devices to precisely locate acoustic events. These characteristics make them widely applicable in fields such as geophysics and traffic detection.

Current DAS devices have a frequency-response range from 0.001 Hz to 50 kHz (e.g., Silixa iDAS), capable of detecting microseismic signals such as Scholte waves and ocean surface gravity waves with frequencies between 0.01 Hz and 1 Hz (Xiao et al. 2022). The broader frequency detection range of DAS devices meets the detection frequency requirements in marine geophysics and enables these devices to better monitor marine targets (e.g., marine mammals like whales).

3　Marine seismic monitoring

The poor spatial coverage of marine observation instruments has long led to a lack of high-density marine observations. This has resulted in biases and low resolution in global seismic tomography models and uncertainties in the specific locations of marine seismic activity (Williams et al. 2019). In this context, submarine optical fiber has gradually become a useful tool for us to observe marine seismic activities. There have been many studies on the use of submarine fiber for marine geophysical applications and seismic monitoring, such as the frequency metrology interferometric techniques method (Marra et al. 2018) and the state of polarization monitoring technology (Zhan et al. 2021). The DAS continuous high-density monitoring capability and convenient layout provide a new means for marine seismic activity observation.

DAS is applicable for seismic monitoring in subsea dark fibers and communication cables (Ajo-Franklin et al. 2019; Williams et al. 2019). Advances in fiber-optic seismology have directly facilitated research on microseisms and related areas. Research teams have demonstrated the capability of underwater DAS to record and analyze seismic events. Microseismic and teleseismic observations were conducted using a subsea fiber-optic cable approximately 42 km long, buried 0.5–3.5 m below the seabed in the North Sea off the coast of Zeebrugge, Belgium (Williams et al. 2019). Data recorded by the DAS system during the August 19, 2018, M_w 8.2 earthquake in Fiji were used to separate and identify marine and seismic signals, analyze observed ocean surface gravity waves and Scholte waves, and extract P- and S-wave phases in the 0.01–1 Hz band (Williams et al. 2019).

A 41.5-km-long telecommunications cable was deployed near the coast of Toulouse, France, spanned from the shallow continental shelf to the deep-sea plain at a depth of approximately 2500 m for observing and recording periodic oscillatory background signals. The first eight kilometers of the cable, deployed on the shallow continental shelf, detected signals in the 0.1–0.25 Hz range, with an average depth of 100 m. When the cable reached the deep-sea plain, at an average depth of more than 2000 m, the recorded data primarily showed high-frequency waves

Fig. 1 Distributed acoustic sensing (DAS) equipment diagram. **a** IDAS; **b** FEBUS A1-R; **c** AP SENSING DAS; **d** OptaSense QuantX DAS; **e** USTC ZD-DAS; **f** Omnisens DITEST

Table 1 Main equipment parameters

Equipment parameter	Maximum measuring range (km)	Optimal spatial resolution (m)	Frequency range (Hz)
IDAS	50	1	0.001–50k
FEBUS A1-R	50	2	< 20k
AP SENSING 5125A	70	1.25	< 20k
OptaSense QuantX	100	-	< 20k
USTC ZD-DAS	80	0.2	0.01–20k
Omnisens DITEST	60	0.5	-

in the 0.2–0.8 Hz range. The cable data exhibited records related to local small earthquakes, ocean surface gravity waves, and microseismic noise, indicating that DAS can be directly applied to subsea communication cables for seabed dynamics monitoring (Sladen et al. 2019).

Backscattered laser pulses and phase-based coherent optical time-domain reflectometry (φ-OTDR) technologies have been used with fibers for optical analysis multiplexing, successfully applying DAS technology to subsea dark fibers. This technique was applied to more than 20 km of 'MARS' cable near California for environmental

noise analysis, demonstrating the potential of DAS for marine seismic observations (Lindsey et al. 2019).

Lior et al. (2021) conducted a comprehensive analysis of underwater DAS measurements. They analyzed noise sources, including ocean surface gravity waves and Scholte waves, using DAS data from three different telecommunications cables in Greece and compared the DAS records with those from nearby broadband stations. In Lior et al. (2021), the DAS data were not sensitive to P-waves. However, Tonegawa et al. (2022) successfully extracted P-waves in the 0.1–0.3 Hz band from submarine ambient-noise data recorded by DAS during a rainstorm. The results in Tonegawa et al. (2022) indicate that the extraction of P-waves by DAS is currently weather-dependent, with higher P-wave intensities during rainy weather improving DAS data quality, whereas calm, clear weather results in poorer P-wave extraction quality. This may adversely affect the application of DAS to marine seismic monitoring.

DAS can detect active-source-generated hydroacoustic signals, such as from air gun shots (Matsumoto et al. 2021). Approximately 50 km of the 128-km Moruto submarine cable near the Dense Ocean-floor Network system for Earthquakes and Tsunamis observatory in Japan was used for DAS measurements. The Muroto cable has a buried section between 0.35 and 2.14 km, with a burial depth ranging from 0.5 to 1.0 m below the seafloor. Beyond this section, due to its own weight, the cable is laid on the seafloor at depths below 500 m (Matsumoto et al. 2021). These researchers compared the frequency and sensitivity of DAS transmission data with data from hydrophones near the optical cable. The results showed that DAS fully recorded the vibration signals from the active source and, under strong coupling between the cable and the seabed, DAS could identify seismic signals caused by regional earthquakes.

Microseismic noise is almost ubiquitous in DAS submarine detection data, providing a novel method for exploring the mechanisms of microseism generation. DAS can record the amplitude and frequency of seafloor strains caused by ocean surface gravity waves, as well as secondary microseisms caused by the interaction of incident and reflected gravity waves from the coast. This offers a new opportunity to search for ocean microseism sources and understand the complex seismic phenomena present in the ocean. DAS sensitivity to ocean surface gravity waves and Scholte waves (Spica et al. 2022) can be applied to locate high-frequency microseism sources in the ocean.

Xiao et al. (2022) analyzed the signal-to-noise ratio (SNR) changes in seaward and landward signals monitored by DAS using a submarine cable buried 1-m below the seabed near the coast of Valencia, Spain. Using a short-term cross-correlation function method, they accurately located ocean secondary microseism sources within a few kilometers of error. Figure 2 intuitively reflects the determination of the source by comparing the SNR of seaward signals (Fig. 2a) and landward signals (Fig. 2b). The results indicate that the locations of high-frequency microseism sources in the ocean are constantly moving (Xiao et al. 2022). A similar analysis was performed for secondary microseism noise sources along the French coast (Guerin et al. 2022). These analyses are crucial for studying the mechanisms of microseism generation, as DAS provides a new low-cost method for long-term continuous observation of source location changes.

4 Ocean-bottom imaging
Ocean-bottom imaging holds significant value for exploring and developing underwater resources, monitoring ocean environmental changes, and providing early warnings for underwater disasters. Using seismic waves from natural earthquakes to study the source and medium is fundamental to seismology. Analyzing these seismic waves to establish body-wave velocity models is crucial for determining the properties of submarine media and imaging the ocean bottom. The advent of DAS provides a new possibility for imaging ocean sediments in areas unreachable by traditional passive seismic surveys. Currently, research on DAS imaging has two directions: active-source imaging and passive-source imaging.

Ambient-noise tomography is commonly used for seismic imaging. DAS has been extensively used for ambient-noise tomography on land (Dou et al. 2017; Ajo-Franklin et al. 2019; Yuan et al. 2020). Ambient-noise analysis in DAS data can also achieve passive-source ocean-bottom imaging. By extracting and inverting Rayleigh wave multimodal dispersion curves, we can obtain a two-dimensional shear-wave velocity profile around the observation cable, combining this with the autocorrelation images of ambient-noise data recorded by DAS, we can analyze the shallow seafloor structure (Fig. 3) (Spica et al. 2020; Viens et al. 2023). This method has already been practically applied in the ocean to reveal small-scale geological structures such as underwater sedimentary basins and faults (Lior et al. 2021). Spica et al. (2022) also proposed a data processing method (gridded slant-stack, GSS) that can detect coherent surface wave energy in the ocean-bottom DAS wavefield for extraction and inversion.

The application of DAS in ocean-bottom active-source imaging has been demonstrated. Active-source seismic data recorded by a submarine cable in Norway's Trondheimsfjord was used to generate seismic profiles of the ocean bottom and underlying geological
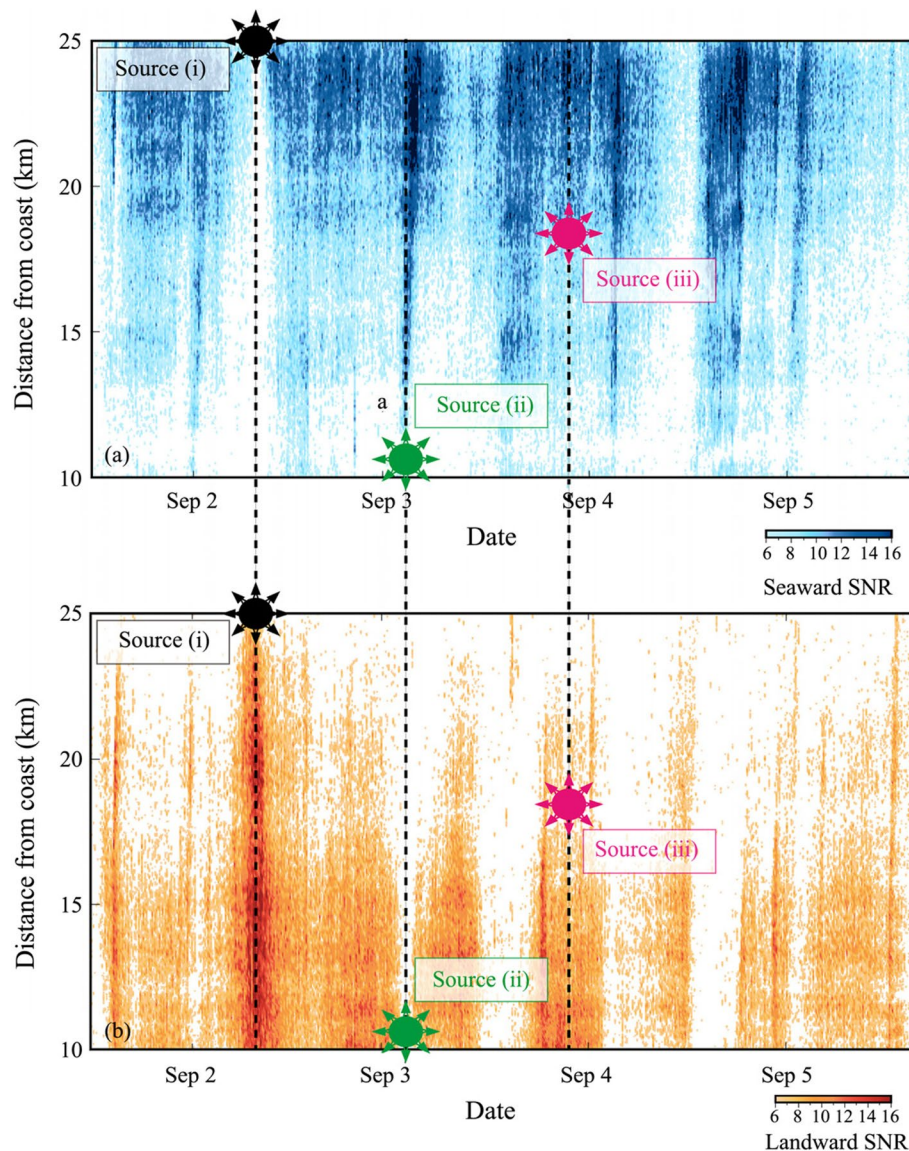
Fig.2 Signal-to-noise (SNR) variations of high-frequency microseisms (0.5–1 Hz) obtained off the coast of Valencia, Spain, by Xiao et al. (2022). The three colored circular symbols are the locations of the detected high-frequency microseismic sources. **a** SNR variation of the seaward signal; **b** SNR variation of the landward signal. (Modified from Xiao et al. 2022)

structures (Taweesintananon et al. 2021). Their research showed that with increased active-source energy, the quality and resolution of DAS imaging would further improve, proving that DAS technology can produce seismic imaging comparable to traditional active-source methods (Taweesintananon et al. 2021).

The quality of DAS observation data is significantly correlated with the coupling degree of the optical cable to the seabed. In areas where the seabed depth changes markedly, DAS observation quality is worse than in areas of consistent depth. Poor seabed coupling of optical cables will adversely affect the quality of the measurement data.

5 Tsunami and ocean-current monitoring

Tsunamis are ocean waves triggered by underwater geological activities such as submarine earthquakes, underwater landslides, or volcanic eruptions, and they are highly destructive. Therefore, real-time monitoring for tsunamis is a significant field in geophysics. Because tsunamis can induce infragravity waves (Bromirski and Stephen 2012), they can be monitored by observing infragravity wave anomalies. Signal-processing methods exist to extract infragravity waves (high-frequency tsunamis) and tsunami waves from DAS data. The specific methods include down-sampling continuous strain
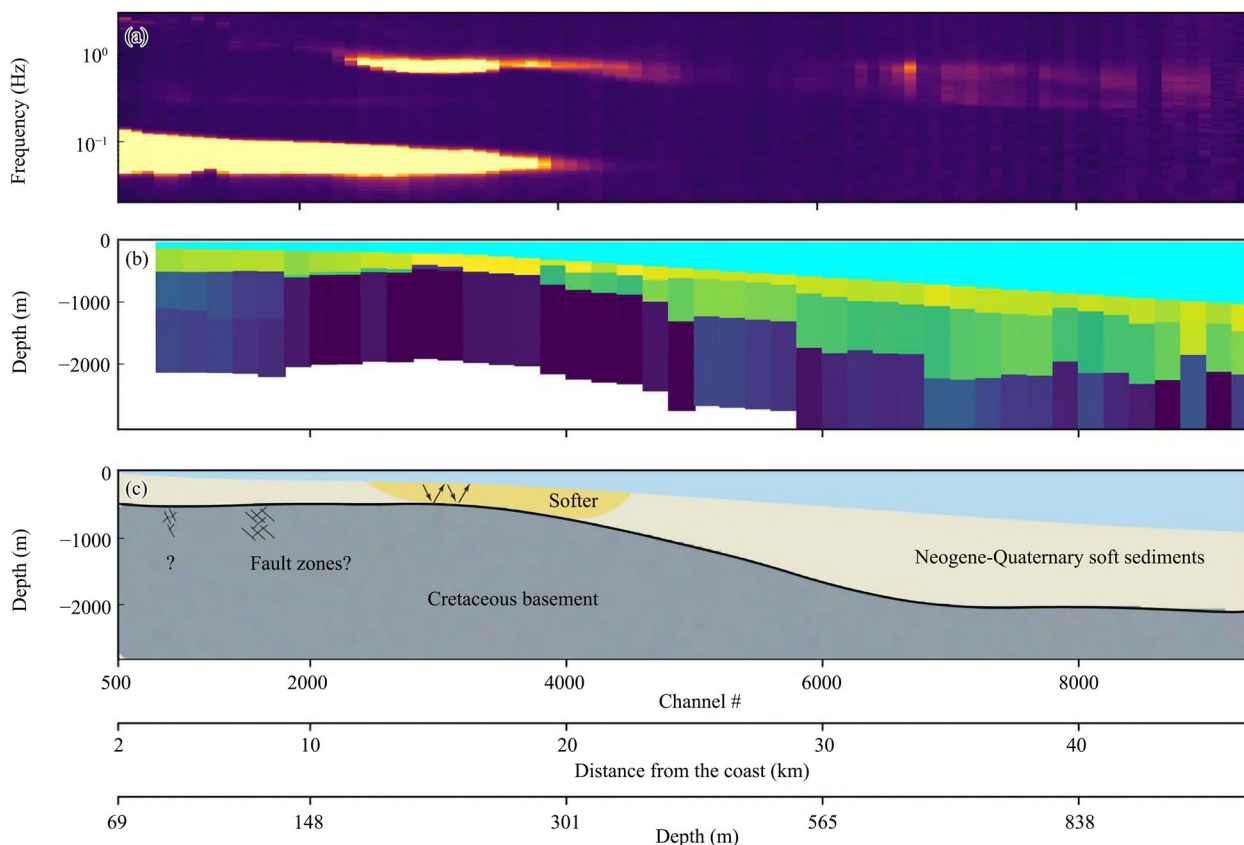
Fig.3 Images obtained through environmental noise tomography (modified from Spica et al. 2020). **a** Power spectral density plot obtained through each channel of the distributed acoustic sensing. **b** Two-dimensional (2D) shear-wave velocity profile obtained by inverting the dispersion curves of each channel. **c** Geological interpretation plot obtained by combining **a** and **b**

rate data to 1 Hz, applying spectral whitening methods for preprocessing, converting subsea DAS datasets to the frequency-wavenumber (F-K) domain by adjusting step size, and finally performing apparent velocity correction (Xiao et al. 2024).

Researchers successfully inverted infragravity waves and tsunami waves off the coast near Florence, Oregon, using an underwater fiber-optic cable and the FEBUS Optics A1-R demodulator (Xiao et al. 2024). The infragravity waves were in the 0.005–0.03 Hz band (Fig. 4a) and wind waves and microseisms were below 0.3 Hz (Fig. 4b). Additionally, Becerril et al. (2024) demonstrated real-time monitoring using DAS technology on submarine cables and analyzed seabed strain induced by tsunami waves through fully coupled three-dimensional (3D) physical simulations, proving that DAS can be used for real-time tsunami monitoring and faster tsunami warnings.

Because current researchers have a limited understanding of the mechanisms by which earthquakes generate infragravity waves, future work will require more extensive data collection and more advanced data interpretation methods.

DAS enables in-situ observations of ocean currents during extreme sea conditions caused by typhoons. Ocean storms are a major source of microseismic noise, which can be effectively used for real-time monitoring and tracking of typhoons (Davy et al. 2014). Williams et al. (2022) first demonstrated the application of DAS technology for seawater flow monitoring by ocean surface gravity wave interferometry. They successfully measured flow velocity variations in the Strait of Gibraltar, showing that ambient-noise interferometry with DAS can monitor ocean currents through gravity waves and ocean waves. Lin et al. (2024) proposed a method for calculating the speed and direction of horizontal ocean currents and successfully conducted in-situ measurements during the passage of Typhoon Muifa. Moreover, ocean currents exhibit a fluid-solid coupling vibration phenomenon known as vortex-induced vibration (VIV) when passing through narrow gaps, characterized by the periodicity of vortex shedding. Flore et al. (2023) used VIV theory to convert the oscillation frequency of a poorly connected section of cable off the coast of Toulon, southern France, successfully deriving an ocean-current velocity time series at a depth of 2390 m.
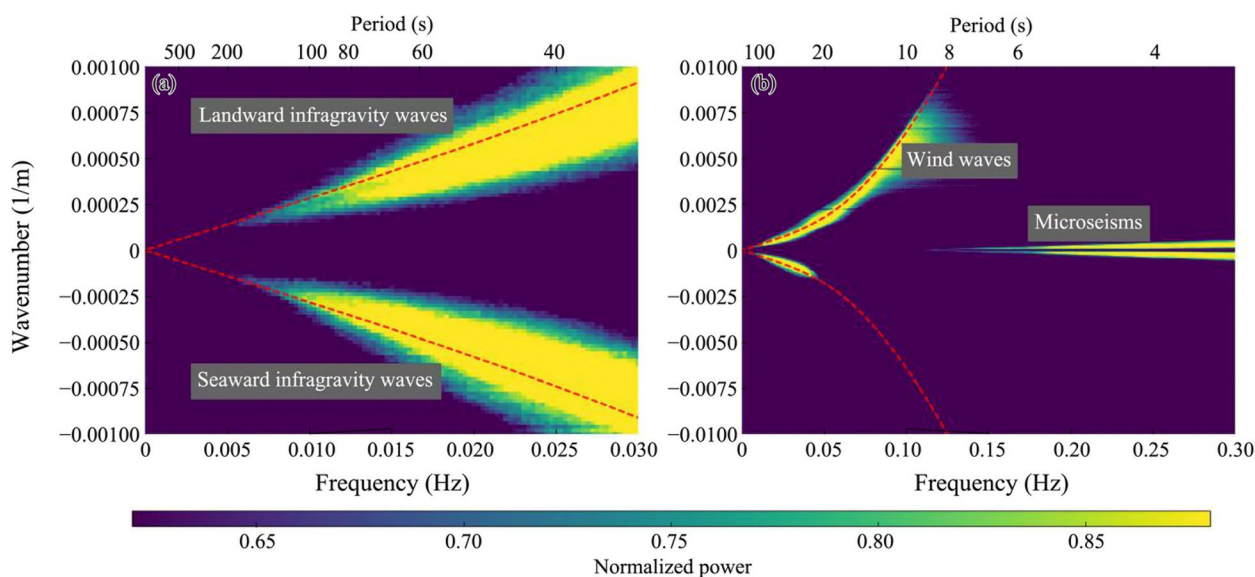
Fig.4 Results of frequency-wavenumber (F-K)-transformed stacking of whole-month data collected by distributed acoustic sensing near Florence, Oregon, by Xiao et al. (Modified from Xiao et al. 2024). The red dashed lines correspond to the theoretical results for a water depth of 120 m. **a** 0.05–0.03 Hz band associated with infragravity waves. **b** Band below 0.3 Hz where wind waves and microseismicity located

6 Ocean thermometry

In-situ monitoring of seafloor temperature is critical for understanding climate change and its impacts on the marine environment. Currently, various monitoring methods are used, including conductivity, temperature, and depth (CTD) sensors, expendable bathythermographs (XBTs), Argo floats, underwater drones, and crewed submersibles. However, these devices often face limitations when conducting long-term and intensive seawater temperature measurements in deep and remote areas. DAS and distributed temperature sensing (DTS) technologies have the potential to fill this gap.

T-waves are the third arrival waves in seismograms following P- and S-waves, propagating horizontally at a speed of approximately 1.5 km/s (Linehan 1940; Tolstoy and Ewing 1950). Because the speed of sound in seawater increases with temperature, changes in T-wave travel time through the ocean can be used to infer deep-sea temperature variations, a method known as seismic ocean temperature (SOT) measurement (Wu et al. 2020). DAS has successfully observed acoustic T-waves generated by marine earthquakes (Ugalde et al. 2021). Shen and Wu (2024) conducted an observational experiment using two cables off the central coast of Oregon, namely ocean observatory initiative (OOI) North and OOI South. The experiment used two OptaSense QuantX demodulators, one Silixa iDAS demodulator, and one Silixa DTS device, collecting approximately 26 TB of data. Shen and Wu (2024) proposed a denoising scheme to enhance T-wave signals in DAS, successfully detecting small T-wave events hidden in the noise. They calculated the robustness of each dataset for different magnitudes by comparing the denoised OOI North data with data from the HYS11 OBS and OOI observatory data (Fig. 5). The results indicate that despite the significant impact of the ocean environment and instrument noise on its application in the SOT method, DAS performs comparably to traditional OBS and remains feasible for sea temperature measurements (Shen and Wu 2024).

7 Marine target monitoring

Monitoring marine targets aims to manage ocean resources, protect the environment, study climate change, ensure safety, and provide early warnings for natural disasters. Current monitoring methods include satellite remote sensing, uncrewed submersibles, ocean buoys, and underwater acoustic detection. DAS technology has now been applied to monitor ships and whales within the ocean (Landrø et al. 2022). DAS can distinguish different frequencies of whale calls, thereby identifying various whale species.

Bouffaut et al. (2022) first used a dark fiber located 120 km from the Svalbard Islands in Norway for wildlife monitoring, recording baleen whale signals at three distinct positions on the fiber (Fig. 6). Their research indicated that DAS has the potential for real-time, low-cost monitoring of whales globally.

Rørstadbotnen et al. (2023) collected DAS data from two 250-km long cables off the central coast of Oregon, recording numerous whale sounds and ship noises.
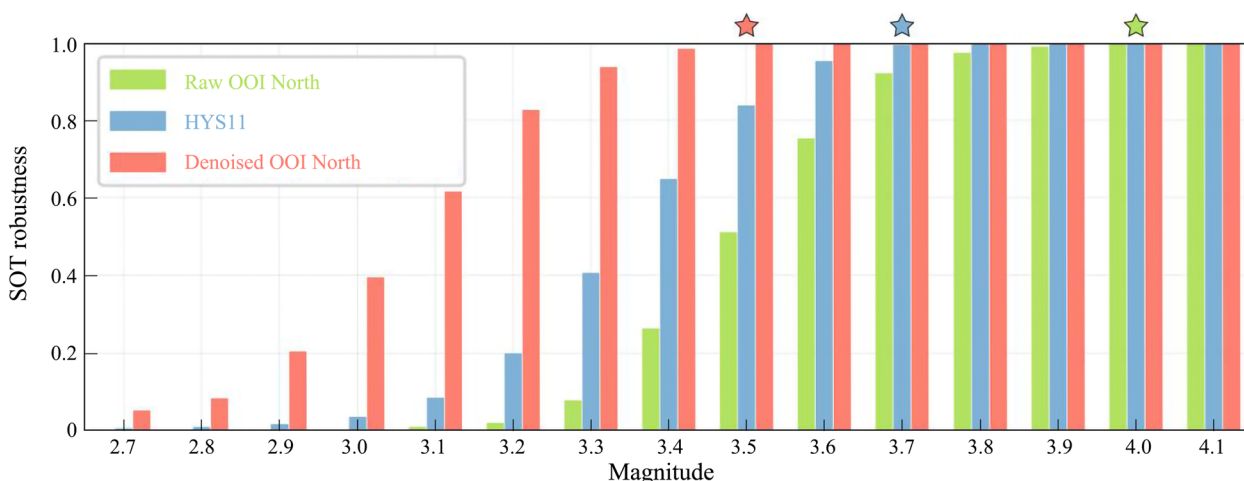
Fig.5 Schematic diagram of the performance comparison between DAS and OBS proposed by Shen and Wu (modified from Shen and Wu 2024). SOT robustness using HYS11 data, raw OOI North data, and denoised OOI North data, as a function of earthquake magnitude
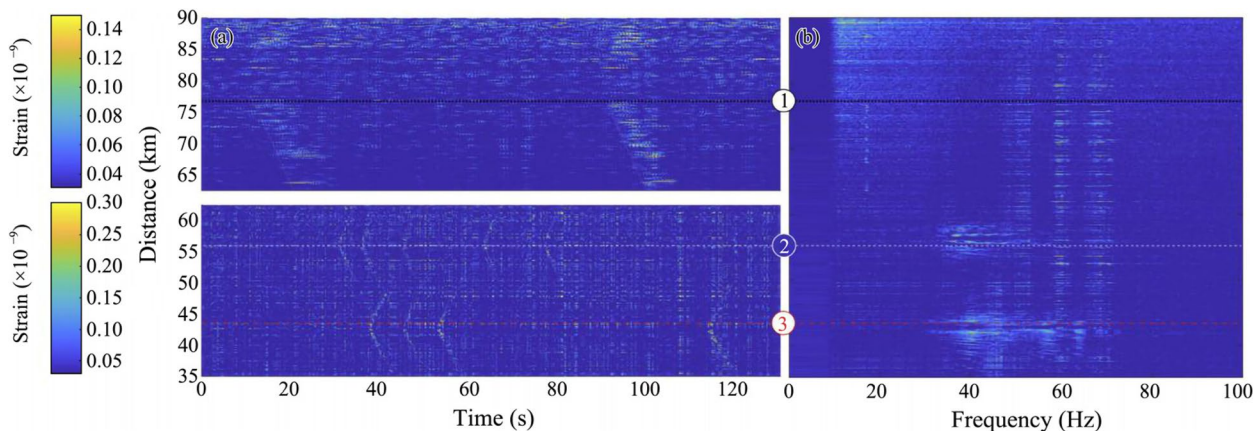
Fig.6 Baleen whale vocalizations recorded by Bouffaut et al. (2022) using the Svalbard DAS array at three distinct locations (44.2 km, 57.5 km, and 76.5 km from the fiber-optic cable). **a** Spatio-temporal (*t-x*); **b** spatio-spectral (*f-x*). (Modified from Bouffaut et al. 2022)

They applied DAS data to both brute force grid search (GS) and Bayesian filter (BF) methods and compared the results. Their study showed that both methods had localization errors of approximately 100 m. In terms of whale track prediction, the GS method had a more dispersed position distribution, whereas the BF method had a smaller error compared to the GS method (Rørstadbotnen et al. 2023). Both methods demonstrate the feasibility of locating cetaceans within an area of approximately 1800 m^2, highlighting the potential of DAS for marine target monitoring.

8 Summary and outlook
This work systematically reviewed the applications of DAS technology in marine geophysics and its equipment parameters. Significant achievements of DAS technology have been reached in various fields, such as marine

seismic monitoring, tsunami and ocean-current monitoring, ocean thermometry, marine target monitoring, and ocean-bottom imaging. In the field of seismic monitoring, the high sensitivity and wide coverage of DAS technology have significantly improved the precision and efficiency of deep-sea ambient-noise analysis and oceanic microseismic source location while promoting related research. It is now possible to perform in-situ monitoring of ocean currents during extreme weather. Marine target monitoring, especially locating marine organisms, has also seen practical applications. The feasibility of DAS in tsunami warning, sea temperature measurement, and subsea imaging has also been verified, highlighting the potential of DAS to produce groundbreaking results in these fields.

As DAS technology research has continued, the equipment has seen significant improvements in deployment under various extreme environments, with

Wei *et al. Intelligent Marine Technology and Systems*　　(2024) 2:26

Page 9 of 10

advancements in deployment distances and spatial resolution. However, the application of DAS-related equipment and technology in marine geophysics is not yet fully mature and faces many challenges. In the future, DAS technology for marine regional observation networks will develop in various fields. To further improve the performance of DAS technology, research should be conducted in two areas as follows:

(1) Cable deployment. The weak coupling of cables to the seabed during deep-sea cable deployment because of terrain variations can affect the resolution and SNR of DAS in local areas. This issue can be addressed by increasing the coupling medium between the cable and the seabed or by improving cable deployment techniques.

(2) Data processing. As the length of seabed cable deployment increases, efficient management of DAS data while maximizing the use of dark fibers and active communication fibers is a key issue for the future. Currently, there are data processing programs like DASPy and DASCore, as well as open-source repositories like PubDAS (Spica et al. 2023). There is not yet a systematic processing method for the massive data generated during the DAS data transmission process. Artificial intelligence can be combined with DAS for data preprocessing and denoising, such as the N2N method for signal denoising using machine learning (Lapins et al. 2024).

After improving the quality and reliability of DAS data, standardization and popularization will lead to large-scale regional deployment. These advances will increase the applications of DAS technology in marine geophysics, providing dedicated support for future marine scientific research and disaster warnings.

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Authors' contributions
Jiayi Wei and Junhui Xing: responsible for the research design, literature collection and screening, and drafting of the manuscript. Wende Gong and Haowei Xu: mainly in charge of revising and editing the manuscript.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Informed consent for publication was obtained from all participants.

Competing interests
The authors declare that they have no competing interests. Junhui Xing is one of the Editorial Board Members, but he was not involved in the journal's review of or decision related, to this manuscript.

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