Eavesdropping at the speed of light: distributed acoustic sensing of baleen whales in the Arctic

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Keypoints:

- This is the first case of wildlife monitoring using Distributed Acoustic Sensing (DAS).
- DAS has the ability to record and localize vocalizing baleen whales in 3D and so to provide fully passive conventional seismic records.

Abstract

In a post-industrial whaling world, flagship and charismatic baleen whale species are indicators of the health of our oceans. However, traditional monitoring methods provide spatially and temporally undersampled data to evaluate and mitigate the impacts of increasing climatic and anthropogenic pressures for conservation. Here we present the first case of wildlife monitoring using distributed acoustic sensing (DAS). By repurposing the globally-available infrastructure of sub-sea telecommunication fiber optic (FO) cables, DAS can (1) record vocalizing baleen whales along a 120 km FO cable with a sensing point every 4 m, from a protected fjord area out to the open ocean; (2) estimate the 3D position of a vocalizing whale for animal density estimation; and (3) exploit whale non-stereotyped vocalizations to provide fully-passive conventional seismic records for subsurface exploration. This first example's success in the Arctic suggests DAS's potential for real-time and low-cost monitoring of whales worldwide with unprecedented coverage and spatial resolution.

Keywords: Distributed acoustic sensing, bioacoustics, Passive acoustic monitoring, Baleen whales, Cetacean conservation, Blue whale, Fin whale.

Plain Language Summary

Slowly recovering from industrial whaling, large whales such as blue and fin whales are considered threatened or critically endangered. Simultaneously, they face climate change and the augmentation of human maritime activities. Their conservation requires global and reliable monitoring efforts. Using whale sounds to study habitat use, map migration patterns, assess stock, evaluate and mitigate human impacts is a well-established practice. However, because dedicated acoustic recorders are relatively costly to deploy and maintain, they are still sparse, causing spatial and temporal monitoring gaps.

Taking roots in an experiment conducted at the doorstep of the Arctic, we introduce distributed acoustic sensing (DAS) for wildlife monitoring. This technology converts already-set fiber optic telecommunication cables into ultra-long acoustic arrays without additional infrastructure costs. We recorded data along 120 km of fiber optic cable, with a sensing point every 4 m. Here, we demonstrate the possibility to record, detect, localize and track large whale sounds using DAS. Furthermore, we show that the array's unique spatial resolution enables new applications such as under-seafloor imaging using a single whale call.

More than 1.2 million km of fiber-optic cables are installed all over the world's oceans. Converted into DAS, it has the potential to revolutionize acoustic-based marine mammal conservation.

1 Introduction

While slowly recovering from industrial whaling, many baleen whale species (*Mysticeti*) [5]) are still threatened or critically endangered [23]. Simultaneously, these animals and their vast ocean habitat are subject to an increasing number of stressors driven directly or indirectly by anthropogenic activities, e.g., entanglement in fishing gear, ship strikes and noise pollution associated with the global increase of ship traffic. Additionally, alteration of water and nutrient cycles by plastic and chemical pollution affect the entire food webs [51]. Climate change has further forced cetaceans to adapt their migration routes (or their timing). Globally, many species shift poleward to their preferred sea-surface temperature [53].

In the Arctic, the climate is changing faster than anywhere else in the world. This has been linked to major shifts in species distributions related to sea-ice loss and the Atlantification of the region [18]. In the high latitudes of the Svalbard archipelago, boreal species e.g., blue whales (*balaenoptera musculus*), fin whales (*balaenoptera physalus*), humpback (*megaptera novaeangliae*) and sei whales (*balaenoptera borealis*), have been considered seasonal residents, traditionally present from late spring/early summer to the autumn and spending their winters at lower latitudes [36]. Recently however, fin whales have been observed year-round [26, 31]. Furthermore, with sea ice-loss came an increase in human activities. While ship traffic is already abundant between the Barents and North sea and Svalbard [16, 43], it will likely intensify in species rich areas [18] with the new cross-Arctic shipping routes [37]. Airgun signals can already be recorded all-year round close by, in the western Fram Strait [1]. It is urgent to establish a baseline of the environment's exposure and marine mammal vulnerability to these anthropogenic stressors to mitigate their impacts, which requires first, monitoring.

From fixed autonomous archival recorders to moving near-real-time multi-sensory platforms [6, 35], passive acoustic monitoring has proven to be a reliable and suitable mean for baleen whale studies [21]. However, it is still relatively expensive to deploy conservation-focused hydrophones and despite the research community's global efforts and the exponentially increasing amount of data collected world-wide [27], recorders are sparse and unevenly spread: the oceans are under-sampled [1, 2, 16, 18].

Meanwhile, Distributed Acoustic Sensing (DAS) has started to conquer many fields both at sea [20] and on land [41], with exponential progresses in terms of data quality, spatial coverage and bandwidth [41, 54]. Using an interrogator, DAS technology re-purposes existing dark fiber optic (FO) cables to record nano strain [14] and has the potential for real-time monitoring over hundreds of kilometers with a spatial resolution of a few meters [17, 54]. Initially applied to geophysical data collection [15, 20, 41, 47], DAS has recently aroused interest with waterborne sound sources, e.g., near-surface ship detection and bearing in the Mediterranean sea [44] and, data quality assessment using controlled airguns sources compared to ocean bottom seismometers recordings in Japan [32] and with seismic streamers in Norway [50] showed similar capabilities in terms of frequency response and signal to noise ratio (SNR). This article demonstrates the untapped potential of DAS for baleen whale monitoring.

Data was acquired during summer 2020 around Isfjorden, Svalbard, Norway, at the doorstep of the Arctic (Fig. 1). At that time of the year, sighting and a previous acoustic study around the archipelago demonstrate the consistent presence of blue, fin and humpback whales, and possible presence of sei whales [2, 18, 38]. Data used in this work is available [9].

2 Results and Discussions

2.1 Experimental Setup

We re-purposed a dark fiber (SMF-28 single mode silica), i.e. a spare fiber in an existing Uninett submarine telecommunication cable connecting Longyearbyen to Ny-Ålesund in Svalbard, Norway (Fig. 1 (a)). To minimize the cost of installation, it is common practice to lay spare fibers in communication cables. The fiber, trenched 1 to 2 m into soft sediment, followed the seafloor bathymetric variations. The Longyearbyen end of this cable was connected to an Alcatel Submarine Networks OptoDAS interrogator. The interrogator injects linear frequency-modulated optical pulses which are back-scattered by anomalies in the fiber [54]. Then, for each sampled position along the fiber, further named channels, it calculates the time-differentiated phase change of the back-scattered response from consecutive sweeps over a section of the fiber, indicated by the gauge length. The delay is converted into longitudinal strain for the corresponding fiber section [19]. Normal signal decay along the fiber 0.2 dB/km. The maximum length of fiber L that can be converted to DAS is mostly constrained by the chosen sampling frequency f_s such as $L = \dfrac{c}{2nf_s}$, with $c = 299792458$ m/s the speed of light in the fiber and $n = 1.4667$ the group refractive index of the fiber. For example, more than 9 km can be converted to DAS if $f_s = 10$ kHz.

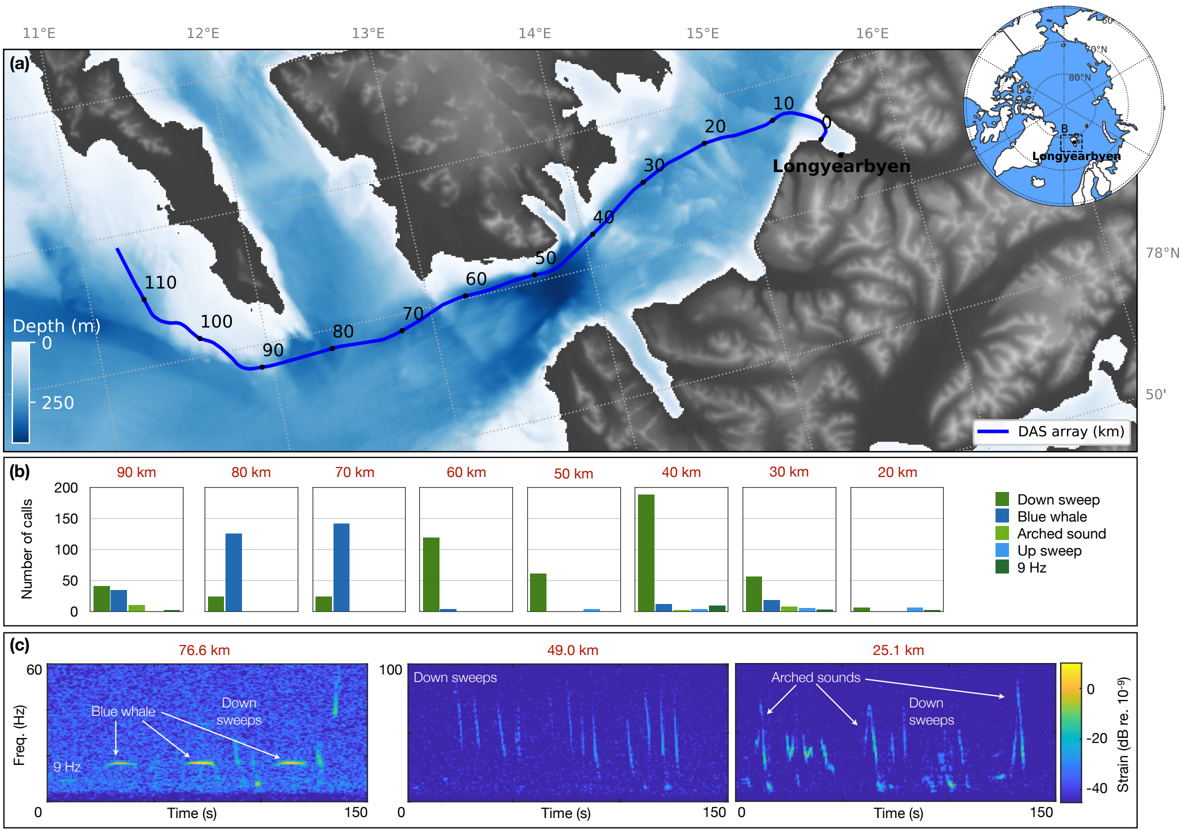

Figure 1: **Baleen whale vocalizations detected over the 120 km of the Svalbard underwater distributed acoustic sensing (DAS) array.** (a) The DAS is trenched on the seafloor of Isfjorden out to the open sea, bypassing the South of Prins Karls Forland in Svalbard, Norway. The interrogator end of the fiber is located on shore in Longyearbyen, recording data with a spatial sampling of 4.08 m at a sampling frequency of $f_s = 645.16$ Hz between June 23$^{\text{rd}}$ and August 5$^{\text{th}}$, 2020. Number (b) and examples (c) representative of the diversity of baleen whale vocalizations detected along the DAS during the entire recording period. Associated sounds are available in supplementary material Audio S1-S3.

In this experiment, 120 km of fiber were converted into a DAS array, heading out the open ocean from Longyearbyen, through Isfjorden. We used light pulses of 1550 nm free-space wavelength with a duration of 100 μs to sample 30000 channels with 4.08 m spacing, covering more than 120 km. The gauge length used was 8.16 m. The signal strength decays along the cable such that the returned signal strength from 100 km is $\simeq -40$ dB with respect to 1 km. Data is streamed from Svalbard to NTNU in near-real-time via the Uninett network by using the 1 Gbit/s network interface on the Alcatel interrogator. The DAS data was continuously sampled over 44 days, between June 23$^{\text{rd}}$ and August 5$^{\text{th}}$, 2020 and streamed over Uninett's research network to NTNU in Trondheim, where they were recorded at 645.16 Hz, providing just over 300 Hz of bandwidth. In the remainder of the article, we refer to the distance along the FO cable from shore as simply *distance*, as illustrated on Fig. 1. Due to the nature of the coupling of acoustic stress to FO cable strain, the FO cable has a sensitivity that varies with the gauge length, the frequency and the angle of arrival between the sound source and the receivers. A notch in the impulse response of the fiber can be observed for perpendicular arrivals [50].

2.2 Acoustic Data Analysis

A sparse visual and aural inspection of the data revealed the presence of different known baleen whale low-frequency signatures along the fiber (Fig. 1 (b&c) - Supplementary Audio S1-S3). Of the 832 annotated calls, we identified 38% as North Atlantic blue whale stereotyped signals (AB call, peak frequency at 16.9 Hz; arched sounds, 9-Hz call) conforming to previous call descriptions [34]. They were recorded during the entire recording period with a higher number of calls detected after 20200723. In four instances, sightings from whale-watching tours confirmed the presence of a blue whale in the area. Down-sweeps (peak frequency 45 ± 15 Hz, average duration 5.4 ± 2.4 s) were the most common calls (60% of the annotations) and can be attributed to blue whales (D-calls), fin whales (D-calls or pulses), but also sei whales [38, 40, 52]. Note that the detection range (maximum distance at which a call can be detected) is frequency-dependent and vary between a 2-5 km cross-line distance from the fiber.

Blue whale low frequency stereotyped calls were mostly recorded outside Isfjorden, between 70-90 km while non-stereotyped down-sweeps were detected in higher numbers in the more sheltered waters of the fjord. The former have been associated with male vocal behavior while the latter can be produced by all male, females and calves and have been associated with group social or foraging contexts [39]. The spatial distribution of these two call types indicates potential variation in habitat use in the monitored area. The call abundance has good overlap with sighting-based models that demonstrate the increasing importance of Isfjord as habitat for large baleen whales in Svalbard [49].

The spatially distributed observations provided by DAS add a new dimension to the previous (and ongoing) passive acoustic monitoring of baleen whales in Western Svalbard [2], highlighting potential variations at an unprecedented scale. However, in regard to the amount of data recorded i.e., almost 7 To a day during our experiment, there is a need for big-data processing methods to scan through, detect and classify vocalizations and improve species identification especially in heterogeneous call types such as down-sweeps [40]. Resorting in occupation and presence maps to communicate with stakeholders to mitigate baleen whale exposure to anthropogenic activities.

2.3 Changing Perspectives: from Single Point to Distributed Sensing

One of the advantages of distributed acoustic sensing in comparison to typical single-point sensing is that it provides a continuity of measurement in both time and space, which requires "new" representation of the data. A common representation in the geophysical community is to use spatio-temporal representation or f-x plots, showing variations in the strain along the FO cable [48].

The low-frequency whale vocalizations (< 100 Hz) are transient acoustic signals emitted in the first tens of meter of the water column and observed on a very long array, the Svalbard DAS FO cable, that is trenched in the bottom of fairly shallow water < 400 m. Therefore, signals will be received only on limited portions of the array, with time delays corresponding to the difference of travel times between the source and the many receivers (channels). These time delays are inherent to the source-receivers configuration and reveal the position of the source.

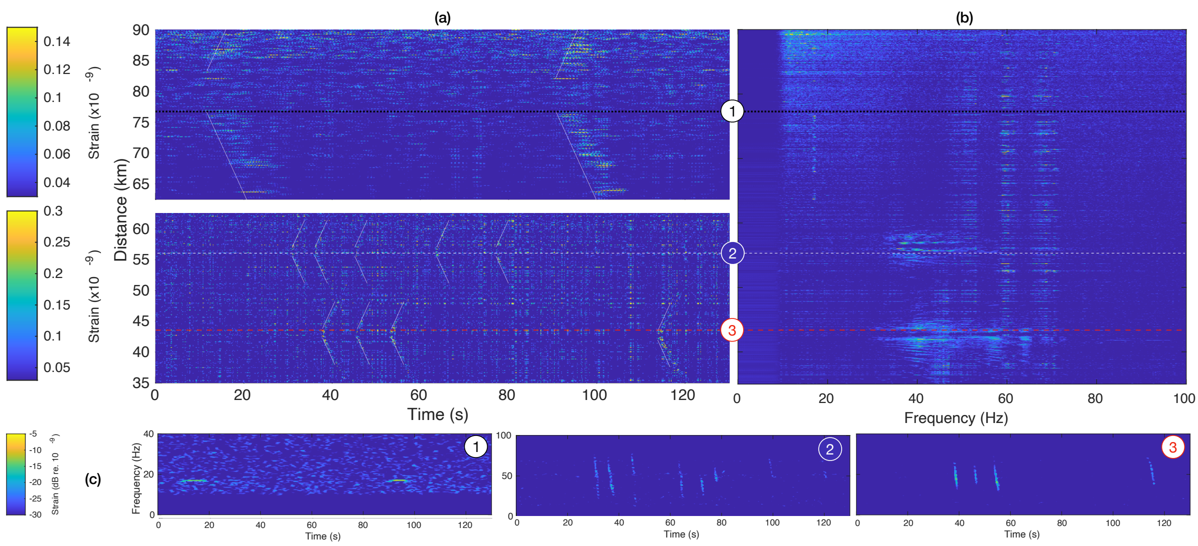

Figure 2: **Vocalizing baleen whales recorded simultaneously at three different locations along the Svalbard fiber optic DAS array.** (a) Spatio-temporal (t-x), (b) Spatio-spectral (f-x) and (c) Spectro-temporal (spectrogram) representations of a 130 s-long portion of recording from 20200627 at 052440UTC, between 35-90 km of fiber. Each whale position (around 76.5 km, 57.5 km and 44.2 km) is given a number between 1-3, to facilitate between panel associations.

Fig. 2 present 180 s of recording on 20200627 at 052440UTC, between 35 and 90 km of the Svalbard DAS FO cable. It reveals the presence of at least 3 individuals at different locations along the cable, indicated by the dashed lines and numbers. Fig. 2 (a) is a spatio-temporal representation of the strain measured along the FO cable, in absolute value and separated around the mouth of the fjord at 62.25 km. To enhance the contrast, the signal out of the fjord (62.5 – 90 km) is band-pass filtered in the frequency domain between [16.7 – 17.2] Hz in (a), highlighting the contribution of North Atlantic Blue whale stereotyped signals while it is bandpass-filtered between $[30 - 43]$ Hz to enhance down-sweeps inside the fjord ($35 - 62.5$ km). Spatio-temporal representations highlight the time delays on the received signals as hyperbolic wavefront arrivals, whose apex indicate the point on the FO cable closest to the source. Lines with a 1500 m/s slope are added to (a) to highlight the received signals. For example a 16.9 Hz North-Atlantic blue whale signal is received on all represented channels outside the fjord (a), on more than 27 km. The apex indicates that the vocalizing individual is closest to channels at $\simeq 77$ km. The received strain amplitude decay is not constant along the fiber which can be interpreted as (1) DAS directivity & coupling between the fiber and seafloor [32, 50], (2) Coherent interferences in the wavefield due to a near-surface source (Lloyd's mirror effect) [10, 11], (3) Upward refracting trends in arctic waters sound propagation, with potential shadow zones [24]. In the fjord, the down-sweeps are recorded over more than $\simeq 5$ km around the apexes, indicating two distinct vocalizing positions around 57 and 44 km. Fig. 2 (c) are spectrograms of the strain content recorded at 76.54, 57.46 and 44.22 km (Distances represented by the dashed lines form matching numbers), averaged over 2 juxtaposed channels (4.08 m apart) for noise removal and displayed in dB re. 10^{-9}. Channels for computing the spectrograms (c-d) are chosen near to the apex to maximize the received amplitude.

Different features are considered to identify the calling species such as the rhythmic or inter-call intervals, the intensity or received levels, the contours in the time-frequency domain. However, for baleen whales, a decisive characteristics is the spectral content of the signal [33, 56]. We therefore propose a spatio-spectral representation of the DAS recordings or f-x plot, as employed in [44], to show the spectral signature and its evolution against the distance. An animation, showing the successive 2-s f-x plots is available in supplementary material Video S4 while the integrated representation, over the 130 s of recording is displayed in Fig. 2(b) with a time window duration of 2-s and 4096 samples fast Fourier transform, resulting in a f-x matrix with a frequency resolution of 0.16 Hz. For the three distances along the FO cable where signals were emitted, the measured bandwidth gives an indication on the species: for example the clearly tonal signals around 70 km can be easily identified as Blue whale stereotyped call. In the two other locations, they cover a wider band, between $35 - 60$ Hz around 57 km (whale 2) and wider $30 - 70$ Hz around 42 km (whale 3). The received signals also show pattern of multi-path coherent interferences (e.g., notches on signals coming from whale 2), modulated by the FO cable reception sensitivity null.

Fig. 2 reveals the full potential of DAS: it can simultaneously record vocalizing individuals over tens of kilometers from a protected fjord area out to the open Ocean, despite varying noise conditions. In addition to the change of environment, the increase of background noise along the length of the FO cable is due to the attenuation of the optical interrogation pulses. It can also be the effect of changes in the coupling between the FO cable and the seafloor [32]. For quality and sensitivity assessment, calibration hydrophones could be temporarily installed close to the DAS array. It would enable the estimation of the seafloor's young modulus and the conversion of the measured strain into acoustic pressure, providing regional scale calibrated measurement of ambient sounds. The spatial distribution inherent to DAS also opens localization and near-field beamforming possibilities (Sec. 2.4).

2.4 Localization, Tracking and Beamforming

The localization problem is seen as an optimization process, that aims to find the best match between measured and theoretical time difference of arrivals (TDOA), estimated for different source position (varying closest FO channel and range). Successive positions are linearized for individual tracking and the time delay information is used for near-field beamforming. The localization, tracking and beamforming method is illustrated on Fig. 3, using a long (more than 10 min) recording with noticeable movement of a blue whale. t-x plots of portion of the recording containing calls and corresponding beamformed signals are represented. The white line indicates the variation of the position of the whale, along the FO cable (x_w) in time, moving from 86.4 to 87.5 km with an apparent speed of 5.4 km/h. The estimation of the range was not as precise as x_w, with a maximum of 700 m and the closest calls emitted (between $420 - 520$ s) within a $\simeq 100$ m range. Considering the few number of points, no specific trend emerged so the beamforming is set for a 200 m range. The resulting spectrogram shows a combination of singular stereotyped unit and D calls, emitted in series, likely from the same animal.

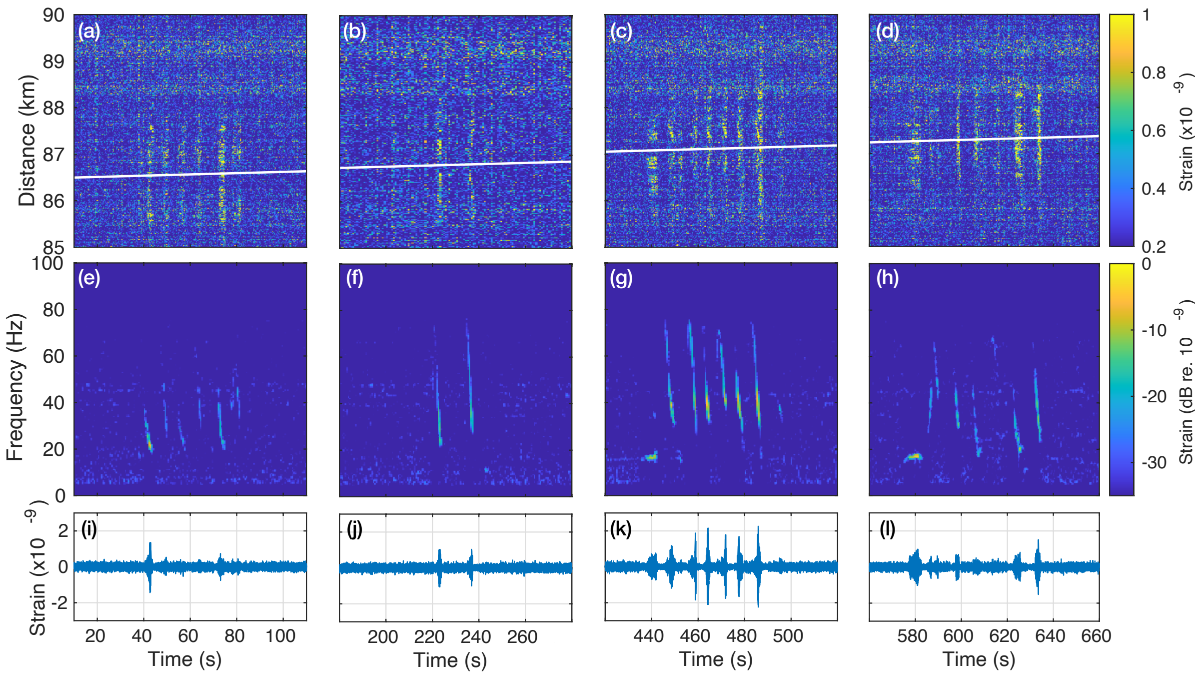

Figure 3: **Tracking and beamforming of series of blue whale calls recorded with a moveout on the Svalbard DAS array.** (a-d) Spatio-temporal (t-x) representations of the recorded observation where the white line indicate the tracking of the apex, beamformed signals' spectrogram (e-h) and waveforms (i-l), displayed as successive 100s-long windows. The audio associated to (c;g;k) is available in supplementary material Audio S5.

The estimated swim speed of 5.4 km/h is a minimum as the true value increases with the angle between the FO cable and the whale's trajectory. It is in the bounds of transiting swim speeds reported for blue whales on feeding grounds, between $2 - 8$ km/h[4, 22], and consistent with the behaviors associated to stereotyped singular unit and D-call vocal production [39].

The example on Fig. 3 demonstrates that whales passing over or near a FO cable can be detected and tracked. The information can subsequently be used, e.g., for counting individuals. Refining the range estimation will increase the resolution of the localization process but note that locally, FO cables are laid on the seafloor in straight lines, introducing a left/right ambiguity. At the experiment location, this issue could be solved by instrumenting another already-installed FO cable running parallel to the used FO cable, only a couple of kilometers away. More generally, localization improvements require a ground truth to calibrate and test algorithms. One option is to train them using ship acoustic signals and their automatic identification system (AIS) position [29, 44]. However, ship signals are continuous while whale calls are transient, which requires a different initial processing step. Another option is to use acoustic bio-logging with Global Positioning System (GPS) to combine rich information from calling individuals and their behavior to DAS observations [30, 39]. Fig. 3 also shows that the high SNR gain available from extended aperture array processing can be used to construct high-quality audio waveforms (e.g., Audio S5), which can be further use e.g. for subsurface exploration (Sec. 2.5).

2.5 Subsurface Exploration

Recent work demonstrated that recordings of fin whale vocalizations by seabed vibration sensors contain seismic responses to subsurface geologic structures [28]. The fin whale song produced by males is composed by series of repeated short and low frequency pulses that share similarities with airgun blasts [13, 55] and when produced at different locations (e.g., while traveling) in the vicinity of a single sensor, they can be used to for a common receiver song gather [28]. Concurrently, DAS has demonstrated its ability to produce seismic images of the subsurface geologic structures using conventional sources [50].

Fig. 4 displays correlated seismic profiles (a-b) and associated received interference pattern introduced by the sea surface (c-d; Lloyd's mirror effect [11]) obtained from two blue whale D-calls one inside Isfjorden (a-c) around 25 km of FO cable (Fig. 1 (c), last call) and the other around 87 km of FO cable (at 458 s on Fig. 3) in the passage between the mouth of the fjord and Prins Karls Forland named Forlandsundet Graben. The water depth at both location is $\simeq 260$ m explaining similar first arrival times (direct waves). The analysis and modeling of the interference patterns (c-d) show a good match for a $\simeq 20$ m source depth, in the bounds of reported values for blue whales [30, 39]. Specifically source depth and range are set at 15 m and 40 m for the call emitted inside the fjord (a) and 20 m and 110 m outside (b).

The correlated call profiles show direct waves, subsurface reflections, and strong water-layer multiple reflections, annotated on both panels. Comparing the sub-surface reflected waves at the two locations

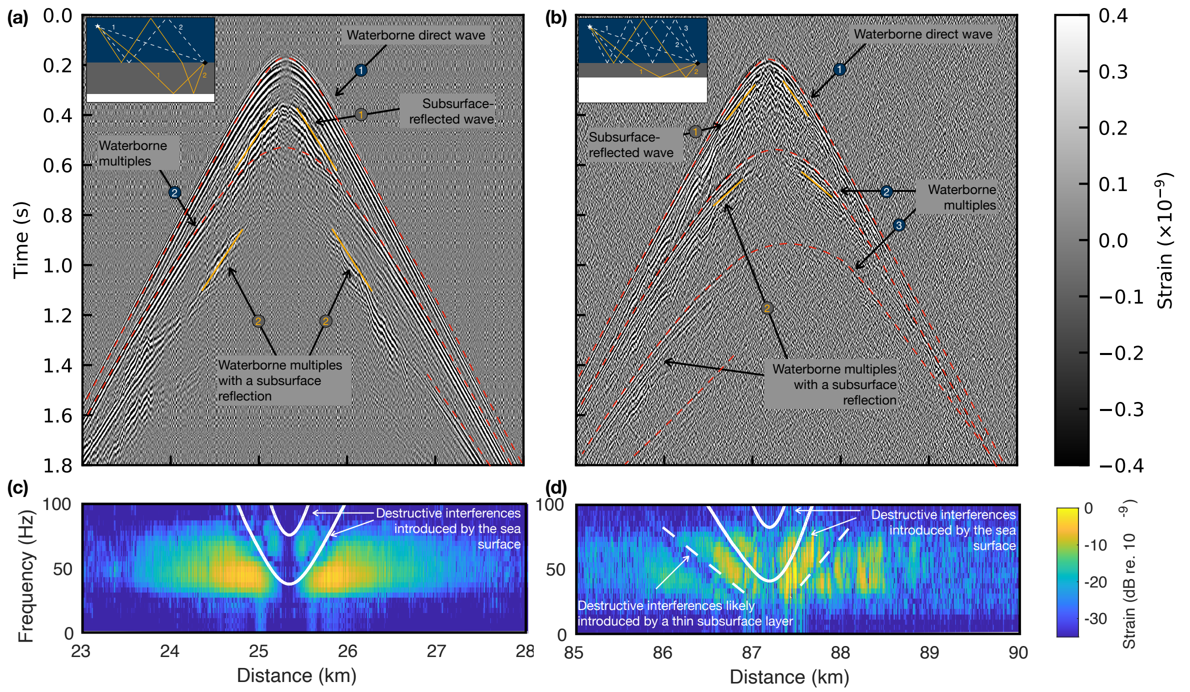

Figure 4: **Correlated seismic profiles from blue whale non-stereotyped calls.** Analysis a D-call (a;c) inside (last from Fig. 1(c, 25.1km)) and (b;d) outside (at 458 s on Fig. 3) Isfjorden. (a-b) correlated seismic profiles at different locations. Key seismic events are highlighted and described by schematic Earth's models in the insets. Observed and modeled interference patterns generated by (c) the sea surface (d) the sea surface and a thin sub-surface layer.

shows longer travel times in Isfjorden (a) than in Forlandsundet Garben (b), indicating a thicker shallow sedimentary rock layer in the fjord (see insets). The short-time subsurface reflections on the thinner layer of Forlandsundet Garben occur in the interference analysis window (110 ms), introducing additional lower frequency interference notches in (d). Two (a) and three (b) waterborne multiples are visible in the call profiles, indicating a higher stiffness of the seafloor in Forlandsundet Garben due to different surface geology, matching traditionally-obtained subsurface structural models [7, Fig. 5f] [3, 8] and reference seismic images [46, Fig. 47] for the area. Note that the subsurface primary reflection events observed in these two call profiles are reflected shear waves, which are probably corrupted by refracted shear waves from the same interfaces.

Fig. 4 demonstrates that each whale frequency-modulated call recorded by DAS can provide conventional seismic records for subsurface exploration. This example goes further than the proposal made by [28] to use stereotyped fin whale male song and uses non-stereotyped vocalizations such as D-calls, produced by all individuals in various baleen whales species [39, 40]. We show that in areas where vocalizing baleen whales and DAS overlap, seismic exploration could be replaced - at least partially - by an entirely passive method keeping the environment and ecosystems undisturbed and unharmed. Therefore, DAS could reduce human activities and anthropogenic stressors such as noise in the oceans.

3 Conclusions

More than 1.2 million km of fiber-optic cables are installed all over the world's oceans. We demonstrate through this work that, with tailored filtering, analyzing, and visualizing methods, DAS can provide data for all passive acoustic monitoring applications with an unequaled and unprecedented spatial coverage and resolution. As a result, we are on the brink of a revolution.

However, to reach its fullest potential, DAS demands big data handling methods and real-time processing along with efficient ways to scan through fast computed time-space-frequency representation of the data (the 120 km of FO cable sampled for this work generated 7 TB of data a day), process and detect potential signals of interest. Besides, while there is a trade-off between the length of cable converted to DAS and the sampling frequency, it is possible to monitor only a specific section of interest at higher frequencies, e.g., 9 km with a sampling frequency of 10 kHz, widening the variety of species recorded. In the future, DAS could be set with an adaptive frequency span: a relatively lower range for long-term and large-scale "standby" and a wider frequency coverage upon the detection of a signal of interest in a designated zone. Thus, DAS can comprehensively monitor ecosystems with unprecedented spatial coverage, contributing to filling up the worldwide monitoring gaps for conservation.

The final example demonstrated that the spatial resolution of DAS enables the generalization of unique passive acoustics applications such as subsurface exploration using whale calls and could contribute to reducing anthropogenic stressors on marine life. Therefore, DAS can help us study, preserve and protect the oceans.

4 Methods

4.1 Acoustic Analysis

The DAS-recorded data was exported as audio files every 10 km of the fiber, starting from 20 km offshore. The analysis was conducted using spectrograms at all locations in parallel and for the 42 days of recording by two independent and experimented analysts (H.J.K. & L.B.) using Raven Pro v1.6.1 [25]. Any potential whale call was then annotated with with a time-frequency contour and given a label.

4.2 Spatio-temporal Representation Conditioning

The data matrices (amplitude versus time and distance) are pre-processed to improve the Signal to Noise Ratio (SNR) and contrast in the spatio-temporal representation. In the following examples, the signal is first band-pass filtered before the application of a 3×3 symmetrical 2D median filter (resolution of 12 m/4.65 ms). Absolute values are used in the t-x representation. The median value is successively subtracted from each time and space sample of the absolute amplitude (median subtracted from each row and column).

4.3 Spatio-spectral Representation

The recordings are analyzed with a time window duration relevant to the minimum duration of whale calls. The frequency content is then calculated on each channel by a fast Fourier transform, constructing the f-x matrix. The median value is subtracted from each row and column for noise reduction. It is possible to generate an image for each time window. For a representation integrated over a longer time period, we used for each point of the f-x grid the difference between its maximum and average value in time.

4.4 Localization, Tracking and Beamforming

DAS receivers at the positions $R\{x, r = 0, z\}$ and whale position is at $S\{x = x_w, r = r_w, z = z_w\}$ where x is the position along the FO cable, r the cross-line range from the FO cable, z the depth and the subscript w stands for the whale. A grid of potential whale positions along the FO cable x_n and ranges r_m are established for the optimization problem, assuming a fixed calling depth $z_w = 30$ m [10, 30]. The source position is estimated by finding the theoretical TDOA that matches best the observed TDOA between all receivers an arbitrary chosen reference receiver position $R_0\{x_0, r = 0, z_0\}$ such as

$$\mathrm{TDOA}m, n = \frac{h_{n,m} - h_{0,m}}{c} \tag{1}$$

with $c = 1500$ m/s the constant sound speed, $h_{n,m} = \sqrt{|x - x_n|^2 + r_m^2 + |z - z_w|^2}$ where $|x - x_n|^2$ represents the distance between each receiver position and the tested position along the FO cable and $h_{0,m}$ is $h_{n,m}$ but for the reference R_0. The search grid used has a resolution of 50 m in x, within predefined 5 km bound around observed signal apexes ($[85 - 90]$ km) and a 20 m resolution in ranges, from $[0 - 4]$ km. Note, that the water depth is deeper than 300 m before 87 m and about 180 m at 90 km.

The t-x observation is sectioned in 5-s windows and band-pass filtered $[5 - 80]$. The 5-s-duration of the window allows to integrate the calculation over a period that is in the same order as the observed signals and, to cover potential time delays over the entire observed FO length. In the TDOA the apex gives information on x_w while the opening of the hyperbola gives information on r_w. The TDOA are estimated for each receiver position as the lags corresponding to the maximum of the cross-correlation between R_0 and the other receivers. Unrealistic values e.g. $|\mathrm{TDOA}| \geq$ observed FO length over c are discarded along with $|\mathrm{TDOA}| \leq 5$ ms.

The optimization process is performed in 3 steps. First, the initialization cross-correlates measured and theoretical TDOA, where the maximum outcome initializes $S\{x = x_w, r = r_w, z = z_w\}$. The process is ran a second time, after filtering out measurement points that diverge from the initialization fit of more than the standard deviation of the difference between the theoretical and measured data points. This second run gives the best x_w. A third step is added to improve the r_w estimation by minimizing the root mean square error between the theoretical and measured points, in a 1 km window around x_w.

To extend the single point localization to tracking, the localization procedure is applied iteratively to each 5-s window and only $S\{x = x_w, r = r_w, z = z_w\}$ points with a correlation coefficient higher than 0.85 are kept. The threshold is chosen to differentiate between signal and noise windows.

Once $S\{x = x_w, r = r_w, z = z_w\}$ known, time delays can be compensated to beamform the received signal. In practice, only the 10 receivers with the most energy are summed-up, to limit the influence of coherent destructive interferences.

4.5 Correlated Call Profiles and Interferences Analysis

It is possible to use frequency-modulated sweep signals from whales' vocalizations measured by the seabed DAS array in Svalbard for subsurface exploration. The used D-calls are $4-8$ s long down-sweeps, similar to the seismic signals from vibroseis [12], a commonly used source in land seismic exploration. Therefore, estimating the emitted signals is necessary to produce interpretable call profiles by cross-correlation with the recorded calls.

Each source signature is extracted from the DAS data using the previously described near-field beamforming method (stacking after time-delay compensation). The source signature derived from this method contains coherent interferences introduced by, e.g., the reflection with a change of phase at the surface, known as the Lloyd's mirror effect [11] or ghost effect. Finally, the interference analysis (Fig. 4) is performed on a short (110 ms) portion of the time-delay-compensated signal, chosen to include the waterborne direct arrival and the sea-surface reflection. The source depth is estimated from the frequency notches associated with the interferences patterns [10, 42] and information on the time of arrival of the sea-surface reflected wave given by the delay in the source signature autocorrelation.

The contribution of the interferences is removed by applying predictive (gapped) deconvolution [45] to the source signature, based on the estimated time delay information. Finally, to obtain a seismic profile, the DAS strain data associated with a whale call is cross-correlated with the corresponding deconvolved source signature.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

LB wrote the manuscript, read and approved by all co-authors. LB and HJK conducted the acoustic data analysis; LB designed and produced most of the results shown in the manuscript, interpreted together with HJK, ML and JRP. KT and ML produced and wrote about the subsurface exploration results and interpretation. LB, KT and RAR developed data handling and processing routines. ML, JKB, AH, SEJ, OS, and FS conceived the experiment, AH and FS collected the DAS data.

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Supplemental Data

1. Audio S1; Audio associated to the series of stereotyped North Atlantic blue whale calls and down-sweeps represented on Fig. 1(c) at 76.6 km, sped up 3.5 times;

2. Audio S2; Audio associated to the series of down sweeps represented on Fig. 1(c), sped up 3.5 times;

3. Audio S3; Audio associated to the series of non-stereotyped arched sounds and down sweeps represented on Fig. 1(c) 25.1 km, sped up 3.5 times;

4. Video S4; Animation showing the successive 2-s f-x plots used to construct the integrated representation of Fig. 2(b).

5. Audio S5; High-quality beamformed audio of the blue whale stereotyped and D-calls represented on Fig. 2.4(c;g;k), sped up 3.5 times.

Data Availability Statement

The DAS-recorded spatio-temporal strain data supporting this analysis is available at `https://doi.org/10.5281/zenodo.5823343` [9].

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