Distributed acoustic sensing recordings of low-frequency whale calls and ship noises offshore central Oregon

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Distributed acoustic sensing (DAS) is an optical technique that can measure strain changes along an optical fiber to distances of ~100 km with a spatial sensitivity of tens of meters. In November 2021, 4-days of DAS data was collected offshore on two cables of the Ocean Observatories Initiative Regional Cabled Array that extend offshore central Oregon. Numerous 20 Hz fin whale calls, northeast Pacific blue whale A and B calls, and ship noises were recorded. This data is publicly available to support studies to understand the frequency and spatial sensitivity of submarine DAS for low-frequency acoustic monitoring.

Keywords: Distributed Acoustic Sensing, Whale Vocalizations, Ship Noise, Fin Whale, Blue Whale, Submarine Cable

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1. Introduction

Low frequency sound within the oceans is generated by a wide number of physical, biological, and anthropogenic sources (Wilcock et al., 2014). These include the wind interacting with the sea-surface, the deformation of sea ice and icebergs, earthquakes, volcanic activity, baleen whale and fish vocalizations, ship propellers and machinery, seismic airguns and pile driving. Passive acoustic monitoring of the ocean soundscape is thus a useful tool to study a variety of processes and to understand the impacts of anthropogenic activities and changing climate on the ocean environment (Duarte et al., 2021). Since sustained hydro-acoustic observations are challenging and expensive to obtain offshore, there is strong motivation to explore new technologies that might enhance our ability to record and characterize sounds within the oceans.

Distributed acoustic sensing (DAS) is a relatively new observational technique that interrogates an optical fiber with repeated laser pulses and applies interferometry to the Rayleigh backscattered light to measure changes in strain along the fiber (Hartog, 2017). The method can work to distances of up to ~100 km and has a spatial resolution of meters and a broad frequency sensitivity. A DAS fiber optic cable behaves similarly to a long line of closely spaced single-axis broadband seismometers oriented in the direction of the fiber, although DAS measures the spatial derivative of ground velocity (i.e., rate of change of strain) rather than ground velocity (Hartog, 2017).

The spatial resolution of DAS measurements is termed the gauge length and is controlled by both the duration of the laser pulse and length of time over which each interferometric measurement is averaged. DAS data is commonly collected with a channel spacing that is much smaller than the gauge length. Increasing the gauge length decreases spatial resolution and the sensitivity to short wavelength strain signals but improves the signal to noise of the measurement and thus allows measurements to greater distance from which the backscattered light is more attenuated. The temporal resolution is limited by the two-way travel time of light along the fiber because there should be no more than one light pulse in the fiber at once. For example, for a 100 km long fiber, the maximum laser interrogation rate is ~1000 Hz. If the sampling rate is at least a factor of 2 lower than the maximum laser interrogation rate, then successive interrogations can be combined to increase signal to noise.

Within industry, DAS has been used for a decade to collect vertical seismic profiles in boreholes (Mateeva et al., 2014). Within academia, DAS is now widely used for a variety of geophysical applications including earthquake studies, seismic imaging and glacier deformation, and it also has application in urban areas for anthropogenic noise sources (Zhan et al., 2019; Lindsey and Martin, 2021). On land, DAS observations can often take advantage of the extensive network of dark fibers that have been laid in urban areas and along transportation corridors to provide growth capacity for telecommunications. In the oceans, DAS experiments are more challenging because submarine telecommunications cables do not generally include dark fibers. Spare fibers in the nearshore portions of cables would be relatively cheap to add but they are of no use for telecommunications without the expensive optical repeaters that are necessary to transmit signals more than ~300 km.

In 2019, three studies documented the utility of submarine DAS for recording earthquakes and oceanographic signals using data from short tests of on the research infrastructure of the MARS cabled observatory in Monterey Bay (Lindsey et al., 2019), the MEUST deep sea cabled observatory in the Mediterranean off France (Sladen et al., 2019) and a cable in the North Sea off Belgium (Williams et al., 2019). This pioneering work has spurred a rapid growth in interest in submarine DAS including its applications to acoustics.

Rivet et al. (2021) showed that DAS could be used to track a tanker passing over the MEUST cable at water depths of both 85 m and 2000 m. Matsumoto et al. (2021) compared DAS and hydrophone recordings of airgun signatures using cable extending offshore Japan to >3000 m water depth. They found both systems were sensitive to airgun signals from 0.1 to tens of Hz although the DAS had lower signal to noise above a few Hz. A comparison of airgun recording between DAS on cable at 100-400 m depth and a towed hydrophone streamer in a shallow Fjord in Norway (Taweesintananon et al., 2021) showed similar noise levels on both systems. Working with the same data set, Bouffaut et al. (2022) present DAS recordings of baleen whales at frequencies up to nearly 100 Hz and demonstrated tracking for animals swimming near the cable.

In this paper, we present an overview of a 4-day public-domain submarine DAS experiment that was conducted on two cables extending offshore central Oregon (section 2), demonstrate the capabilities of DAS to recording hydro-acoustic signals (section 3) from fin whale calls (section 3.1), blue whale calls (section 3.2) and ship noises (section 3.3) and discuss the preliminary results and opportunities for future research with these acoustic signals (section 4).

2. OOI DAS Experiment

The Ocean Observatories Initiative Regional Cabled Array (Figure 1, inset) operates two submarine cables that land at Pacific City, Oregon (Smith et al., 2018). The northern cable runs ~500 km west to Axial Seamount while the southern cable extends ~150 km offshore onto the Juan de Fuca plate before wrapping around to the south and east onto the continental slope and shelf off Newport, Oregon. Both cables include a single twisted pair of optical fibers that support 10 Gbps ethernet to primary nodes on the trunk cables that connect via secondary cables and junction boxes to suites of sensors on the seafloor and on moorings.

From November 1-5, 2021, a scheduled shutdown of the RCA for maintenance provided an opportunity for a 4-day community fiber sensing experiment to interrogate the fibers in each cable extending out to the first optical repeaters, which are located at 1600 m depth 95 km along the south cable and at 600 m depth 65 km along the north cable (Figure 1). These nearshore sections of the cables are buried to a nominal depth of 1.5 m depth below the seafloor. On the south cable DAS data was collected on both fibers using an Optasense QuantX interrogator and a Silixa IDASv3 system. On the north cable DAS data was collected on one fiber with a second Optasense

QuantX interrogator while a Silixa ULTIMA SM distributed temperature sensor was deployed on the other fiber. The data has a total volume of 26 TB and can be accessed through a data repository hosted by the University of Washington along with information about the experiment configuration and data format (https://oceanobservatories.org/pi-instrument/rapid-a-community-test-of-distributed-acoustic-sensing-on-the-ocean-observatories-initiative-regional-cabled-array/).

Table 1 summarizes the DAS recording parameters. Although there were some intervals of recording at sample rates up to 1000 Hz and with gauge lengths down to 3 m, most of the data were collected with a sample rate of 200 Hz and gauge length of 30-50 m. These parameters were selected to ensure sufficient signal to noise to record to near the distal ends of the fibers.

TABLE 1. Summary of recording parameters for the OOI RCA DAS experiment. For each of the 3 DAS interrogators the table identifies the fiber used, the length of fiber interrogated, the channel spacing, the gauge length and the sampling frequency with the parameters only listed when they change.

	Optasense - north cable	Optasense - south cable	Silixa - south cable
Nov 1 (2-6 hours)	Testing various configurations	Testing various configurations	Testing on receive fiber of north cable
Nov 1-2	Transmit fiber 65.2 km 2 m channel spacing 30 m gauge length	Transmit Fiber 95 km 2 m channel spacing 50 m gauge length	Receive Fiber 80.6 km 2 m channel spacing 30 m gauge

	1000 Hz sampling	200 Hz sampling	length 200 Hz sampling
Nov 2-3	500 Hz sampling		
Nov 3-4	50 m gauge length 200 Hz sampling		40.4 km 1 m channel spacing 10 m gauge length
Nov 4-5			19.7 km 3 m gauge length 1000 Hz
Nov 5 (3 hours)	Receive fiber	Receive fiber	Transmit fiber 80.5 km 2 m channel spacing 30 m gauge length 200 Hz

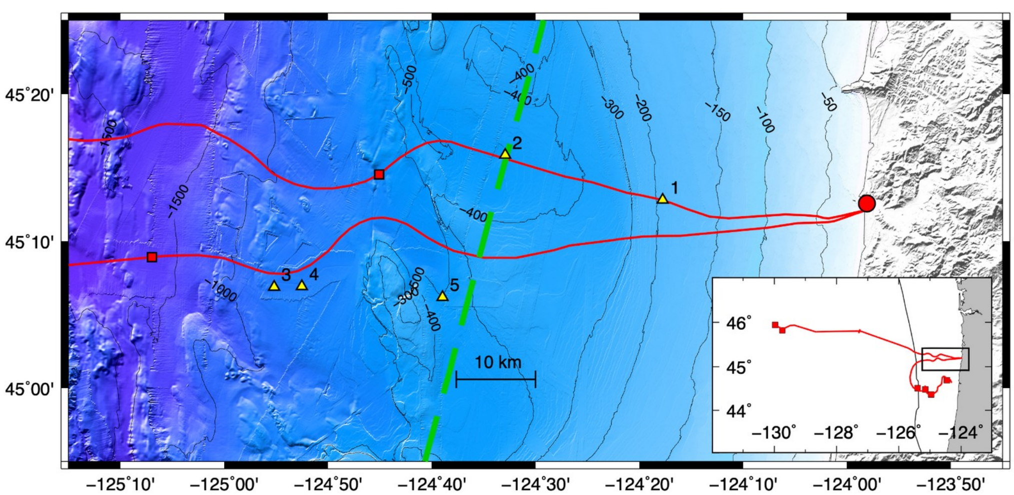

Fig. 1. Bathymetric map showing the nearshore portion of the two OOI RCA cables as red lines, the shore station as a red circle and the first optical repeaters as red squares. Also shown are the fin whale call locations obtained

by time difference of arrival for the data shown in Fig. 2c, f (numbered yellow triangles) and the northward track of the cargo ship for which data is shown in Fig 4 (bold green dashed line). Contours are labeled in meters and are unevenly spaced (50 m to 200 m depth, 100 m to 500 m depth and 500 m at larger depths). The inset map shows the geometry of the complete RCA cable with primary nodes on the cable as red squares, the area of the main figure as a black box and the base of the continental slope as a faint black line.

3. Results

The unfiltered DAS data (Fig. 2a) is dominated by the long period signals from ocean surface waves (primary microseisms) in shallow water and secondary microseisms in deeper water (Sladen et al., 2019; Williams et al., 2019) but acoustic signals are readily apparent when the records are filtered above ~10 Hz (Fig. 2b). Acoustic signals can be further enhanced by applying an *f-k* filter to remove signals propagating along the cable at less than the speed of sound (Fig. 2c)

2.1. Fin whale vocalizations

The experiment occurred during the breeding season for fin whales and songs of the stereotypical 1-s-long 20-Hz fin whale chirp are recorded throughout. Fin whale calls are observed everywhere along the cables except within about 10 km of the coast. Individual calls are observed out to distances of tens of kilometers, forming a characteristic V-shape in the record sections (Fig 2b-c, f). Spectrograms show that DAS records frequency content of calls with most songs characterized by a doublet pattern of alternating lower and higher frequency notes (Fig. 2d) that now dominates songs in the northeast Pacific (Wierathumeller et al., 2017). The recorded amplitudes are low at the location on the cable closest to the whale (Fig. 2e), as would be expected for a measurement that is sensitive to strain along rather than across the cable.

The fin whale calls can be located using time difference of arrival. Figures 2c, f show an example where vocalizations from 5 whales can be located at distances that range from 25 km to 75 km offshore and within no more than a few kilometers of one cable (Fig. 1).

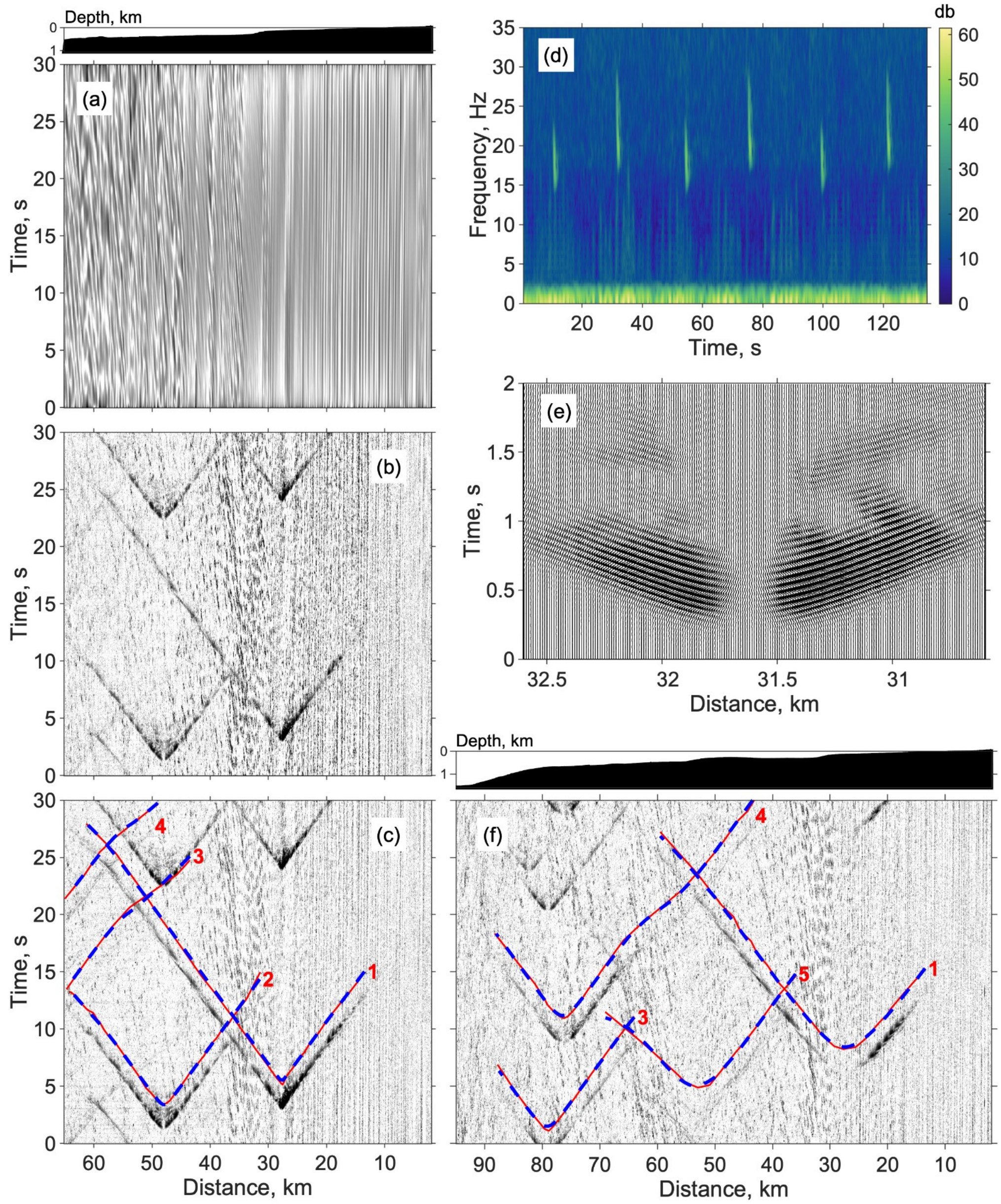

Fig. 2. Example of fin whale recordings (a) Record section beginning at 04-Nov-2021 02:00:27 UT, showing 30 s of unfiltered data recorded by the Optasense interrogator on the north cable. Distance from the interrogator is plotted on the horizontal axis and time is plotted on the vertical axis with the amplitude envelope shown by logarithmically scaled shading after normalizing each trace to its median amplitude. (b) As for (a) except after the application

of a 15-27 Hz bandpass filter. Fin whale arrivals are visible as dark shaded “V” shapes with the apex marking the location on the cable closest to the whale. (c) As for (b) but with a *f-k* filter to remove all energy with an apparent velocity along the cable less than 1.4 km/s. Manual picks of the fin whale arrivals (red solid line) and model times (bold blue dashed line) for a uniform velocity of 1.48 km/s are shown offset 2 s from the fin whale calls and are numbered to indicate the corresponding whale location in Fig. 1. (d) Spectrogram beginning at 02-Nov-2021 18:15:40 UT, for the Silixa interrogator on the south cable, averaged over 100 channels, showing 6 notes in a fin whale doublet song. (e) Record section beginning at 02-Nov-2021 18:16:54 UT, for the Silixa interrogator showing channels within ~1 km of the closest point to a fin whale call. (f) As for (c) but for the Optasense interrogator on the south cable.

2.2. Blue whale vocalizations

The calls of the Northeast Pacific blue whale were much less common during the experiment, but several sequences of the A and B calls are observed (Fig. 3) with the first 3 harmonics of the B call well recorded. In contrast to fin whales, blue whale calls are only recorded out to distances of ~10 km.

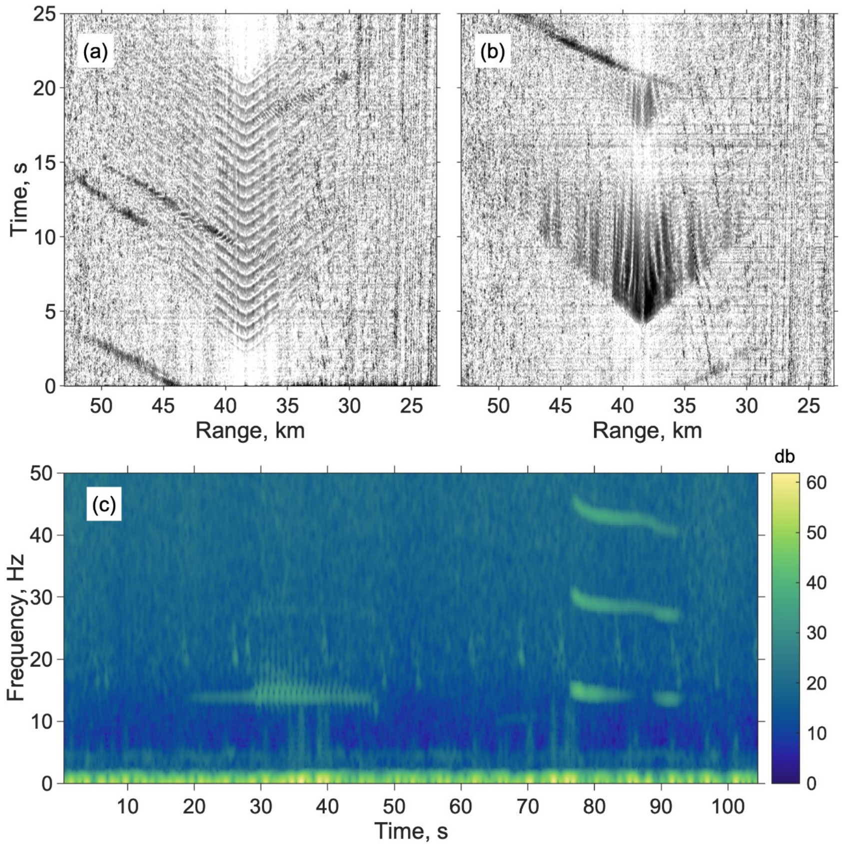

Fig. 3. Example of Northeast pacific blue whale recordings on the Silixa interrogator on the south cable. (a) Record section beginning at 02-Nov-2021 10:36:09 UT, showing an example of an A call with the closest location on the cable at a distance of 38 km. The A call is overlain by several higher amplitude fin whale calls. The data have been filtered with a 10.5-18 Hz bandpass filter and an *f-k* filter to remove energy propagating along the cable at less than 1.4 km/s. (b) As for a but showing a B call with record section beginning at 02-Nov-2021 10:33:36 UT. Frequency filtering has removed all but the first harmonic. (c) Spectrogram beginning at 02-Nov-2021 10:32:24 UT, averaged over 100 channels, showing an A call followed by a B call.

2.3. Ship Recordings

Figure 4 shows an example of ship noise recorded by the Optasense interrogator on both north and south cables. Using the Automatic Identification System (AIS) data, this ship was determined to be a cargo ship of length 180 m that passes above the cable with an approximate speed of 13.2 knots. The data have been filtered with a 10-90 Hz bandpass filter and an *f-k* filter to remove energy propagating along the cable at less than 1.4 km/s.

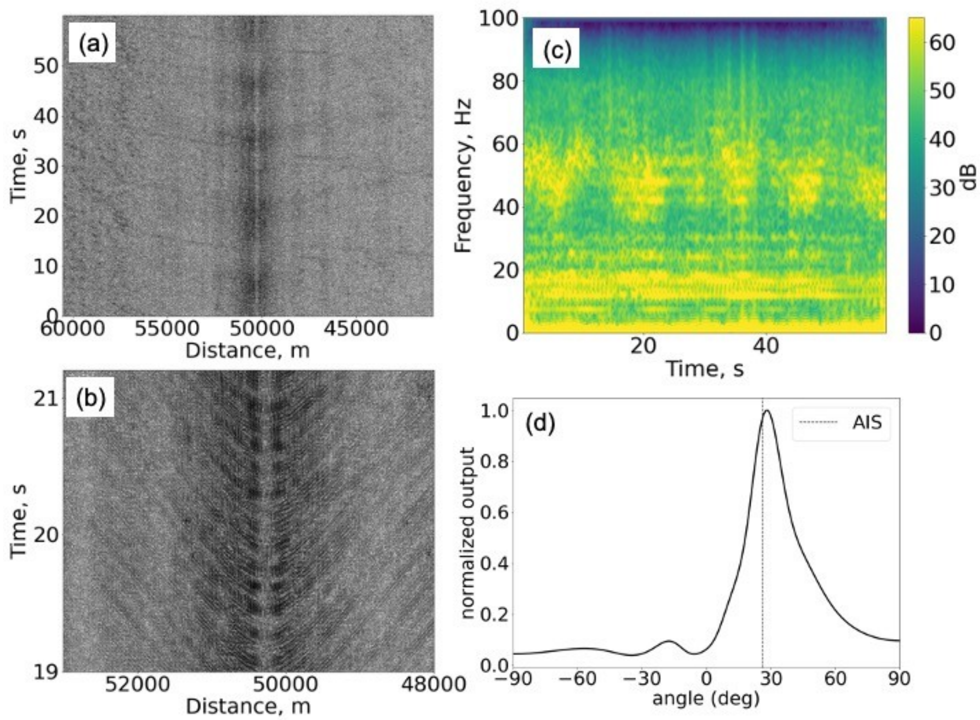

Fig. 4. Example of ship sound recording beginning at 03-Nov-2021 01:57:31 UT, traveling at 13.2 knots over both cables recorded by the Optasense interrogator with a sample rate of 200 Hz and gauge length of 50 m (a) Record section showing 60 s of a cargo ship sound with the closest location on the south cable at a distance of 50 km. (b) Record section showing channels within

~5 km of the closest point to the ship. (c) Spectrogram averaged over 100 channels, showing acoustic energy between 10-60 Hz. (d) Plane-wave beamformer output for the signal shown in (a) using a sub-array of the fiber optic cable consisting of 150 channels starting at 49.7 km. The estimated bearing is in agreement with the bearing calculated from the AIS data.

Compared to fin whale and blue whale calls, ship noises are recorded over a shorter distance (~5 km). The multipath interferences are noticeable in Fig. 4b which could be affected by the ship's motion over the cable, varying coupling of the fiber, different bathymetry along the cable, and fiber curvature. Similar to Fig. 2e, the recorded amplitudes are low at the location on the cable closest to the ship (at a distance of 50 km) which is due to the cable sensitivity to strain along rather than across the cable.

Plane-wave beamforming (Jensen et al., 1994) is used to calculate the bearing of the vessel relative to a 150-channel sub-array between 49.7-50 km. The beamforming output is maximum at 29.6 degree which is consistent with the bearing of 26 degree calculated using the ship location from the AIS data.

3. Discussion

The OOI community DAS experiment confirms earlier work which shows that buried submarine telecommunication cables can record low frequency acoustic signals. Numerous fin whale calls, blue whale calls, and ship noises were recorded to distances of up to ~40km, 10 km and 5 km, respectively.

An important question is why these detection distances differ. Studies suggest that the source levels for fin and blue whales are similar. Average values of 186 (Watkins et al., 1987), 189 (Wierathmueller et al., 2013) and 171 dB re 1 μPa at 1 m (Charif et al. 2002) have been reported for fin whales in the northeast Pacific, with the last estimate likely 10-15 dB lower due to the methodology (Wierathmueller et al., 2013). For the B call of the northeast Pacific blue whale, reported values are 180 dB (Thode et al., 2000) and 186 dB re 1 μPa at 1 m (McDonald et al., 2001). While the uncertainties in these estimates are consistent with fin whale calls being somewhat louder, such an explanation for the difference in the maximum detection distance in the DAS data, would be inconsistent with work using ocean bottom seismometers and hydrophones where blue whale B calls are detected to larger ranges (e.g., Wilcock and Hilmo, 2022).

The differences may be related to the frequency sensitivity of the DAS data. First, the optical fiber within an armored buried submarine cable may couple better to acoustical strain at lower frequencies. Second, DAS observations average strain changes over the gauge length and when this length approaches or exceeds the signal wavelength, the summed strain change measurements will experience aliasing, reducing the recorded amplitude. The blue whale B call has a significant amount of energy in higher order harmonics and particularly the 3rd harmonic at 40-45 Hz (Thode et al., 2000). The 35 m wavelength of the 3rd harmonic is similar to the 30-50 m gauge length so that at larger distances, when the call is propagating sub parallel to the cable it may be poorly recorded.

The reported source levels of commercial ships vary from 177-188 dB re 1 μPa at 1 m (McKenna et al., 2012; MacGillivray and de Jong, 2021) which suggests that ships have similar or slightly lower source levels than fin and blue whales. However, ships radiate acoustic energy in a broad frequency range that can go as high as 1000 Hz with most ships having significant energy to ≥100 Hz. (McKenna et al., 2012). The ship noises recorded in the OOI DAS experiment do not show acoustic energy above 60 Hz which again would be consistent with reduced sensitivity at higher frequencies as an explanation for the lower detection range.

Another potential explanation for differences in detection range could be the depth of the source. Ship propellers are located close to the surface while studies with acoustical tags show that fin and blue whales vocalize at depths of up to a few tens of meters (Oleson et al., 2007; Stimpert et al., 2015; Lewis et al., 2018). With warming ocean surface temperature, the mode excitation depths move deeper than the typical ship source depths and this can cause a reduction in the ship noise band spectral level (Dahl et al, 2021). Additional work is needed to understand the impact of speed of sound profile on the detection range of different sound source recordings on DAS.

The DAS sensitivity, as expected, is strongly directional with the recorded amplitudes of both whales (Fig. 2c) and ships (Fig. 4d) very low at the position of closest approach where the propagation direction is perpendicular to the cable. This effect is understood to be due to the cable-longitudinal strain rates being insensitive to plane acoustic waves at normal incidence. It also appears from the fin localizations that whales are only clearly detected on both cables which are spaced ~10 km apart, when the curvature of the cables results in the call propagating sub-parallel to both cables (e.g., locations 3 and 4 in Fig. 1 and the corresponding detections in Fig. 2c, f).

The OOI DAS experiment recorded tens of thousands of fin whale calls, which provide a remarkable data set both to investigate the directional and depth dependent acoustic sensitivity of DAS near 20 Hz and characterize the spatial distribution, depth of calling and behavior of vocalizing fin whales offshore central Oregon. One of the challenges of DAS is determining accurately the location of each channel, given uncertainties in the path of the fiber and the speed of light in the fiber. A joint inversion for the location of fin whale calls and DAS channels would serve as an analog to the tap tests used to locate fibers on land (Lindsey and Martin, 2021). The fin whale calls can also be exploited to study low frequency sound propagation with water column velocity structure potential including this as an unknown in inversions. Finally, beamforming approaches should be used to explore whether the DAS data can be used to detect fin whales at azimuths and ranges where they are not apparent in the filtered plots.

The acoustic signals from ships and whales recorded by the OOI DAS experiment with gauge lengths of 3, 10, 30 and 50 m (Table 1) can be used to understand frequency sensitivity of DAS at lower frequencies and its dependence on gauge length. Such work should motivate future experiments that deploy hydrophones near cables to ground truth recordings and that explore the utility of DAS to detect high-amplitude higher-frequency signals such as those from humpback or sperm whales.

DAS generates large data sets; extrapolating the OOI DAS experiment to continuous recordings would generate O~2 PB/year of data. To give a sense of scale, six months of data at this rate is about the size of the entire Incorporated Research Institutions for Seismology Data Management Center archive as of April 2022 (https://ds.iris.edu/data/distribution/). Managing such data volumes will require a variety of approaches. Further work is required to determine optimal channel spacing and to determine whether the 2m channel spacing used in the OOI experiment is justified by its scientific utility. Other approaches could involve a return to the triggered data acquisition paradigm common with seismic data before about the year 2000. A modern approach to triggered acquisition could leverage smart, potentially machine learning-based algorithms run in an edge-computing topology so as to only record signals of interest at high spatial and temporal sampling rates, while still defaulting to a lower rate data that would enable studies of the ambient field. Both lossy and lossless real-time data compression should be considered, and recent results have shown promise in this topic (Dong et al., 2022). The public domain OOI DAS data provides a resource to support the development of such approaches

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