Near Real-Time Passive Acoustic Mitigation Monitoring: Three Case Studies

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Contents

Abstract

Near real-time mitigation monitoring using passive acoustics is increasingly required for marine mammals surrounding industrial activities in the ocean. Furthermore, it is beneficial to understand not just whether marine mammals are present, but also where marine mammals are with respect to a given mitigation zone, to both minimize potential adverse impacts on the species of concern and determine what level of mitigation, if any, is required for the development activity. In response to this, SMRU Consulting developed a multi-channel autonomous passive acoustic monitoring system: the CAB (Communications Acoustic Buoy). Here, three case studies are presented. (1) *Pile driving*: CABs were used to

OPEN ACCESS with major support from JASCO APPLIED SCIENCES

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A. N. Popper et al. (eds.), *The Effects of Noise on Aquatic Life IV*,
https://doi.org/10.1007/978-3-031-94229-7_92-1

assess the extent of the modelled exclusion zone by providing real-time field measurements to expedite pile-driving construction and optimize bubble curtain mitigation efficacy. (2) *Offshore wind*: a playback study demonstrated that real-time whale localization information reduced delays in construction brought about by unrequired mitigative shutdowns, compared to non-bearing PAM systems. (3) *Dredging*: CABs successfully detected dolphins during dredging and spoil disposal to meet regulatory requirements alongside a port redevelopment. Across applications, CAB uptime exceeded 98% and the latency of audio clips, noise measurements, and detections were 95% <1.6 s, highlighting that near real-time PAM represents a powerful tool to reduce costs whilst enhancing regulatory compliance.

Keywords

Autonomous · Noise pollution · Marine mammal · Cetacean · Exclusion zone · Bearing calculation · Localization · Risk assessment

Introduction

Real-time mitigation monitoring is increasingly required for marine mammals surrounding industrial activities taking place in the marine environment. Activities such as pile-driving, dredging, and seismic surveying, amongst others, produce anthropogenic noise which can mask marine mammal communication and echolocation, lead to habitat exclusion, elicit behavioral responses, or cause auditory injury, and in extreme cases, death (Erbe et al. 2018; Southall et al. 2021; Hermannsen et al. 2025). Real-time monitoring alongside these activities provides the opportunity to pause activities if species of concern are detected nearby or if noise levels have reached a cumulative threshold (Baumgartner et al. 2018). Such monitoring can occur alongside or in lieu of a variety of mitigation options for reducing the levels of underwater radiated noise from industrial activities at sea, depending on the regulatory context. For example, should a species of concern be detected and this detection is transmitted in a timely manner, conservation actions efforts can be triggered, such as initiating immediate vessel slowdowns (e.g., as in Indeck et al. 2025). Similarly, air gun arrays for seismic surveying have triggered shutdowns when real-time quantification of the acoustic environment exceeded pre-defined behavioral response sound levels (e.g., as in Rutenko et al. 2022).

Exclusion zones, or mitigation zones, need to be managed so as to reduce the likelihood of disturbance to marine life, and are often used in offshore development context, across regulatory contexts, are thoroughly reviewed in Macrander et al. (2022). Importantly, the size of a mitigation zone and measures pertaining to a given mitigative context will vary according to the anticipated disturbance and marine species present there, which may consider their conservation status, as well as their life history, physiology, auditory capabilities, and behavior. In addition, developments are costly endeavors which sometimes require large exclusion zones over which monitoring is to be conducted, and so knowing not just whether a species is present, but whether the species is located within an exclusion zone can also serve as a cost-saving measure (Palmer et al. 2022).

There are various methods for monitoring mitigation zones including visual monitoring through the use of Marine Mammal (MMO) or Protected Species Observers (PSOs) who scan the sea surface with the naked eye or binoculars to detect the presence of marine mammals using sighting cues (e.g., dorsal fins, flukes, blows). However, visual observation efficacy can be hampered when visibility conditions are sub-optimal (e.g., in hours of darkness, large swells, high seas, fog, wind, rain, etc.) (Verfuss et al. 2018). Further, some projects require monitoring to take place over large exclusion zones for which visual observation alone is impractical. Often, for developments to complete their works on schedule, activities persist throughout hours of darkness and poor visibility, mandating mitigation monitoring in all conditions. While technologies for low-light conditions (e.g., thermal infrared cameras, RADAR) have demonstrated their effectiveness for marine mammal monitoring, this is not always suitable for the species of concern or the size of the area to be monitored (Verfuss et al. 2018). For example, if the species of concern rarely surfaces, or if exclusion zones are large enough to require multiple IR cameras, for example, to be deployed in a broad array, low-light monitoring technologies may be impractical.

A longstanding solution for marine mammal monitoring has been to use passive acoustics monitoring (PAM), which can log continuously, in remote places, and regardless of light conditions or weather (Baumgartner et al. 2018). PAM takes advantage of the fact that many marine mammals spend majority of their time underwater, and is suitable for frequently soniferous species. PAM can be used to monitor trends in both the soundscape and in species presence, and for monitoring changes in behavior or distribution as a result of at sea activities (Van Parijs et al. 2021). Broadband acoustic data can further be analyzed for the presence of other species, and to assess non-target anthropogenic sources (e.g., boat traffic) to facilitate evaluation of multiple stressors (Palagyi et al. 2024). The capabilities of real-time PAM have been noted as essential for mitigating potential effects from industrial developments, including offshore wind farms (Van Parijs et al. 2021; Palagyi et al. 2024). The need for measuring, monitoring, and mitigating noise impacts has repeatedly been demonstrated, and real-time systems that do so (e.g., Kahn et al. 2024; Troussard et al. 2023; van Toor and Beleza Vaz 2025) contribute to the safeguarding of species of concern and their habitats.

In response to industrial needs for around-the-clock and near real-time monitoring for marine mammals and their soundscapes, SMRU Consulting developed the CAB (Communications Acoustic Buoy). Here, "real-time" is defined as instances where sounds are received, processed (detected, classified, measured), transmitted, and received immediately, and *near* real-time as instances where delays are on the order of seconds and relevant for mitigative purposes. The CAB is an autonomous passive acoustic monitoring system with an onboard acoustic processing system running PAMGuard in near real-time. Automated detections and classifications of echolocation clicks and whistles/moans, as well as in situ noise measurements, are communicated in real time. In addition, CABs have three hydrophones, and using differences in the time of arrival of the same sound on different hydrophone channels, bearing information of marine mammal sounds can be calculated, allowing for location information of sounds of interest. This combination of readily available information allows for resulting mitigative actions to be timely and well-informed, supporting both science and conservation efforts.

This paper explores three real-world case studies of near real-time passive acoustic mitigation monitoring using CABs. This includes: (1) near real-time cumulative sound exposure level measurements during pile-driving to inform the sizes of zones needed to adhere to the Marine Mammal Protection Act for seals, (2) a demonstration on the efficacy in acoustically monitoring a large exclusion zone for endangered whales in the context of offshore wind construction, and (3) mitigation monitoring during a dredging campaign which partly overlaps with a Special Area of Conservation for dolphins. These case studies are used to discuss important considerations when customizing technology to best suit the opportunities and constraints of a given project and location.

CAB

CAB Set-up

Hardware

CABs consist of a moored lander, a communications buoy at the water surface, and a data cable connecting the two (Fig. 1). The weighted lander rests on the seabed. Trawl floats below the communications buoy provide distributed buoyancy, reduce entanglement risk, as well as work to decouple any surface wave action from tension on the lander below.

Three equidistant arms, all separated by 2 m, extend from the lander, each with a hydrophone. The hydrophones used are manufactured by HTI (High-Tech Inc, https://www.hightechincusa.com/). Depending on the acoustic frequencies of the sounds of the marine mammal of interest, various hydrophones have been used, for example HTI-96-Min hydrophones for applications with North Atlantic right whales (*Eubalaena glacialis*), and HTI-99-UHF hydrophones for applications with harbor porpoises (*Phocoena phocoena*). The hydrophones are connected to the instrument pressure housing in which sounds are processed (see "Software" section below). Inside the instrument housing is a Linux digital signal processor and data acquisition board. The instrument housing is connected to two lithium-ion battery housings (each 385 Ah at 16.8 V), allowing for variable deployment durations depending on the sampling frequency, software configuration, and duty cycling.

Data are transmitted up the vertically oriented, Kevlar-reinforced data and power cable (Falmat Xtreme-Cat-5), to the communications buoy at the water's surface. Data from the communications buoy are transmitted either via a radio transmitter (as in Palmer et al. 2022, and as in *Piling* example below), by cell mobile network via cell modem (as in the *Dredging* example below), or by satellite.

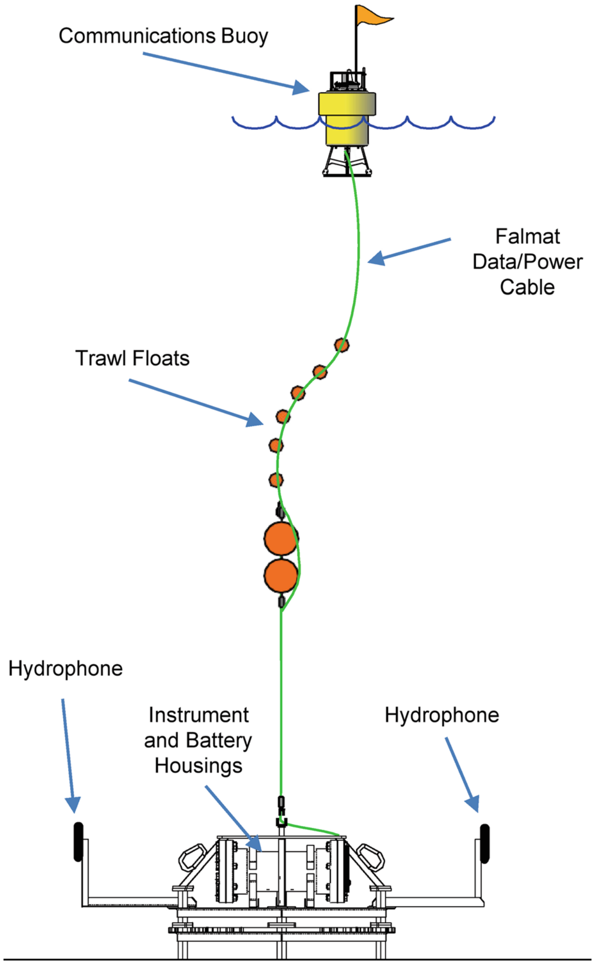

Fig. 1 Schematic of the Communications Acoustic Buoy (CAB)

Software

An onboard acoustic processing system runs the free, open-source, industry-standard passive acoustics monitoring software, PAMGuard (www.pamguard.org) on the edge in real-time. In keeping with other uses of PAMGuard, its modular nature allows for customizable configurations. This includes modules for the adjustable automated acoustic detections, classifications, and localizations. For example, parameters for the acoustic detection and classification of species of interest (including echolocation clicks, whistles, and moans) can be tweaked to suit the particular deployment environment. In addition, settings for recording bandwidth, duty cycling, and noise band monitoring can be adjusted to best suit the intended application and recording duration. Bearing estimations of automatically detected sounds are also provided, via calculations completed on the time delays of the same signal on the three hydrophones (as in Gillespie and Macaulay 2019).

Data packets in the form of binary files, which include detections and summaries of the acoustic data, are then transmitted to a modified version of PAMGuard for data display and further processing. If this is transmitted via cell modem, the display could be on a virtual computer in the cloud, accessible by a PAM Operator or MMO from anywhere with an internet connection (as in the *Dredging* case study below). Alternatively, if this is transmitted via radio network, the display could be on a remote base station. When multiple CABs are deployed simultaneously, data packets can be sent to the same central PAMGuard for streamlined processing. This near real-time set-up then allows for evaluation of whether mitigative actions may be required, based on the position of the marine mammal of interest with respect to a given mitigation zone, for example. Broadband, archival raw WAV files (or X3 compressed WAV files) are also recorded and available for direct download upon recovery.

Case Study 1: Monitoring Pile-Driving

CABs have been used to assess the extent of a modelled exclusion zone by providing field measurements of noise in real-time. In this example, in Hood Canal, USA, pile-driving was used to install 36-inch diameter monopiles during upgrades of a dock. A bubble curtain was also used to mitigate noise levels and optimize mitigation efficacy.

The piling can stun fish in the immediate vicinity (e.g., JNCC 2010), which can attract harbor seals (*Phoca vitulina*) who were observed to opportunistically predate on the stunned fish. However, if seals do so, they could be within the permanent threshold shift (PTS) zone for Level A takes, under the Marine Mammal Protection Act (MMPA) and as set by the National Marine Fisheries Service (NMFS 2018). If a seal is within the Level A Zone of Influence (ZOI), it is considered a form of harassment that results in an injury or permanent change in hearing sensitivity. Under this project's IHA (Incidental Harassment Authorization), a certain number of seal Level A takes were permitted. Visual marine mammal observers (MMOs) monitored seal presence, and kept count of the number of phocid Level A takes.

To mitigate adverse auditory impacts on seals, and to monitor noise levels in real-time, two CABs were simultaneously deployed at ~140 and ~500 m from the piling location. Binary files were sent back to a base station running MATLAB software, where automated detections of piling strikes were converted into single-strike sound exposure levels (SEL_{ss}). These SEL_{ss} accumulated to produce a cumulative SEL (SEL_{cum}) in real-time. In addition, the real-time noise monitoring was able to identify a period where the bubble curtain malfunctioned (Fig. 2). These sound field verification measurements with near real-time sound reception, processing, and transmission (on the order of seconds) allowed for live adjustments and tuning of the settings of the bubble curtain, as well as accurately determining the in-situ zones in which PTS was expected (Fig. 2). The original estimate of the seal Level A zone was 217 m, and real-time feedback of actual exposure levels updated the seal Level A zone to 92 m. The smaller radius of the Level A take zone, based on in situ noise measurements, allowed for the completion of works within permitting frameworks.

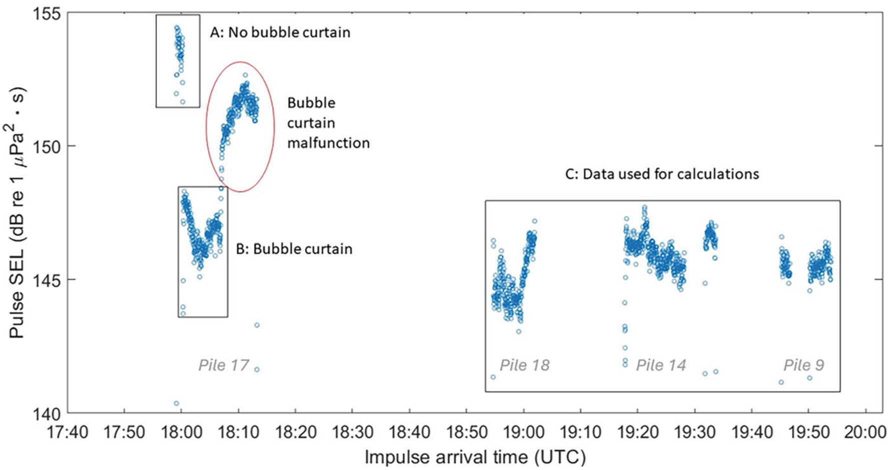

Fig. 2 Sound exposure levels (SEL) of single-strikes during dock construction across time, containing the installation of four different piles. On the left, the performance of the bubble curtain is shown, relative to no mitigation (A) and an identified malfunction (B). On the right, the bubble curtain is functioning and the SEL values here were used for real-time in-situ calculations of PTS zones (C)

Case Study 2: Clearing Offshore Wind Exclusion Zones

In this example, the habitat of the endangered North Atlantic right whale, along the east coast of North America, overlaps significantly with the planning areas of many offshore wind farms (Van Parijs et al. 2021). The construction noise and increased shipping activity associated with this has the potential to harm marine mammals, and in this area in the USA, incidental harassment authorizations often require a 10 km mitigation radius (Offshore Wind Energy Development in New England/Mid-Atlantic Waters). In other words, a vast area of 314 km^2 is required to be monitored to ensure that it is clear of endangered whales prior to and during pile driving.

To address these requirements, five CABs were simultaneously deployed in extensive field trials along the east coast seaboard of the USA (see detailed demonstration and performance review in Palmer et al. 2022). The CABs recorded playbacks of North Atlantic right whale upcalls, in order to characterize their detection function, as well as evaluate how readily an offshore wind exclusion zone could be determined to be free of North Atlantic right whales. Individual CABs each provided a bearing to the playback sound, and where the bearings from each CAB intersected indicated the location of the origin of the playback sound. This enabled localizations of whale sounds over the large exclusion zone ranges required for offshore wind construction in this area. Determining whether a whale is inside or outside of the exclusion zone can help to mitigate potential negative impacts on whales, as well as avoid costly construction delays. This study demonstrated that whale localization information reduced delays in construction, compared to PAM systems without any bearing information (e.g., single-channel systems), between a factor of 6 and 12; specifically, the inclusion of bearing information to whale sounds substantially improved false alarm rates, from 6–12 times, as dependent on the number of CABs deployed, the placement of the CABs relative to one another, and the signal-to-noise conditions in the environment (Palmer et al. 2022).

Furthermore, an interactive Shiny app was created to explore and demonstrate the benefits of multiple simultaneously deployed CABs in comparison to a single-channel acoustic sensor (Fig. 3). Here, detection probabilities of right whale upcalls are shown as a function of the number of CABs simultaneously deployed, the ambient sound level, the source level of the whale's call, and the exclusion zone radius. When using several multi-channel acoustic sensors simultaneously (i.e., the CABs), the vast majority of the following mitigative actions are correct; Fig. 3 shows this with three CABs. In other words, mitigative shutdowns are appropriately called for when right whales are localized to be within the exclusion zone, and mitigative shutdowns are appropriately not called for when right whales are localized to be outside the exclusion zone (Fig. 3, top panel). This is in contrast to mitigative actions that would be called for when using single-channel acoustic sensors, whereby due to no acoustic bearing information being available, it cannot be assumed that the whale is inside or outside of the exclusion zone (Fig. 3, bottom panel). In the instance of using a single-channel sensor, yielding no bearing information, right whale calls were conservatively assumed to all originate within the exclusion zone, thereby leading to many called for but unrequired mitigative shutdowns (Fig. 3,bottom panel). This work complements recent simulation work which has similarly evaluated the efficacy of PAM for mitigating the risks from wind energy construction on North Atlantic right whales (Baumgartner 2025).

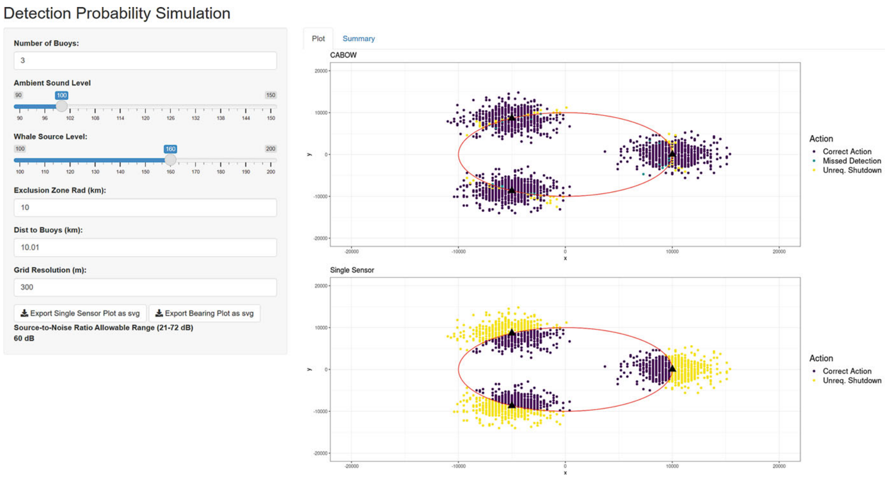

Fig. 3 Screenshot of R-shiny app, which displays simulation results of acoustic detection probabilities and the consequential mitigation action that these would lead to when either using multiple CABs (top) or using multiple single-channel acoustic sensors (bottom). Given the input parameters, purple dots show the locations of whales, which result in correct mitigative actions, green dots show the locations of whales where acoustic detections were missed (false negatives), and yellow dots show the locations of whales which, as detected by the either multi-channel (top) or single-channel (bottom) acoustic sensors resulted in unrequired shutdowns of industrial activity

Case Study 3: Mitigation Monitoring During Dredging Campaign

Following on from previous demonstrations of full system CAB field validations (Palmer et al. 2022), two units were deployed in the Moray Firth, Scotland, UK. Here, real-time mitigation monitoring was required alongside the redevelopment of Ardersier Port, which is to become a key hub for the offshore renewable energy transition in the north of Scotland. This campaign included ~4 months of both dredging and spoil disposal, in an area that partly overlaps with the Moray Firth *Special Area of Conservation* designated for the resident population of bottlenose dolphins (*Tursiops truncatus*) under the UK Habitats Directive.

Two CABs were deployed: one near the dredging area near the entrance to Ardersier Port, where a cutter suction dredger was operating, and one approximately 30 km away, situated on the perimeter of the spoil disposal area. These were used to acoustically monitor for dolphins. If dolphins were detected within mitigation zones during critical windows, pauses in dredging or spoil disposal operations were observed until the dolphins had cleared the area. This approach both reduced the adverse disturbance impacts on dolphins, as well as reduced costly delays in dredging operations.

Detections of dolphin sounds were uploaded via cell modem to a virtual computer in the cloud, accessible by PAM operators and marine mammal observers from anywhere with an internet connection. The PAM operator was able to visualize on a map the bearings to detected dolphin sounds, relative to each CAB, and visualize whether these bearings overlapped with their mitigation zones. Any overlap in dolphin bearing with a mitigation zone was conservatively interpreted as the dolphin being within the mitigation zone. In addition, the PAM operator was able to view real-time streams of click detections and noise band levels, as well as listen to 2-s automatically detected audio

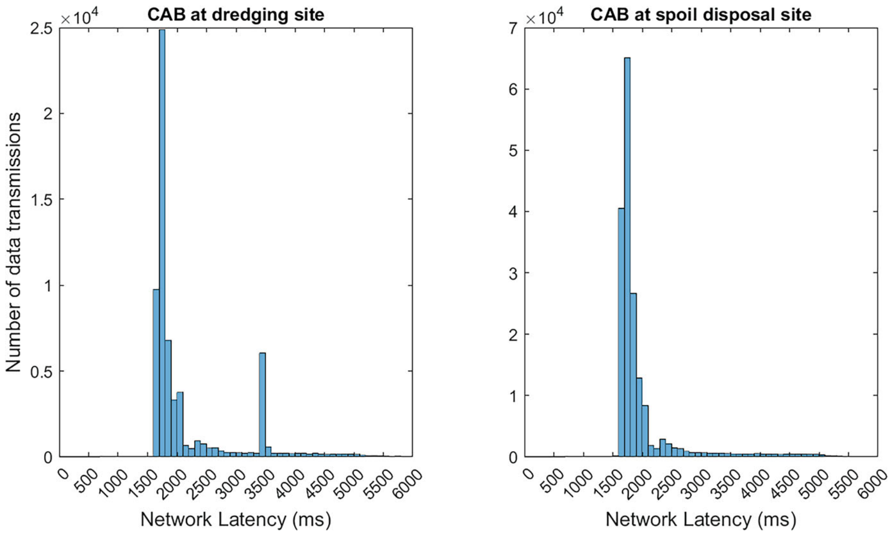

Fig. 4 Latency in data transmission, between CABs at both dredging (left) and spoil disposal (right) sites. 95% of data packets were received within 1.7 s

clips to cross-confirm whether the sound was of biological origin. Data packets were received in near real-time, with 95% of data packets across the entire dredging campaign received within 1.7 s (Fig. 4).

This configuration allowed for the evaluation, in near real-time, of whether mitigative actions were required, based on the position of the dolphin(s) with respect to the mitigation zone. These detections, along with any annotations made by the PAM operator as the data streamed in, were stored so that they were able to be used later, along with dredge log data, to audit mitigative compliance to the project's Marine Mammal Protection Plan.

Conclusions

Through three real-world case studies, this paper has demonstrated that CABs are a powerful tool for delivering near real-time passive acoustic mitigation monitoring, in the form of sound field verification to marine mammal detection, classification, and localization. In all case studies, the reliable and customizable data streams contributed to safeguarding the acoustic environments of marine mammals and enhancing regulatory compliance, as well as reduced costs (of dock construction, of offshore wind farm construction, or of a dredging campaign). Future directions for the CAB include its continued use in marine mammal and noise mitigations alongside industrial activities at sea, its use farther offshore as enabled by the newly implemented satellite communications option, as well as design modifications of deeper moorings to allow for the measurement of underwater radiated noise source levels from ships. These contributions to real-time acoustic mitigation add to a growing suite of tools that demonstrate the rising standard for robust and reliable marine conservation efforts.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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