Passive Acoustic Sensing of the Ocean

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Introduction

What can we learn by listening to the ocean? The ocean contains a myriad of sounds, both natural and human-made, and methods to scientifically extract information about the ocean and what is occurring within it using the sounds have made exciting advances in recent decades. Most dramatically, our abilities have progressed from listening to what is happening to the ocean (e.g., wind blowing and rain falling on the surface) to actually listening to the structure of the ocean and seabed and the physical properties of seawater itself (e.g., temperature, salinity, and pH). This article highlights some of the ways acoustical oceanographers use underwater ambient sound to measure the complex internal structure of the ocean just by listening.

Sound for Detection

Since the sinking of the Titanic in 1912 and the threat of submarine warfare starting in World War I (Manstan, 2022), sending pulses of underwater sound to find icebergs or U-boats has been the primary method for sensing in the ocean. As a result, underwater sound became and remains the mainstay of finding and mapping objects in the sea through a multitude of increasingly clever flavors of active sonar (*so*und, *na*vigation, and *r*anging) devices.

Similarly, the detection, localization, and classification of human machines and sound-producing animals using passive (silent) sonar systems has advanced to the development of listening arrays capable of surveilling the entire Atlantic or Pacific Ocean (Nishimura, 1994). As both types of sonar became increasingly sophisticated, some attention was eventually paid to characterizing the background sounds present in passive and active sonar measurements. As is often the case in scientific and engineering pursuits, this seemingly minor task, minimizing the effect of ambient noise on remote sensing *in* the ocean, resulted in the creation of a new discipline altogether, a method for sensing *of* the ocean, acoustical oceanography.

Passive Sensing in the Ocean

When we listen to the background sound in the ocean, ignoring the identifiable, attributable, and transient signals, we primarily hear what is occurring at the boundaries, the sea surface or seabed. The remote sensing of widely distributed physical processes by their random, noise-like (stochastic) acoustic signals has been a fruitful field of study since the days of Knudsen et al. (1948) and Wenz (1962). Using the power spectrum captured with just a few seconds of recording and some knowledge of the local conditions, the acoustic signatures of mechanical actions and the forces that cause them can be resolved. The frequency content can reveal the height of breaking waves at the ocean's surface (Felizardo and Melville, 1995), the microseism wave field generated by the oscillating pressure of ocean waves (listen bit.ly/47zqqiR) (Kibblewhite and Wu, 1989), the wind speed (Vagle et al., 1990), and the relative direction of the wind and surface currents (Robinson, 2020). The collective sound of rain drops give up their size, fall rate, and even their interaction with the wind and waves (listen bit.ly/3Rj8ZNA) (Ma et al., 2022). Snowflakes landing on the sea surface can produce a sound that tells the story of the atmospheric conditions under which they formed (listen bit.ly/3Gpxgvc) (Alsarayreh and Zedel, 2011). At high latitudes, the sea ice freeze up and break up provide an overture and finale to winter (Cook et al., 2022). In the darkness, the cracking sounds on the ice cover provide indications of temperature changes (listen bit.ly/3N673FG), whereas the saltation noise of snow skipping over the surface can be linked to the wind speed (Ganton and Milne, 1965). In the pack ice, wind and tidal current forcings make fragments of ice collide and rub with a predictable regularity (listen bit.ly/3N7SCRy). The sound of sediment being transported by currents flowing along the seabed can be used to estimate the grain size and the speed of the flow (Thorne, 1990). Characterizing the sounds of glaciers where they meet the sea has seen rapid progress toward the quantification of processes like calving and melting (listen bit.ly/3uDKTUW) (Deane et al., 2019).

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The acoustic signatures of hydrothermal vents reveal their presence (listen bit.ly/3RmgR0U), although the physical meanings of the sounds they generate are still to be determined (Smith and Barclay, 2022).

All these methods for extracting information about the activity of the natural world from underwater ambient sound with just a single, stationary hydrophone (underwater microphone) offer the potential to improve and inform the study of the ocean, weather, and climate. The measurement of wave-breaking statistics over large areas of the sea surface tell us about air-sea gas exchange and the ocean's ability to suck up CO_2. Quantifying precipitation on the ocean's surface is needed to understand the exchange of heat and momentum between the air and the sea as well as the mixing in the upper layers of the ocean (Laxague and Zappa, 2020). Ice coverage and freeze up and break up times in the dark and often overcast Arctic are important processes to track to improve our understanding of the changing climate at high latitudes. The presence and nature of wind, waves, rain, snow, and ice at the ocean's surface are all pragmatically monitored by sound on subsurface hydrophones.

Similarly, measuring the transport of sediments using passive acoustics avoids many biases introduced by bottom-mounted mechanical measurement devices and provides information needed to understand the stability of riverbeds, beaches, and the seafloor. Measurements of the melting and calving of glaciers, crucial to our understanding of the earth's future climate, can be made at safe distances from the unstable glacier terminus, where collapsing walls of ice can produce deadly tsunamis. The ability to determine any property of a hydrothermal vent without having to stick a sensor into its caustic, high-temperature fluid could enhance our ability to monitor these structures and their flow over long time scales and understand their contribution to the ocean's chemical cycles.

Passive Sensing of the Ocean

However, the most exciting advances in recent acoustical oceanography have combined contemporary knowledge of wave physics and methods in signal processing with innovation in ocean technology. Using massive passive acoustic datasets collected using permanent underwater listening stations connected to the shore by underwater cables, moorings tethered to seafloor, buoys floating on the sea surface, and autonomous underwater vehicles carrying arrays of hydrophones, researchers have uncovered details about the ocean's composition encoded in the background sound field. This article explores some of the answers to the question "What can we learn about the structure of the ocean and its internal properties by simply listening?" The new methods in passive-acoustic remote sensing described here can track the layering of water masses in the ocean, map the seafloor and subbottom, and solve questions related to climate change, the carbon cycle, and ecosystem health.

Noise Modeling and the Advent of Acoustical Oceanography

Applied problems, such as the detection of surface ships and submarines, are the staple of underwater acoustics. To aid in the design of optimal underwater arrays for this detection, two researchers at the US Navy Underwater Sound Laboratory, Cron and Sherman (1962), developed a basic model for the directionality and spatial correlation (statistical measure of similarity between measurements taken at two points) of underwater noise. Here, noise is defined from the opening sentence of Urick's seminal work (1984) on the subject *Ambient Noise in the Sea*, "Noise is unwanted sound." Cron and Sherman's (1962) version of the ocean was simplified to have no change in sound speed with depth, no bottom, and a smooth, perfectly reflecting sea surface. Breaking waves were modeled as totally uncorrelated sound sources, uniformly distributed across the infinitely large sea surface, collectively generating an unchanging, stationary noise. Despite these simplifications, the model predictions were found to agree very well with observations at any depth in the deep ocean (Barclay and Buckingham, 2013).

A more sophisticated physics-based model appeared a few decades later that could predict the spatial correlation of wind-driven wave noise in an ocean with a realistic bottom and sound speed profile (Kuperman and Ingenito, 1980). The expression was used to predict the performance of sonar localization algorithms that used realistic depictions of the ocean environment.

Both the Cron-Sherman (1962) and the Kuperman-Ingenito (1980) noise models treated breaking waves as uncorrelated sound sources spread across the entirety of the ocean's surface, radiating sound into the ocean below. It was noticed that this was analogous to the blue sky above, an infinite sheet of uniformly distributed uncorrelated sources of light (sunlight scattered by particles in the atmosphere), illuminating everything below.

Inspired by this analogy between ocean noise and daylight, a system to "see" underwater was built, the Acoustic Daylight Ocean Noise Imaging System (ADONIS). It consisted of a large spherical dish that reflected sound onto a dense elliptical billboard array placed at its focal point (**Figure 1**). Once placed underwater, the system made use of the ambient noise in the ocean to produce two-dimensional images of objects in the ocean, acting like an acoustic camera. When the dish was pointed in the direction of an object such as a 55-gal drum, ADONIS was capable of capturing the effect of the drum's shape, position, and composition effect on the noise field. By visualizing this acoustic information on a screen, an image of the scene was created. For example, when the 55-gal drum was placed on the seafloor, ADONIS captured images at a rate of 25 images/s, which was fast enough to create a smooth moving picture (or video) of objects within "view" of the giant dish (Buckingham, 1999).

Figure 1. *Acoustic Daylight Ocean Noise Imaging System (ADONIS) on the Scripps Institution of Oceanography Point Loma wharf, La Jolla, California. When placed in the ocean, the* ***black spherical dish*** *with a diameter of 3 m reflects and focuses underwater background noise onto the planar array of hydrophones (****yellow disc****). The dish and the array work together to create a spatial map of the noise field, arriving at the dish from different angels. This acoustic information is combined and visualized on a screen to produce images of objects in the ocean. Photo courtesy of the Buckingham Laboratory, used with permission.*

Reflections from the Seabed

During the development of the analogy of ocean surface sound as daylight, a series of experiments showed that the reflection of breaking-wave-generated ambient sound off the seabed could be used to infer geoacoustic properties. It was first shown that the measured vertical directionality of the ambient sound could be used to determine the angles at which perfect (total internal) reflection of acoustic energy did and did not occur (Buckingham and Jones, 1987). The critical angle, the largest grazing angle (angle relative to the horizontal) where total internal reflection does occur, is easily related to the acoustic impedance (sound speed and density) in the seabed.

Thus, just by listening to the directionality of background sound, one can determine the seabed acoustic properties. This technique was improved by increasing model complexity, first with analytical models that considered the seabed as an infinite extent of fluid (Deane et al., 1997), then as an elastic layer over a subbottom (Carbone et al., 1998). More recently, the theory was extended to determine the composition and thickness of the New England Mud Patch, an anomalous region of the seabed south of Martha's Vineyard, Massachusetts, where a 12–m-thick layer of mud has accumulated over the last 10,000 years. The mud has a sound speed slower than water, thus no critical angle, but the method of relating the noise directionality to seabed properties still holds (Barclay et al., 2019).

Meanwhile, an analogous theory of surface-generated ambient sound using rays in the place of waves was in development (Harrison, 1996). Application of the theory to estimate the reflection properties of the bottom was successful, using a string of vertical hydrophones in an array to measure the noise directionality (Harrison and Simons, 2002). However, the ingenious finding from the work was that the distance from the array to the seabed could also be measured. A conventional depth sounder generates a sound signal, then measures the time of flight to the seabed and back to determine the distance traveled. By the new method, the background noise is used in place of the signal by some clever signal processing on

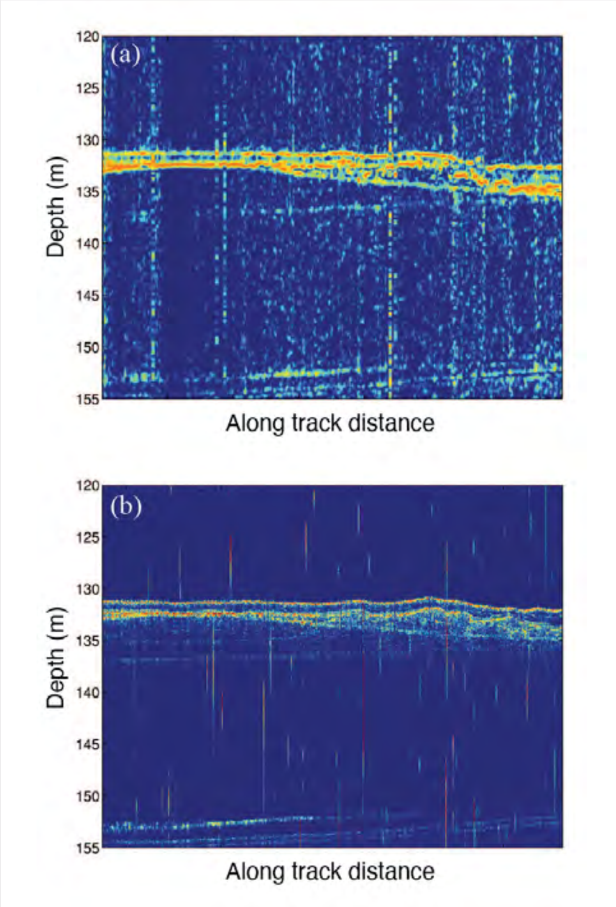

Figure 2. *The measured depth of the seabed and subbottom layers over a section of the seafloor.* ***Color scale:*** *intensity of the acoustic return (****red*** *is high;* ***blue*** *is low).* ***a:*** *Produced using ambient-noise fathometer processing applied to a drifting vertical hydrophone array.* ***b:*** *Made using a ship-towed active sonar used for seismic surveys. The two measurements were made over approximately the same segment of the seafloor, where the ship's track followed that of the drifter. The* ***vertical axis*** *is two-way travel times converted to depths using 1,500 m/s sound speed and the* ***color scale*** *covers 12 dB in dynamic range. Adapted from Siderius et al. (2006).*

the data from the vertical array. This technique of depth sounding with ambient noise turned the drifting array into a passive fathometer, capable of mapping the ocean bottom and its subbottom structure without putting any new sound into the environment (**Figure 2a**) (Siderius et al., 2006). For comparison, a very loud active sonar normally used for seismic surveys was towed behind the ship and used to measure the bathymetry along the same drift track as the passive fathometer (**Figure 2b**).

The idea of using noise to determine the position and properties of the seabed was pushed further to acoustically monitor the health of grasses growing on the seabed. Near Italy, in a region of the ocean where *Posidonia oceanica* (see bit.ly/3N5JDQY), a sea grass known as the blue lungs of the Mediterranean, covers the seafloor, it was observed that the time variability of the ambient sound directionality was synchronized with the hours of daylight. Direct measurement of O_2 in the seawater confirmed that the daily cycle of photosynthesis by the seagrass was the cause. As the grass soaked up dissolved CO_2, it expelled O_2 bubbles that lowered the effective sound speed in the vegetation layer near the bottom. The bubbles also scattered and absorbed energy from the ambient sound field, changing the ambient sound directionality. Thus, just by listening, the health and activity of a plant in the ocean can be determined.

Self-Sensing

Sensing with noise has also been an active area of research in the geophysics and physical acoustic communities. In diffuse sound fields, where sources are spread somewhat evenly in space and not concentrated in one area, it is always possible to retrieve the (empirical) Green's function, which mathematically defines the propagation of sound from one point to another (Lobkis and Weaver, 2001), through the time averaged cross-correlation of ambient sound. In the ocean, the Green's function depends on the seawater properties (temperature, salinity, density) between the source and receiver. The background sound recorded on two hydrophones separated by distances of centimeters to 100s of kilometers can be cross-correlated to find the travel time between them. That travel time can either be used to determine the separation distance between the hydrophones (provided you know the sound speed) (Sabra et al., 2005b) to the sound speed in the medium (provided you know the separation distance) or be used to synchronize the data recording systems' clocks, if you know the separation and the sound speed (Thode et al., 2006). Even when the environment (or Green's function) and the background noise becomes more complex, given a long enough averaging time, the dependence between position, sound speed, and sensor clocks can be resolved (Sabra et al., 2005a).

Passive Acoustic Thermometry

The deep ocean is a vast volume of water capable of absorbing and removing atmospheric heat. Ocean currents carry warm surface waters to the poles, where cooling causes the water to sink and store some fraction of the heat in the deep ocean. However, considerable uncertainty around the functioning and fragility of the ocean circulation system and the extent to which it buffers and softens climate change exists. Thus, measurements of the heat content of the deep ocean are critically important in monitoring and predicting the earth's climate health (Ditlevsen and Ditlevsen, 2023). Still, because of the ocean's vastness, direct ship-based or autonomous profiling float point measurements of temperature in the deep ocean are sparse. Luckily, temperature is the dominant thermodynamic quantity that determines the speed of sound in seawater, allowing acoustics to play an important role in ocean climate monitoring.

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) maintains strategically located hydrophone stations around the globe, designed to have complete acoustic coverage the world's oceans for the purpose of detection underwater nuclear explosions (Bradley, and Nichols 2015). Each station consists of two triangular arrays with a nominal separation (**Figure 3**). The sensors are positioned on the axis of the SOund Fixing And Ranging (SOFAR) channel, the depth at which decreasing seawater temperature and increasing pressure conspire to produce a minimum in the sound speed depth profile. Distantly generated sounds, natural or human-made, can be trapped by refraction about this minimum and travel around the entire world with minimal losses (Munk et al., 1994). The method of computing the Green's function from the time-averaged cross-correlation of ambient sound was used to transform decades of acoustic-monitoring data from these stations into a temperature record of the deep ocean (Woolfe et al., 2015). These measurements provide a spatially averaged estimate of the temperature over the path between the two arrays. In the Atlantic, an acoustic measurement of warming by 0.013° ± 0.001°C/yr was reported, in agreement with the available direct measurements (**Figure 4**).

This measurement of the decadal increase in temperature in the deep ocean provides crucial information on the extent and reach of climate change. The measured increase in the concentration of carbon dioxide in the earth's atmosphere (the Keeling Curve; see bit.ly/47BxriX) provides a stark image of human activity altering the state of the globe's outer layers. **Figure 4** shows the scale and timing of the earth's reaction in the deep ocean, the place most isolated from human activity. The

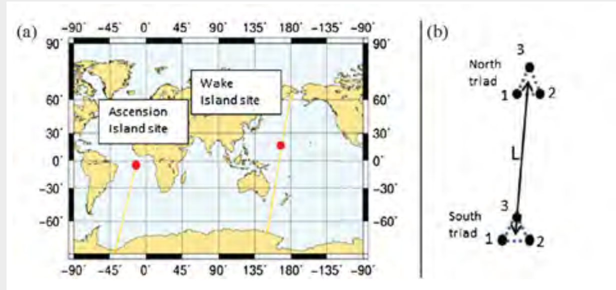

Figure 3. ***a:*** *Location of the two hydroacoustic stations (**red dots**) near Ascension Island and Wake Island.* ***b:*** *Zoomed-in schematic of the hydrophone array configurations for the Ascension Island and Wake Island sites. Each hydroacoustic station consists of a northern and southern triangle array of three hydrophones or triad, with each triangle side having a length of ~2 km. The distance (L) between the triad centers is equal to 126 and 132 km for the Ascension Island and Wake Island hydroacoustic stations, respectively.* ***Yellow lines*** *in a join the centers of the northern and southern triads. Adapted from Woolfe et al. (2015), used with permission.*

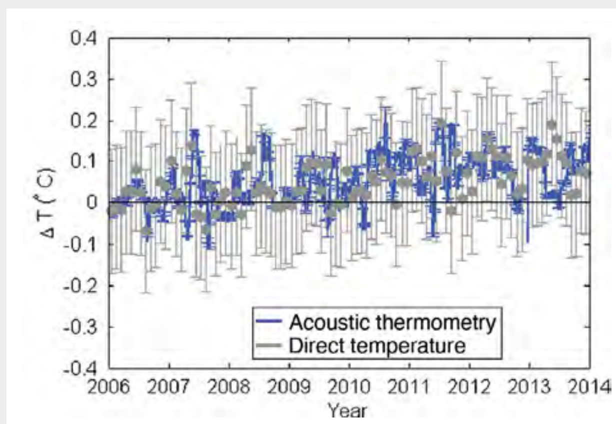

Figure 4. *Comparison of the deep-ocean temperature variation at the Ascension Island site as estimated from passive acoustic thermometry (**blue lines**) with direct temperature measurements (**gray dots**), along with the corresponding error bars. The data series is normalized so that a linear fit on the data would have a y-intercept at zero. The low error bars on the acoustically measured temperature in the deep ocean allows the linear trend of 0.013° ± 0.001°C/yr to be resolved. Adapted from Woolfe et al. (2015), used with permission.*

measurement highlights the ability for passive acoustics to monitor in one of the most remote and hostile places on earth over decades, with minimal maintenance and virtually no environmental impact.

Listening to the Sound Speed Profile

In a deepwater setting, it was demonstrated that computing the cross-correlation of the ambient sound field could be used to determine the ray travel times between all elements of horizontally separated vertical line arrays (Godin et al., 2010). The set of all rays can then be used to estimate the sound speed profile. In shallow water, the sound field can be represented as a set of vertical normal modes, standing waves trapped between the surface and the seabed, propagating in horizontal directions. Each mode has a characteristic speed of horizontal propagation called the group speed. The mode shapes and group speeds are determined by the properties of the seabed and the depth-dependent sound speed in the water column. By estimating the mode speeds and shapes from the cross-correlation of the ambient noise, changes in the sound speed profile can be observed just by listening (Tan and Godin, 2020).

Other features of the sound speed profile can be heard indirectly. Thus, the passing of nonlinear internal waves (waves that occur between seawater layers of differing density with amplitudes of ~35 m and periods of ~10 min) could be observed through sound generated by an increase in current along the seabed, leading to an increase in sediment-generated noise (Katsnelson et al., 2021).

The Timbre of Ocean pH

The absorption of sound in seawater is due to the chemical concentrations of the compounds boric acid and magnesium sulfate in the water. These compounds are in solution, and their exact concentration depends on the temperature and pressure of the seawater. As a sound wave passes through seawater, the chemical reactions of ionic disassociation are driven forward and backward by the increase and decrease of acoustic pressure. This effect, known as chemical relaxation, defines the shape of the frequency-dependent absorption curve. Boric acid releases a hydrogen ion (H^+) when is disassociates, so its concentration is a direct measure of pH.

Using an autonomous acoustic profiler, like the Deep Acoustic Lander (**Figure 5**), a continuous broadband

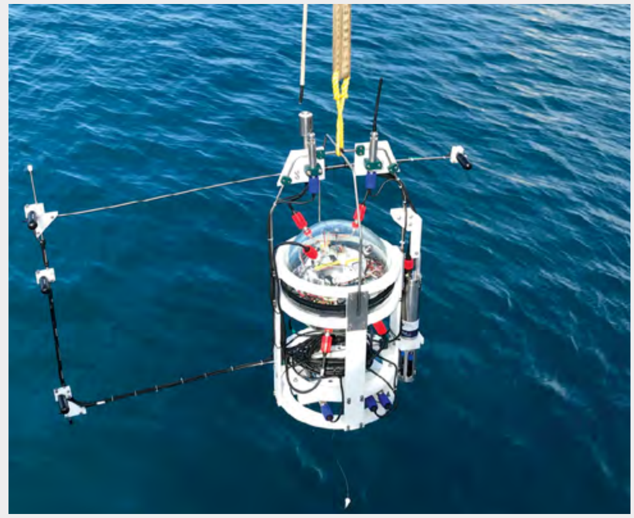

Figure 5. *The Deep Acoustic Lander is a fourth-generation full-ocean depth-rated free-falling acoustic-recording platform designed to capture profiles of ocean sound on a four-channel reconfigurable array. In 2021, the device descended, landed, and returned from the bottom of the deepest known spot in the world's oceans, the Challenger Deep in the Mariana Trench.*

measurement of acoustic absorption can be made using the sea surface as the source as the sensor descends away from the sea surface. When local winds are greater than 10 m/s, the ambient-noise field in the deep ocean is dominated by locally generated surface noise (Barclay, 2013). The breaking-wave-generated sound field has a depth-independent directionality, a weak frequency, and a depth-dependent intensity due to sound absorption. When two measurements of the power spectral density of ambient sound are compared from two different depths with a separation of more than 100 m, the spectral slope of the deeper measurement will be steeper. This is due to the longer propagation path between the source and receiver and the frequency dependence of the absorption. Higher frequencies are attenuated more rapidly than lower ones; thus the spectral slope will steepen with depth. This depth-dependent character of the spectrum of the wind-driven surface wave sound can be used to determine the frequency dependence of the absorption and thus the pH.

Just by listening to the timbre of the background sound, measurements of pH allow the acidity of the ocean to be monitored with hydrophones. Ocean acidification has a negative impact on ocean species like oysters and corals, who make hard shells and skeletons by combining calcium and carbonate from seawater.

This method is analogous to (passive) optical absorption spectroscopy, where the compositions of atmospheres of distant exoplanets are remotely sensed using light from a star of convenience. Unlike optics, which exploits sharp spectral lines associated with different atoms, acoustic absorption spectroscopy only has the slow change in the absorption spectrum of seawater, with frequency driven by the relative concentration of boric acid and magnesium sulfate.

The Future of Passive Acoustic Sensing of the Ocean

Acoustical oceanography is primarily a branch of science and engineering focused on the development of methods. Innovation in measurement, signal processing, remote sensing, and inversion are constant and inevitable within the talented cohort of researchers found in **References**. Adoption of these techniques by the wider oceanographic community will depend on the visibility of the science and the transdisciplinary relationships of physical, biological, and chemical oceanographers and climate scientists. If we continue to ask what we can learn simply by listening to the ocean, recent history shows that passive acoustical oceanography will continue to provide robust, inexpensive, low-power, precise, and accurate measurement techniques to be applied to some of the most important natural science problems on earth.

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