Near Real-Time Underwater Passive Acoustic Monitoring of Natural and Anthropogenic Sounds

Mark F. Baumgartner, Kathleen M. Stafford, and G. Latha

Abstract Passive acoustic monitoring takes advantage of the relative opacity of the ocean to sound. Traditionally, long-term monitoring has employed archival instruments from which data are accessed only when the recording instrument is retrieved. Recent advances in low-power instrumentation and computational speed allow passive acoustic data to be collected, processed and relayed to shore in near real time from fixed and mobile platforms deployed at the sea floor, in the water column or on the ocean's surface. Measurements of ambient noise provide insight into natural sound sources, such as rainfall, earthquakes or marine animals, as well as anthropogenic sound sources, such as shipping or resource extraction. Near real-time passive acoustic measurements allow scientists and agencies to monitor shipping, observe underwater seismicity and detect the presence of critically endangered large whales. The development and use of real-time passive acoustic monitoring systems will grow in coming decades to help better manage increasing industrialization of the oceans. This chapter reviews the capabilities of real-time passive acoustic monitoring to address civilian scientific needs. The currently available suite of instrumentation and platforms used for passive acoustic monitoring are discussed along with the wide variety of measurements that can be made with this technology. Finally, examples of how real-time passive acoustic monitoring has improved our understanding of the ocean are presented.

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1 Introduction

Sound in the ocean has been used to study a wide variety of phenomena ranging from rainfall in the deep ocean to the migration patterns of great whales. Researchers can study the acoustics of both abiotic and biotic sources because of the relative transparency of the ocean to sound. Unlike light or chemical signals that dissipate within tens to hundreds of meters underwater, sound waves can travel for tens to hundreds, even thousands of kilometers with little attenuation. The degree to which sound propagates through the ocean depends on its frequency; a high-frequency echosounder on a fishing boat can provide information on schooling fish a few hundred meters away, while the low-frequency sounds produced by the propeller of a large cargo ship may be detected hundreds of kilometers away. Both the production and reception of underwater sound have been used in military applications for over a century; however, the widespread civilian use of passive acoustic monitoring is a relatively recent development that rapidly has become a common tool to study properties of the world's oceans. Passive acoustic monitoring involves instrumentation that listens for sounds, but does not produce any sound itself (in contrast to active acoustic instrumentation, which produces sound and records or processes the echo of the sound).

Traditionally, passive acoustic monitoring has been conducted with autonomous archival instruments that record audio in-situ; however, information derived from these recordings is unavailable until the instrument is recovered and the data are offloaded and analyzed. Critical ephemeral events, such as an earthquake or the presence of a vocalizing endangered species, cannot be detected until long after the event has occurred. For many research applications, such delays in data access and analysis are perfectly acceptable, but most passive acoustic recording systems are unhelpful for applications involving real-time response or where storage or recovery of audio recordings is not feasible. In such cases, access to the audio, or measurements derived from the audio, is needed in real time or near real time. Meeting this requirement is challenging, however, because audio is often sampled at much higher sampling rates than the transfer rates of most available communication systems. For example, the detection of dolphin whistles requires audio sample rates of at least 5 kHz (often much higher) or 10,000 bytes per second for a 16-bit audio system, and Iridium satellite communications currently support data transfer rates of only 300 bytes per second. Audio is therefore difficult to transfer from sea to shore in real time except over very high bandwidth communication channels (e.g., cables). Without the appropriate communication infrastructure, audio must be either sent in short noncontinuous snippets or processed in-situ to derive and relay measurements of interest. Fortunately, advances in instrumentation are now allowing the collection and processing of audio in-situ, enabling near real-time access to passive acoustic measurements.

The capability to detect the presence of sound sources via passive acoustic monitoring in real time (i.e., at the time of detection) or in near real time (e.g., within minutes or hours of a detection) is growing within the scientific community, and it is becoming more widely available on a variety of manned and unmanned platforms for both short-term and long-term monitoring applications. One of the tremendous strengths of combining passive acoustic monitoring with unmanned autonomous platforms is persistence: the ocean can be acoustically monitored in real time continuously over long timescales. This persistence is revolutionary. Monitoring marine mammals, for example, has been traditionally conducted by human observers from ships or aircraft, and relies on the fact that air-breathing marine mammals must return to the surface where they can be visually detected. However, visual detection is severely limited by conditions of low light, fog, rain, and high winds-observations can only be made during daytime in quite good weather conditions. Real-time passive acoustic monitoring relies on animals making sound, but it can be done continuously regardless of weather or light conditions, and with the use of long-endurance autonomous platforms, it can be done in remote locations that are difficult to access by human-occupied platforms. This approach is significantly less expensive than large-scale ship or aircraft operations. Most importantly, a real-time capability allows immediate action in response to detection events, which can support improved science and conservation efforts. In the case of marine mammal monitoring, real-time detections can trigger immediate responsive changes in industrial activities such as shipping, fishing, or seismic exploration to reduce impacts of these activities on marine animals, or it can alert scientists to locations where they can find study animals for follow-up research using photo-identification, biopsy, or tagging.

In this chapter, we review the capabilities of real-time passive acoustic monitoring to address civilian scientific needs. The chapter discusses the suite of instrumentation and platforms used for passive acoustic monitoring, the wide variety of measurements that can be made with this technology, and finally presents examples of how real-time passive acoustic monitoring has improved our understanding of the ocean.

2 Instruments

The instrument that is central to all passive acoustic monitoring is the hydrophone. Hydrophones work by converting acoustic energy from the water into electrical energy using a piezoelectric transducer that measures pressure changes produced by a sound wave. Hydrophones can be omnidirectional, sensing sounds from all directions around the instrument, or directional, providing bearings to a sound. When used in arrays, techniques such as beamforming [19], normal mode backpropagation [53], or hyperbolic fixing via time difference of arrival [10, 110] can be used to estimate bearings, ranges, and (or) locations of sounds. Directional hydrophones can have multiple pressure vector sensors and a single hydrophone that together provide a bearing to a sound [35].

3 Platforms

There are a wide variety of instrument configurations and platforms from which real-time passive acoustic monitoring can be accomplished. Platforms can be fixed, mobile, surface-bound, bottom-mounted, or profiled throughout the water column, and instrument data can be transferred to a ship or shore via a cable, radio, or satellite. Each platform has particular space and timescales over which it can operate (Fig. 1), and it is critical to match these scales to those of the motivating research questions or monitoring needs. One of the most important aspects of a platform is the noise generated by the operation of the platform itself. Buoyancy-driven platforms, such as ocean gliders and profiling floats, produce almost no self-noise and minimal low-frequency flow noise while passively sinking or floating through the water column. In contrast, oceanographic ships produce an abundance of broadband noise and induce flow noise that makes low-frequency monitoring impossible; for

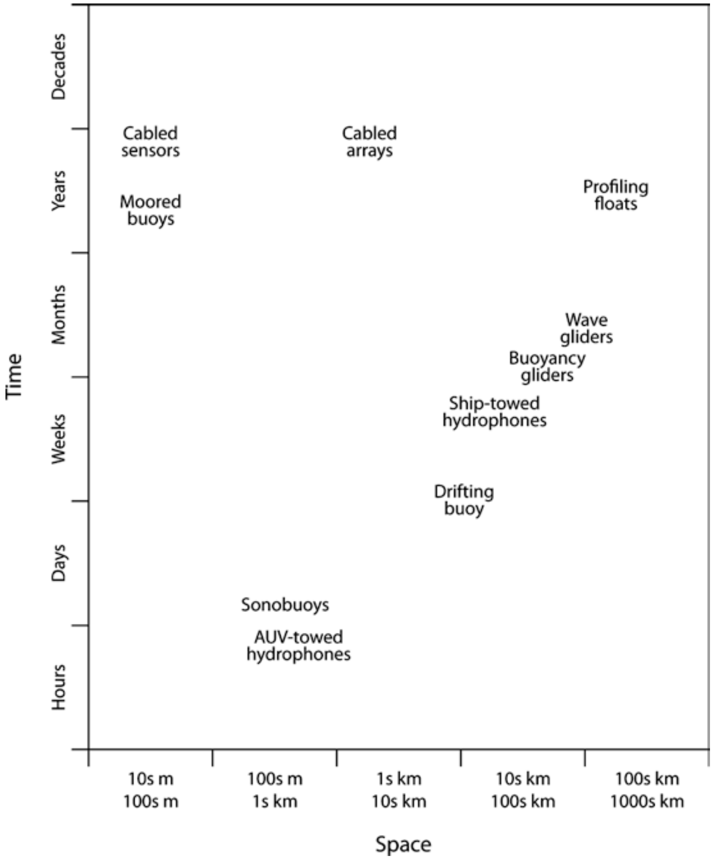

Fig. 1 Space and time scales of near real-time passive acoustic monitoring platforms

mid-frequency and high-frequency monitoring, the noise can only be mitigated with towed hydrophone arrays that can beamform to directionally monitor received sound at bearings that exclude the ship.

3.1 Fixed Platforms

Fixed platforms, such as moored buoys, cabled sensors, and cabled arrays, can offer extremely low self-noise when the hydrophones are mounted at or near the seafloor. Cabled sensors and arrays (i.e., those connected directly to shore) have the tremendous advantage of unlimited power and data storage, since the cable provides both power and a high bandwidth data communication channel. This allows for nearly continuous operation over very long timescales (years; although maintenance may still be required for biofouling, cable breaks, or instrument fatigue), and audio can be delivered directly to shore where it can be processed and stored in real time. Examples of cabled systems include (1) the Integrated Undersea Surveillance System that has been used to detect underwater earthquakes, volcanic eruptions, and track baleen whales [26, 97], (2) the Comprehensive Test Ban Treaty Organization (CTBTO) hydroacoustic stations that are designed to monitor illegal nuclear tests but are also capable of detecting Antarctic iceberg calving events [16], and (3) deep-sea observatories that can be used to monitor marine animals, shipping, and other anthropogenic activities [2].

In contrast to cabled acoustic sensors, autonomous moored sensors that transmit acoustic measurements in near real time must have a surface buoy to allow communications with shore via radio, cellular, or satellite communication systems (Fig. 2a). Like all autonomous platforms, the endurance of a moored buoy is limited by power, since it relies on batteries, and the bandwidth of the communication systems is quite low compared to a cabled sensor. Consequently, moored buoys are limited to transmitting measurements derived from audio collected in-situ, or to sending short snippets of audio recorded during detection events. Self-noise on moored systems with a surface expression can be substantial. Typical mooring components such as chains and shackles are exceedingly noisy if not properly treated (e.g., chains can be quieted by encasing them in urethane), and wire rope has the propensity to strum in strong currents, even when faired. Motion of the surface buoy caused by waves can create sloshing noise at the surface as water directly impacts the buoy, as well as impart motion in the mooring components, which may also cause noise. This motion can be dampened with the use of a compliant “stretch hose” [78] and subsurface flotation to isolate the lower part of the mooring (between the flotation and the seafloor where the passive acoustic instrument is located) from the motion of the surface buoy.

The challenge of delivering data from the submerged acoustic instrument to the surface is not trivial. If the instrument is close to the surface, electromagnetic (EM) cables can be used to transfer data from the instrument to an electronics package in the buoy for immediate or delayed transfer via radio, cellular, or satellite communications. While data delivery is straightforward, there are challenges to making

Fig. 2 Some near real-time passive acoustic monitoring platforms, including (**a**) moored buoy, (**b**) profiling float, (**c**) Slocum ocean glider, and (**d**) wave glider. Photographs (**a**, **b**, **d**) copyright Woods Hole Oceanographic Institution, (**c**) copyright The Nature Conservancy

acoustic measurements very close to the surface because of surface noise (unless the goal is to directly measure surface noise, such as waves or precipitation). Depending on the mooring design, these cables may or may not carry the strain of the buoy (i.e., mechanically connect the buoy to the anchor). For instruments that are placed deeper in the water column or at the seafloor, armored EM cables can be used to both connect the surface buoy to the anchor and transfer data from the depth to the surface. Inductive modems can also be used to transfer data from anywhere along a continuous mooring cable to the surface buoy. A signal can be induced in the mooring cable by an instrument through the coupler that attaches the instrument to the mooring cable, and that signal is received through a similar mechanism at the surface buoy. This system has been used in some moored ocean observatory systems (e.g., [109]). Data can also be transmitted from depth to the surface buoy via an acoustic modem [27, 28], although transfer speeds are low (up to 625 bytes per second).

As one example of meeting the challenges of quieting a mooring and delivering data from an underwater passive acoustic instrument to the surface buoy, the Woods Hole Oceanographic Institution (WHOI) developed a mooring design that uses a surface buoy, stretch hoses, subsurface flotation, EM cable, urethane-jacketed chain, and a bottom structure on which the acoustic instrument is mounted (Fig. 3). The patented hose (EOM Offshore) can stretch to nearly twice its relaxed length; hence,

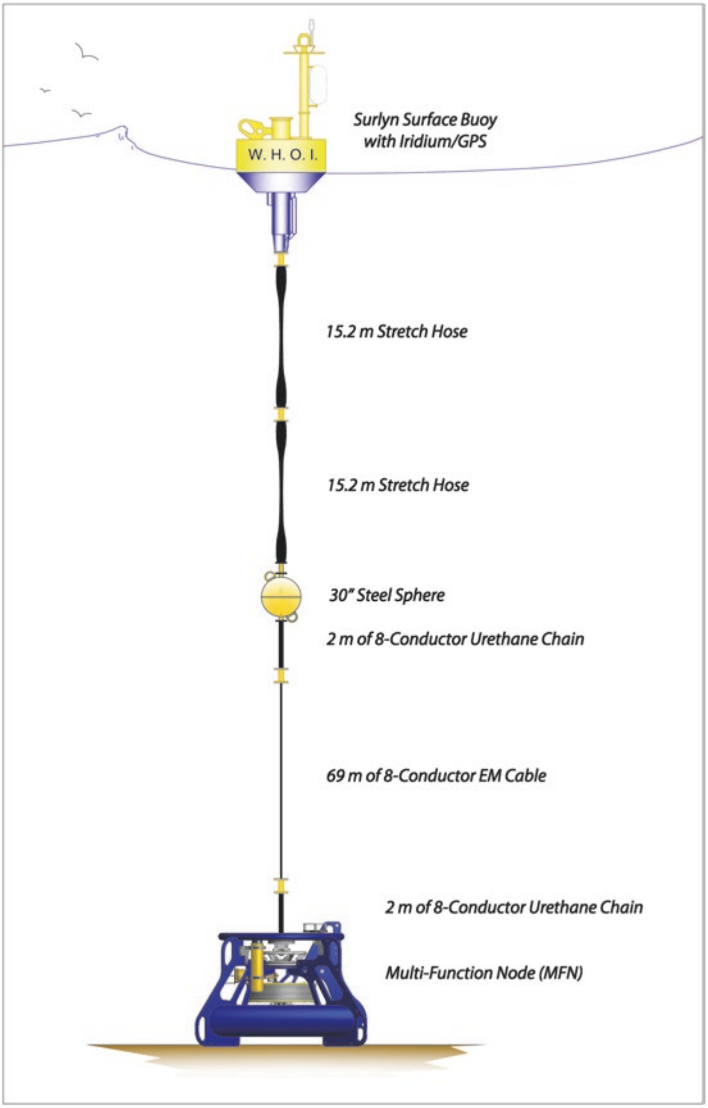

Fig. 3 Quiet moored buoy design for near real-time passive acoustic monitoring. The digital acoustic monitoring (DMON) instrument is mounted near the bottom on the multifunction node, and marine mammal detection data are transferred through the electromagnetic (EM) cable and stretch hoses to an electronics package in the surface buoy where the data are stored and transmitted to shore every 2 h via Iridium satellite communications

it is capable of decoupling the subsurface float from the motion of the surface buoy [78]. Helically wound conductors are embedded in the hose to allow EM signals to be passed through the hose despite its changeable length. Urethane-jacketed chains with integrated EM cables are used to further dampen both mooring motion due to the motion of the surface buoy as well as the transmission of cable strumming energy to the bottom structure. The bottom structure, termed the multifunction node (MFN), consists of an aluminum frame with integrated flotation that is weighted by an anchor that, in turn, is attached to an acoustic release and a spool of Spectra line that is used to retrieve the anchor upon recovery. A digital acoustic monitoring (DMON) instrument (see below) is mounted to the MFN at the seafloor, and it sends marine mammal detection and classification data through the EM cables and stretch hose to an electronics package in the surface buoy for transmission to shore every 2 h via Iridium satellite.

3.2 Mobile Nonnavigated Platforms

Floats have been used extensively for passive acoustic monitoring, including for real-time acoustic measurements (e.g., [61]). They can be used at the surface, at depth (with a tethered surface expression to allow data transfer), or in a profiling mode where they dive to depth and return occasionally to the surface to transfer data to shore. Most floats cannot be navigated, as they passively drift and are thus advected by local currents. Profiling floats (e.g., APEX, Teledyne Webb Research; SOLO/S3A, MRV Systems) can sometimes be crudely navigated by remaining at a depth of favorable currents or by parking (station-keeping) at the bottom with only occasional visits to the surface to transfer data (Fig. 2b). Surface floats are not commonly used for passive acoustic monitoring because of the noise produced by waves and precipitation at the surface; however, sonobuoys have been used extensively for monitoring underwater sound in real time. Matsumoto et al. [61] outfitted an APEX profiling float with a system to passively record audio, process the audio to detect beaked whale clicks, and to transmit those data to shore via Iridium in near real time. Despite the availability of near real-time beaked whale detections, the float was designed to be recovered after 2–3 weeks of operation to allow access to the archived audio. Profiling floats are typically used in physical oceanography applications for much longer periods (years; Fig. 1) and are intended to be expendable [84]. For such missions, near real-time data transfer is the only practical way to access acoustic information collected by the float.

Sonobuoys have been used since World War II in military applications to detect and track underwater sounds [39], as well as to study marine geological structure (e.g., [42]), monitor seismic activity (e.g., [59]), and measure meteorological conditions (e.g., [75]). Considerable research has also been done with sonobuoys to detect and track marine mammals in real time (e.g., [52, 54, 98, 111]). Sonobuoys are ship or air deployable, and separate upon entering the water into a hydrophone section and a surface float section that are connected with a conducting cable. The surface float has an integrated antenna that permits radio transmission of audio in real time to a nearby receiver. Reception range is on the order of a few tens of kilometers for a nearby ship, depending on the height of the receiving antenna. In addition to omnidirectional versions, sonobuoys can also be equipped with directional frequency

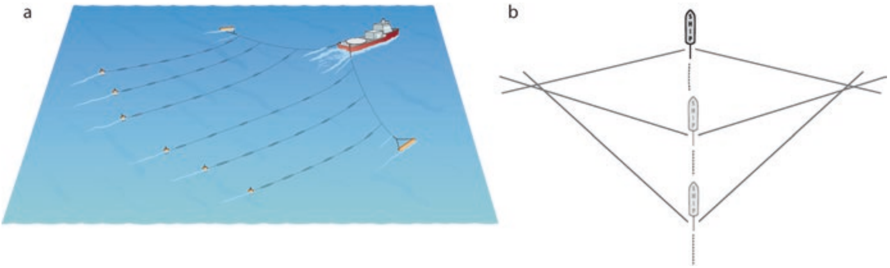

Fig. 4 (**a**) Ship towing multiline towed hydrophone array and air gun for seismic exploration. (**b**) Depiction of localization of a presumed stationary sound source from a single-line towed hydrophone array where bearings from the ship are estimated via beamforming, and multiple bearings from the moving ship allow localization from bearing crossings. Note left-right ambiguity in the localization using a single-line towed hydrophone array

analysis and recording (DIFAR) capability to provide bearings to low-frequency sounds [62]. The endurance of sonobuoys is limited to hours or tens of hours, depending on the configuration, and while battery life limits this duration, the need to attend the sonobuoy with a nearby receiving system can also limit the operational endurance of the system (i.e., a ship or aircraft needs to be in radio range to receive the audio).

3.3 *Mobile Navigated Platforms*

Mobile platforms that are capable of real-time passive acoustic monitoring consist of human-occupied platforms (ships), autonomous underwater vehicles (AUVs), and autonomous surface vehicles (ASVs). Despite significant self-noise, ships towing hydrophone arrays are used routinely for seismic and marine mammal surveys. Hydrophone arrays can be single-line or multiline arrays; the former are used for marine mammal detection and localization, and the latter for seismic surveys (Fig. 4a). The array configuration allows detection of sounds with directivity via beamforming, and so both detection and bearing estimation are possible. For marine mammal surveys, multiple bearing estimates for an assumed stationary source from the moving ship allow estimation of source location using bearing crossings (Fig. 4b).

Autonomous underwater and surface vehicles all operate on similar principles of navigation. Each vehicle has some way of ascertaining its position, either by a global positioning system (GPS) receiver if the vehicle visits the surface, or by acoustic localization of the vehicle itself if it remains constantly submerged. A set of onboard waypoints is used to traverse a course, and a pilot can often update this list of waypoints in near real time; however, it is the vehicle's responsibility to determine how to navigate between the waypoints. There are three primary means of propulsion: active, buoyancy-driven, and wave-driven. Many AUVs have motors and propellers to actively provide forward motion; hence, they can move quickly, and only the strongest currents impact their navigation (e.g., REMUS, Kongsberg Hydroid). They have limited endurance (hours to tens of hours) and range (hundreds of meters to kilometers), however, because active propulsion consumes significant power. Moreover, these AUVs produce significant self-noise. Like ships, towed hydrophone arrays are being developed for these active propulsion AUVs to provide real-time detection and bearings to acoustic sources. For many applications, a nearby ship must attend the AUV to receive real-time data and to facilitate recovery after a relatively short deployment.

Buoyancy-driven ocean gliders (e.g., Slocum glider, Teledyne Webb Research; Seaglider, Kongsberg; Spray glider, Scripps Institute of Oceanography) make small changes in their volume to alternately become more or less dense than the surrounding seawater, allowing them to sink or float, respectively (Fig. 2c). They also have short wings to provide lift, which generates forward movement during both the dive and climb. To move forward, ocean gliders must continuously profile through the water column in a sawtooth pattern. Typical travel speeds in quiescent waters are slow, roughly 0.35–0.40 knots, and their navigation can be severely affected by strong currents. Self-noise is very low for these platforms when diving and climbing, consisting primarily of mechanical noises associated with occasional rudder adjustments. The most significant advantage of ocean gliders is their long endurance. Since adjusting volume does not consume much power, gliders can remain at sea for weeks to many months, depending on the sensor payload and battery configuration. Passive acoustic recording has been conducted with ocean gliders since the mid 2000s [67, 8], including some applications to detect, classify, and report marine mammal sounds in near real time [11, 12, 44]. Because of their mobility, low self-noise, and native radio and satellite communication systems, ocean gliders are ideal for passive acoustic monitoring and the transfer of derived acoustic measurements from sea to shore.

The wave glider (Liquid Robotics, Inc.) is a unique ASV that uses the energy of waves for propulsion and the energy of the sun for recharging batteries; so, its endurance is theoretically unlimited (in practice, biofouling and mechanical wear limits the endurance of the wave glider to several months). It consists of a surface float shaped like a surfboard with solar panels, navigation and communications packages, and GPS and Iridium satellite antennas (Fig. 2d). A 7 m tether with embedded conductors connects the surface float to the sub, a relatively simple structure with vanes and a rudder. As waves lift the float, the vanes on the sub pivot down so that the sub moves up and forward; as waves drop the float, the vanes on the sub pivot up so that the sub moves down and forward. The sub is always moving forward while dragging the surface float along with it, and the rudder on the sub allows the navigation computer to direct the glider's movements. The wave glider moves faster than the buoyancy-driven gliders, allowing it to cover more ground with similar endurance. Self-noise is a challenging problem for doing passive acoustic monitoring on wave gliders, as there is considerable motion associated with the propulsion mechanism, including the vanes, a spring mechanism meant to act as a shock absorber, and the tether mount. Moreover, the relatively fast speed of the wave glider imparts flow noise to a mounted or towed hydrophone. Vehicle noises can be quieted with mechanical techniques, and flow noise can be minimized with appropriate hydrophone fairings. Real-time audio or derived acoustic measurements can be transferred through the tether's conductors to a payload bay in the surface float, and a custom electronics package is needed to store and transfer these data to ship or shore by radio, cellular, or satellite communication systems.

4 Measurements

Ambient noise, the soundscape of the ocean, is the result of both biotic and abiotic sources. Biotic sources include soniferous fish, crustaceans, and marine mammals. Abiotic sounds can be further divided into natural and anthropogenic (human-caused) sources. The former includes mid-frequency sounds from wind and rain, and low-frequency sounds from underwater earthquakes and volcanoes and icebergs. The latter includes primarily low-frequency sounds from ships, oil and gas exploration, pile driving, and even nuclear explosions. In this section, we focus on how sounds are used to provide information about sources of both biotic and abiotic signals in the ocean.

4.1 Biotic

Perhaps the best-known producers of sound in the ocean are marine mammals, ranging in size from the 1.5-m harbor porpoise (*Phocoena phocoena*), which produces ultrasonic clicks (120–140 kHz; [7]), to the 30-m blue whale (*Balaenoptera musculus*), which produces infrasonic moans (10–30 Hz; [97, 103]). Sound is used for two purposes by marine mammals: communication and environmental sensing [104, 105]. Marine mammals are social animals, often organized in groups. Because the ocean is optically opaque during daytime and dark at nighttime, individual members of groups cannot rely on visual contact to maintain cohesion. Sound travels much farther in water than light; so, marine mammals have evolved the ability to communicate with one another acoustically. The toothed whales and dolphins (odontocetes) communicate over a few kilometers using mid-frequency whistles (2–35 kHz; [55, 76]), while baleen whales (mysticetes) communicate over tens and possibly even hundreds of kilometers using low-frequency moans (10–2000 Hz; [79]). Odontocetes also use echolocation, the repeated production of short-duration broadband clicks and the reception and characterization of the click echoes, to detect and capture prey [6], measure their altitude above the seafloor [33, 41], and classify other objects ([69]; including other marine mammals, [32]).

Mysticetes do not use echolocation (although see [99]), but they are capable of sensing their environment with sound by monitoring the echoes of their vocalizations [104]; for example, Arctic-adapted bowhead whales likely use the echoes from their calls to detect thin sea ice through which they can break to breathe air [22, 30].

Many fish and invertebrates can also produce sound for a variety of purposes. Fish sounds are produced at frequencies between 20 and 4000 Hz by two mechanisms: drumming on a swim bladder or stridulation [1, 87]. The swim bladder is used primarily for buoyancy, but the sonic muscles flanking the swim bladder in many species are used to expand and contract the swim bladder to make a drumming sound [93]. Stridulation is the process by which two body parts are rubbed together to make a sound, such as with the pectoral fin and pectoral girdle in marine catfishes [49]. Fish use these sounds to attract a mate, repel a competitor, or as a fright response. Marine invertebrates such as lobsters, crabs, urchins, mussels, scallops, and shrimps can also produce sound, either incidentally during movement or feeding, or purposefully via stridulation or other mechanisms. For example, lobsters produce sound with fundamental frequencies around 5 kHz via a stick-and-slip method similar to a bowed violin [51, 77]. A snapping shrimp generates a high-speed water jet and cavitation bubble by the rapid closing of its large snapper claw, and the collapse of this cavitation bubble creates a loud broadband sound [108]. The water jet is used both as a weapon to stun prey or attack predators, and for intraspecific communication [37]. In some regions, the sounds of invertebrates such as snapping shrimp can dominate the soundscape.

4.2 Abiotic Sources – Natural and Anthropogenic

Natural abiotic sources of sound in the ocean can emanate from (1) the atmosphere in the form of weather (wind and rain), (2) the bottom of the ocean as seismicity from earthquakes and underwater volcanoes, or (3) sea ice via glacier calving, iceberg grounding, or wind-driven and current-driven shear of sea ice. The acoustic energy produced by each of these sources is significant, and can be readily quantified and measured using acoustic observations.

Wind and rain increase ambient noise levels between 200 Hz and 30 kHz for wind and up to 50 kHz for rain [112], allowing the direct measurement of the duration and amplitude of these atmospheric phenomena via passive acoustic monitoring [4, 47, 56, 58, 71, 74, 81, 106, 112]. Acoustic measurements of these sources allow for near-field estimates of wind speed or rainfall amounts in remote or difficult-to-measure regions over smaller areas and shorter timescales than is possible via satellite measurements. The acoustic signatures of both wind and rain are distinctive and can be detected well below the surface of the ocean [24]. Wind injects noise into the ocean through the creation and breaking of waves at the surface. Likewise, the contribution of rainfall to the underwater sound field is the result of raindrops impacting the water's surface, with different sized drops having distinct acoustic signatures [13, 64]. Ma and Nystuen [56, 57] developed an algorithm that uses received sound pressure level and bandwidth to determine rainfall rate.

Acoustic monitoring can also be used to study underwater seismicity and other geophysical processes, including underwater earthquakes, landslides, seafloor spreading events, and volcanic eruptions [14, 15, 25, 26]. These signals are of very low frequency, with fundamentals well below 100 Hz that can last many tens of seconds. Although seismicity occurs within the Earth's crust, acoustic energy from geophysical processes propagates into the water column and can therefore be detected by hydrophones. Acoustic data have been used to establish the duration and amplitude of seismic events and map the patterns of seismicity at geologically active sites over long time and space scales [26, 34]. In addition to monitoring persistent seismicity in remote regions throughout the world's oceans, hydroacoustic data can be used to identify the characteristics of underwater events that may result in tsunamis, therefore allowing for better prediction or earlier detection of such events [17, 36, 100, 113].

A relatively recent development in the use of passive acoustics to understand abiotic sources of sound is the study of sounds produced by drifting and grounded Antarctic icebergs [16, 101]. Widely spaced hydrophone arrays can be used to track the paths of drifting icebergs [21, 68]. The acoustic signature of an iceberg grounding can be distinguished from a free-floating iceberg that is breaking up [21]. Ashokan et al. [5] have recently studied ice calving and ice bobbing noise in the Arctic Kongsfjord. Low-frequency tremor signals from grounded, drifting, and disintegrating icebergs have been shown to increase ambient noise levels in the Southern Ocean seasonally, and these signals can be detected as far north as the equator in some oceans [60].

In addition to the natural sources of noise in the ocean, passive acoustic monitoring can listen for anthropogenic, or human-caused, sources. These sound sources are relatively novel in the oceans, having only emerged in the nineteenth century as artifacts of industrial development. Since this time, anthropogenic sources have increased ambient noise levels in all oceans and over long timescales. Anthropogenic sources that have been monitored with passive acoustic data include shipping, atomic explosions, and oil and gas exploration and extraction. These sources all tend to be of relatively low frequency (<1000 Hz) and are therefore detectable over distances from tens to thousands of kilometers.

Shipping, particularly commercial shipping, injects low-frequency sound into the water from cavitation of air bubbles created when the propeller spins [85]. This produces blade lines that are quasi-tonal low-frequency bands with harmonics, the fundamental frequency of which can be used to determine the propeller blade rate of a ship. Commercial shipping is the chief contributor to underwater ambient noise levels from ~5 to 1000 Hz in most of the world's oceans and has increased with each decade since the 1960s [3, 63, 86].

Passive acoustic monitoring has also been used to monitor illegal nuclear explosions. The Comprehensive Nuclear Test Ban Treaty (CTBT) organization has, in addition to land-based seismometers, underwater hydroacoustic stations as part of their International Monitoring System (IMS). This system is designed to detect and localize the source and magnitude of nuclear explosions to inform the global community of illegal testing [20]. Although designed to detect the infrasonic signals of such explosions, the data accumulated by the IMS have been used to detect baleen whales [29, 88, 95, 96] and study global noise levels [65, 66].

Another dominant source of low-frequency ambient noise in most oceans is seismic air gun explosions used during oil and gas prospecting and, to a lesser extent, scientific research. Air guns, usually deployed in arrays, produce very loud sounds by releasing compressed air that creates an impulsive, low-frequency (~1–188 Hz) signal designed to penetrate the ocean floor. The reflected sound of these pulses is received by a towed hydrophone array and used to estimate the bottom and subbottom composition of the ocean floor in the quest for oil and gas deposits [83]. Scientists also use the data to determine the structure and dynamics of the Earth's crust. These signals can be detected at distances of well over 1000 km [73, 102]. In the Atlantic, air gun signals are recorded year-round from oil and gas surveys that have been acoustically localized in both the northern and southern hemispheres and the eastern and western Atlantic [72].

Interestingly, undersea substrate properties can also be studied using new techniques that include both direct measurements and inversion schemes using passive acoustic data and an understanding of the physics of signal propagation through complex media (i.e. [70, 89]). Seabed properties, such as critical angle and reflection loss, can be estimated directly from passive array measurements of ambient noise produced by wind and ships [31, 80]. Sanjana et al. [89] used a vertical line array of 12 hydrophones in the northern Indian Ocean to obtain ambient noise measurements in conjunction with wind speed and rainfall information, and they found that the critical angle derived from the noise measurements matched well with sediment samples acquired at the same time as the experiment. Sanjana et al. [90] then conducted a geoacoustic inversion experiment to further estimate surface and subsurface seabed acoustic parameters, including sound speed, density, attenuation, and layering, and again found that the derived sediment characteristics matched well with the core sample data collected during the experiment.

5 Experience

The capability to detect the many different sound sources that comprise ocean ambient noise, be they biotic or abiotic, has expanded significantly over the past 40 years. For the most part, the great majority of studies have used passive acoustic recordings that were analyzed after being retrieved from underwater instrumentation. Near real-time studies have been fewer but are becoming more common as the required technology matures. In this section, we provide examples of the use of real-time technology that has permitted rapid response to an event or events that could only have been detected through the use of passive acoustic monitoring.

5.1 Marine Mammal Monitoring in Real Time

A number of systems have been built in recent years to detect and report marine mammal occurrence in near real time from autonomous platforms [11, 18, 44, 61, 92, 94, 107]. These systems have focused on baleen and beaked whales, as conservation needs are greatest for these taxa. The North Atlantic right whale (*Eubalaena glacialis*) is critically endangered and is prone to ship strikes and fishing gear entanglements in its calving and feeding habitats along the east coast of USA and Canada [45, 46, 48]. A network of buoys developed by Cornell University has been used near Boston, MA, USA, to detect the presence of right whales and relay that information to mariners via a government-sponsored advisory system [18, 94, 107]. The system runs an in-situ detector to identify a particular call that right whales produce (the upcall), and sends audio snippets to shore of putative right whale calls via satellite communications. On shore, a human analyst listens to the snippet and assesses whether the sound was truly a right whale call.

The Cornell University Bioacoustics Research Program pioneered near real-time detection and reporting from a moored buoy by focusing on a single call type produced by a single species in a single location. Automated detection and reporting from mobile autonomous platforms show great promise for assessing the spatial distribution of vocalizing animals [44, 61], but both moored and mobile systems need to be expanded to simultaneously detect the calls of a wide variety of species. Baumgartner et al. [11] report the use of a near real-time system that is capable of detecting, classifying, and reporting the presence of fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*), sei (*Balaenoptera borealis*), and North Atlantic right whales in near real time from Slocum electric gliders. The system uses a generalized detection and classification system [9] that generates pitch tracks for detected sounds, classifies each pitch track via discriminant function analysis, and relays both pitch tracks and classification information to shore via Iridium satellite. On shore, an analyst can review both the classification information as well as the context in which calls are detected to determine the occurrence of each of the four baleen whale species. Baumgartner et al. [12] describe an extension of this system for detecting bowhead and beluga whales as well as bearded seals from Slocum gliders in the Arctic.

5.2 Seismic Activity Monitoring

Monitoring underwater seismicity from earthquakes and volcanoes has provided important information about hydrothermal venting, the chemistry of the global ocean, seafloor spreading, and the risk of tsumanigenic earthquakes based on subduction zone characteristics. Real-time passive acoustic monitoring has been used in numerous applications to detect volcanic activity and seafloor spreading events and to direct shipboard responses to document, characterize, and study these

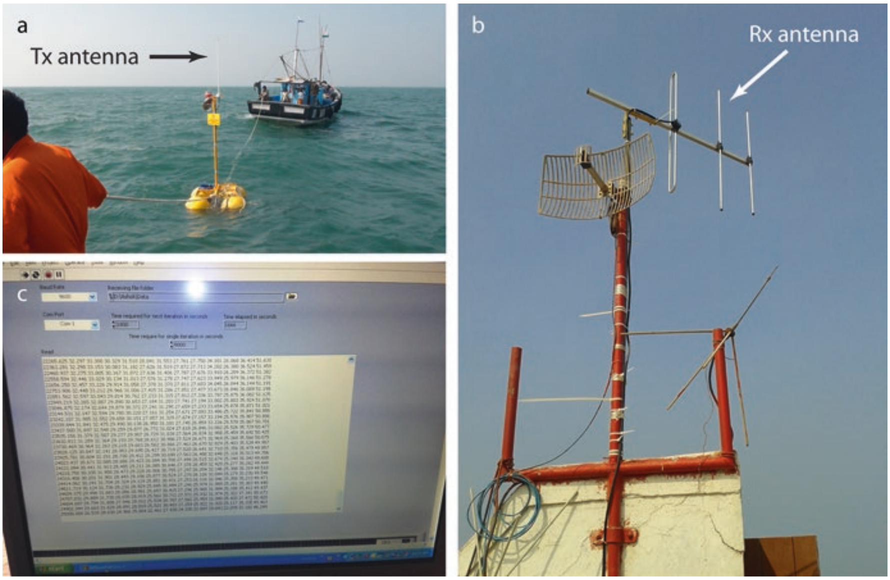

Fig. 5 (**a**) NIOT vertical line array surface buoy with radio frequency (RF) transmitting antenna, (**b**) land-based receiving antenna, and (**c**) real-time display of power spectral density estimates

events [25, 26]. Interdisciplinary research of such events in near real time has provided novel insights into the linkages among geological perturbations, local chemistry, and biological processes in remote difficult-to-study regions. This includes discoveries of active hydrothermal plumes and associated microbial communities that, while ephemeral in time and space, can stimulate broad changes in the local environment [23, 38, 40, 43].

5.3 *Real-Time Ambient Noise Monitoring*

To obtain long-term near real-time ambient noise data, an automated system (Fig. 5) has been developed and deployed by the National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences, Government of India [50]. The system has been deployed in shallow waters off both the east and west coasts of India. The system (for which a patent has been filed) is comprised of a vertical line array of omnidirectional hydrophones in an oil-filled polyurethane tube with tilt sensors. Initially, a 12-element array (design frequency 5 kHz) cabled to a surface buoy was used, which was later enhanced to 21 elements (design frequency 10 kHz). The data acquisition modules and battery pack are housed in the surface buoy along with data communication modules. The mooring line is comprised of subsea floats, marker floats, and sinker weight. An acoustic pinger designed for offshore use is mounted with the array to aid in locating the system. The hydrophone array is calibrated at the Acoustic Test Facility of NIOT.

Since each element of the array samples simultaneously, the amount of raw data acquired is very large and poses problems for real-time transmission. To meet this challenge, a program was developed for the digital acquisition system to compute power spectral density (PSD) estimates, which are small enough to be transmitted in real time. Different communication modes have been tested, including Wi-Fi, radio frequency (RF), general packet radio service (GPRS), and Indian National Satellite System (INSAT) (patent to be filed). The real-time PSD estimates enable the identification and classification of noise sources such as rain, shipping, and wind. With a proper database of ship noise, the type of ship being monitored could be determined in real time. Further work in this area will enable the system to be used as an intruder detection system. Wi-Fi communication is feasible only for short range, with a maximum distance from sea to shore of <2 km. Data are transmitted from the surface buoy to shore and then relayed via high-speed Internet to NIOT. Radio frequency signals can be used for long-range transmission of data, with a maximum distance of up to 15 km given clear line of sight. Data are transmitted from an RF modem in the surface buoy to an RF receiving system on shore where, as with Wi-Fi, data are relayed to NIOT via high-speed Internet. PSD estimates can also be transmitted directly from the surface buoy to NIOT using GPRS over very long ranges and do not require a shore station intermediary. Finally, although there are data transmission size limitations that preclude the sending of PSD estimates, INSAT can be used to transmit data on the status of the real-time system directly to NIOT.

One of the challenges of autonomous systems that have a surface expression in shallow waters is protecting the hardware from human interference. At present, manned watchkeeping boats are used to monitor the installation to prevent damage or theft of the equipment. A GPRS system is placed on the watchkeeping boat to monitor its movement and ensure uninterrupted functioning of the system. Because the system is attended, the raw acoustic data can be downloaded from the installation at regular intervals. The voluminous amount of data acquired is then subjected to initial processing and further detailed analysis to understand site-specific characteristics of ambient noise, including wind speed/rainfall estimation as well as bioacoustic, geoacoustic, and anthropogenic signals [81, 82, 91].

5.4 The Future of Real-Time Passive Acoustic Monitoring

Real-time passive acoustic monitoring provides a very different capability than archival recorders; it enables action. Whether detecting an earthquake, nuclear explosion, ship, or whale, a human is alerted to that detection within seconds to hours, and there is an opportunity to do something with that information. Real-time systems will not take the place of archival recorders; there are many instances when real-time information is not necessary, because no response is planned or required.

But as detection algorithms expand and improve in accuracy, and instrumentation capable of running those algorithms in-situ become more available, real-time passive acoustic monitoring will only grow along with the myriad of applications that can take advantage of it. Industrial activities such as oil and gas exploration and extraction, dredging, shipping, and wind farm construction introduce loud sounds into the ocean that have an impact on marine animals [83]. Real-time passive acoustic monitoring offers the opportunity to monitor those sounds and reduce or halt activities when sounds reach a particular instantaneous or cumulative threshold. Similarly, the intensity of industrial activities can be adjusted based on the presence of marine mammals detected in near real time. There are only a few examples of using such real-time systems for mitigation of anthropogenic activities today, but it seems inevitable that real-time passive acoustic technology will be mandated in future regulatory frameworks.

Our changing climate will force changes in the distribution of marine organisms. For highly mobile predators like marine mammals, changes in distribution may be dramatic, occurring quickly over large spatial scales. No observing system exists today that is capable of documenting and studying these changes in marine mammal distribution. However, there is an outstanding example of a global autonomous observing system that has been built to monitor ocean variability driven by climate change: the ARGO profiling float program [84]. Through technical innovation and international cooperation, the ARGO program now consists of a few thousand expendable profiling floats distributed from tropical to subarctic waters monitoring ocean heat content in near real time. Imagine a similar array of hundreds of long-endurance autonomous platforms reporting in-situ detections of marine mammals. Such a listening array would be able to monitor changes in marine mammal distribution over time, as well as the temporal and spatial distribution of ocean noise throughout nearly the entire world's ocean. Because these platforms have long endurance and are expendable, archived audio could never be retrieved; hence, near real-time detection, classification, and reporting are central to this grand vision of a global marine mammal observing system.

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