Twenty-Thousand Leagues Under the Sea: Recording Earthquakes with Autonomous Floats

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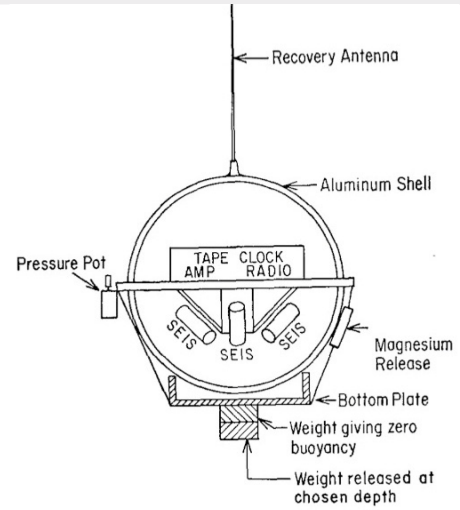
Fifty Years

Much like medical doctors who use X-rays or acoustic waves to make three-dimensional images of our insides, geophysicists use the elastic wavefield generated by earthquakes worldwide to scan the deep interior of our planet for subtle contrasts in the propagation speeds of seismic waves. To image the deep Earth using seismic tomography, over the years, seismologists have densely covered the continents with seismometers to measure ground motion. As with medical tomography, where sources and detectors are rotated all around to illuminate our bodies from all angles, achieving similarly evenly distributed geographical coverage for seismology requires making measurements all over the Earth surface, including the two-thirds that are covered by oceans. Yet, although some ocean islands do host geophysical observatories, gathering data over marine areas continues to present unique challenges.

As early as the 1960s, seismologists began making seismic measurements on the ocean bottom, using motion sensors known as geophones that were sunk into the sediment. The small movements of the seabed convert to acoustic waves that can also be recorded in the water layer itself. Hence, soon thereafter, scientists started using deep current-tracking oceanographic floats to make measurements midwater, away from the difficult-to-access ocean bottom and away from the sea surface where wind and water waves generate unwelcome noise. This strategy opened up the oceans to drifting sensors capable of roaming over large areas. In particular, last year marked the 50th anniversary of the invention of a "neutral buoyancy free-floating midwater seismometer."

Bradner et al.'s (1970) drifting instrument (see **Figure 1**) was first and foremost meant to characterize the poorly known marine acoustic soundscape, or noise spectrum, at the very low frequencies where seismic measurements are made. However, to detect and locate signals from specific earthquakes and measure the travel times of individual seismic waves so that wave speed variations can be calculated, the position of the receivers must be precisely known and the time accurately kept. Both requirements presented unsurmountable challenges for drifting underwater instrumentation at the time. Hence, by the mid-1970s, the action moved to sonobuoys (which could be kept track of using radio telemetry) and moored underwater buoys (which did

Figure 1. *Schematic view of Bradner et al.'s midwater seismometer. A three-component triaxial seismometer (SEIS) is contained in aluminum pressure housing, along with amplifiers (AMP), a crystal clock, a tape recorder, a pressure "pot" to measure depth, and a radio recovery beacon transmitter. Reproduced from Bradner et al., 1970, with permission.*



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not drift). Instead of measuring ground displacement directly, hydrophones now listened for ground motion conversions to acoustic water pressure variations.

Although these approaches jumpstarted the use of hydroacoustics for earthquake seismology, subsurface moorings were expensive and surface sonobuoys were noisy and had short lifetimes. As a result, the idea of having any seismological instrumentation drift with the currents at depth, let alone at the surface, was largely abandoned. Earthquake signals picked up by newer float models incorporating both geophones and hydrophones did continue to get reported through the late 1980s, but design improvements of ocean-bottom seismometers ultimately took the science of instrumenting oceanic areas for global seismology in an altogether different, and successful, new direction (Suetsugu and Shiobara, 2014). Semipermanent hydrophone arrays in the oceans today continue to play a role in Nuclear Test Ban Treaty verification (Bradley and Nichols, 2015), but they do not reliably detect earthquake arrivals.

Nevertheless, the costs of deploying and recovering ocean-bottom sensors remain prohibitive, and the vision of a long-lived network of easily launched, passively drifting low-cost hydrophones to detect and report distant earthquakes lived on. Guust Nolet, at Princeton University in New Jersey, carried on building the science case. In the decades since the earliest forays, battery technology leapt forward, the Global Positioning System enabled precise surface location and timing anywhere in the oceans, and satellite communication matured to the point where commercial systems provided coverage anywhere on Earth, allowing for near real-time data transmission.

Ocean-float technology also came of age (Gould, 2005). By the mid- to late 1990s, the development of freely drifting repeatedly diving "profiling" floats brought together the oceanographic community into worldwide collaboration. Fast forward, and as of this article, some 4,000 so-called "Argo" floats (see argo.ucsd.edu) are surfacing every 10 days, collectively returning almost 400 conductivity-temperature-depth profiles per day for oceanographic and climatological research. Additionally, novel biological and geochemical sensors (Riser et al., 2018) have vastly widened the range of instrumental capabilities compared with what was originally envisioned.

Figure 2. *Location of last surfacing of the instruments in the South Pacific Plume Imaging and Modeling array of third-generation Mobile Earthquake Recording in Marine Areas by Independent Divers MERMAID instruments, an international project coordinated by the EarthScope Oceans consortium (see www.earthscopeoceans.org). The legend identifies every instrument's institutional owner. Image courtesy of Jonah N. Rubin.*

Fifty Mermaids

In the early 2000s, John Orcutt and Jeff Babcock at the Scripps Institution of Oceanography in La Jolla, CA, spearheaded the development of a system for "Mobile Earthquake Recording in Marine Areas by Independent Divers" (MERMAID). They equipped an oceanographic float with a hydrophone recording package, and the first-generation MERMAID was born (Simons et al., 2006).

The development of MERMAID is told starting in **First Sound**. Spoiler alert! Here's how this story ends. Fifty years after Bradner et al.'s (1970) visionary instrument, 50 third-generation MERMAIDs, each with a life span of about 5 years, have been launched in the Pacific, freely drifting at depth but surfacing for data transmission and reporting seismograms triggered by earthquake sources around the world, ready for seismological analysis (see **Figure 2**). A recent modification designed to report acoustic spectral densities for the environmental analysis of marine sound is set to debut in the Mediterranean this year.

A consortium, EarthScope Oceans, now coordinates autonomous midwater robotic seismometry worldwide while hatching ambitious plans for other applications of hydroacoustics and ocean observation writ large. Here, we provide a brief history and a current status report and share our dreams for the future.

Mission Objectives

Mapping the three-dimensional structure inside our planet is key to elucidating the origin of Earth, its subsequent evolution, and its ongoing dynamics (Romanowicz, 2008). Information on deep-Earth structure is gleaned via seismic wave speed tomography and other advanced seismic-imaging techniques (Tromp, 2020) from the transient elastic wavefield emitted by earthquakes that are large enough to be recorded worldwide.

The interior of our planet consists of roughly concentric shells named crust, mantle, liquid outer, and crystalline inner core, but such a one-dimensional subdivision is inadequate. To begin, the crust is very heterogeneous, broken up into a patchwork of tectonic plates and ranging in thickness from 0 km at midocean ridges to some 70 km under the Andes and the Himalayas. Furthermore, the solid mantle slowly moves about, ultimately mixing but maintaining inhomogeneities of temperature, chemical composition, and crystal structure. Much like the crust, the base of the mantle, some 2,891 km down into the Earth, is also extremely heterogeneous, and the core-mantle boundary is a "mountainous" surface. Last, even the solid inner core displays strong contrasts in physical properties, related to its growth by the continued solidification of the liquid outer core. Its seismic wave speed varies from place to place, often anisotropically, that is, depending on the look angle. Taken all together, a multitude of observations shows that the interior of the Earth manifests significant lateral variations from merely depth-dependent structure, which therefore requires three-dimensional mapping.

Different rocks and minerals all have different seismic wave speeds, but, to a good approximation, seismic wave speeds in the mantle are primarily a record of its internal temperature distribution. Unlike the speed of sound in air, which increases with temperature, hot rocks transmit sound more slowly. In contrast, when rocks are colder, their wave speed increases. (For more on the acoustic properties of rocks, see TenCate and Remillieux, 2019.) Because hotter rocks are buoyant and colder rocks are denser than their surroundings, the mantle slowly convects, deforming internally. Tomographic images reveal zones of high seismic wave speed that outline sinking sheets of subducted material (van der Hilst et al., 1997), while isolated columnar upwellings or mantle plumes are manifest as low wave speed regions (Montelli et al., 2006). Seismic wave speed maps provide a snapshot of the Earth's interior temperature distribution as it slowly, but inexorably, cools down overall.

Whatever the nature of the seismological probing method, the ability to measure small variations in seismic propagation velocities is crucial. Land-based global networks help us map origin times and locations of earthquake sources. Seismic waves from distant earthquakes convert at the ocean bottom to acoustic pressure variations in the water column. On the receiving end, determining the location of the recording station and keeping track of time are of fundamental importance. To measure seismic velocities of earthquake arrivals with sensors drifting at depth, we must quickly tag the instrument's location and time of recording. In practice, this entails surfacing within days, if not hours, for the Global Positioning System location determination and time acquisition to perform instrumental clock-drift corrections and to transmit the detected data via satellite.

Not all earthquakes are created equal, and to be useful for tomographic imaging of the Earth's mantle, we must be judicious in reporting "data" and avoid false triggers. Diving, surfacing, and data transmission are energetically costly. Although future generation instruments might run on thermal-energy conversion (Jones, 2019), the instruments of today have a finite battery supply.

In the end, what we require is an autonomous robotic oceanic vehicle with a hydrophone that sensitively hears, actively listens to, and expediently reports the sounds from distant earthquakes. And, to truly conquer the oceans, we need a large number of them.

First Sound

The first prototype, MERMAID-001, fulfilled the core requirements of seismological functionality, namely, earthquake detection. **Figure 3** shows the design, including the acoustic payload of an off-the-shelf hydrophone. Data were stored on a flash memory card.

Over the course of 3 recovered field tests, MERMAID-001 gathered a mere 120 hours of acoustic pressure data from a depth of around 700 m offshore from La Jolla. Several positive earthquake identifications stood out from the noise. One of these was a tremor large enough and distant enough to prove the utility of the new instrument for

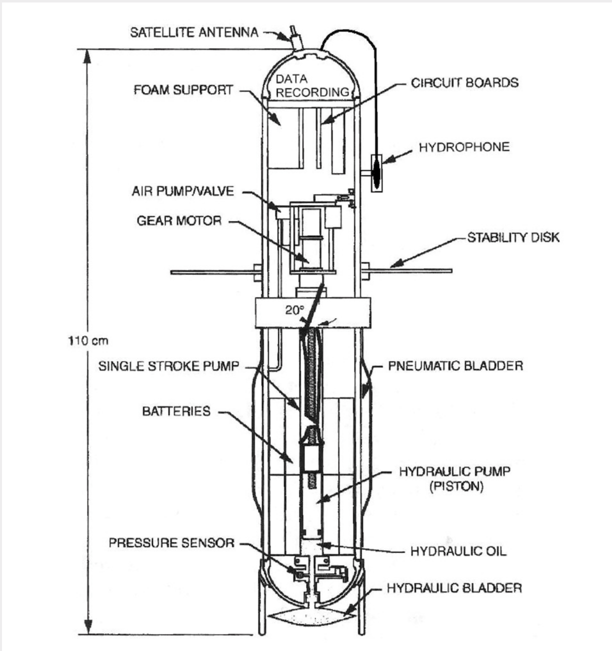


Figure 3. *The first-generation MERMAID prototype: an oceanographic profiling float equipped with an externally mounted hydrophone, and a recording and processing unit. Reproduced from Simons et al., 2009, with permission.*

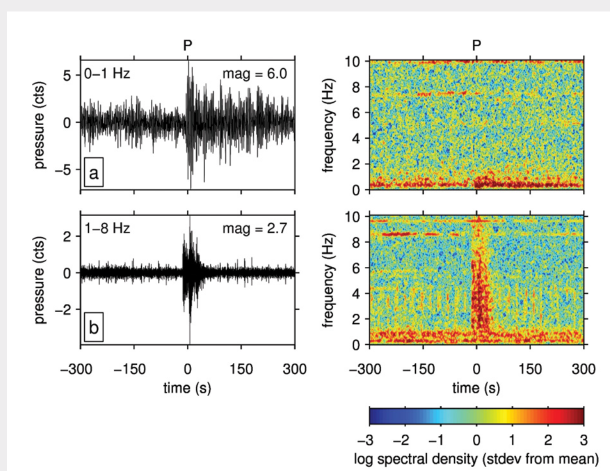
global seismology (Simons et al., 2009). Several smaller magnitude events were, strictly speaking, bycatch and not useful for deep-Earth imaging. They are, however, suitable for assessments of local and regional seismicity and to study crustal structure. The difference in character between global and local seismicity (**Figure 4**) is apparent from the records themselves. **Figure 4** shows the time-domain records, centered on the arrival of the earthquake's compressional wave marked "*P*" for "primary," and their Fourier spectrograms.

Every type of earthquake (large or small, deep or shallow, distant or close-by) has a distinct acoustic fingerprint. Efficient signal-processing techniques onboard MERMAID reduce the streaming time-domain samples to an evolving "bar code" whose character reveals which records are due to the types of waves most useful for whole-Earth wave speed imaging. Acoustic "*T*" waves from very shallow sources, for example, carry over long distances, bouncing around in the Sound Fixing and Ranging (SOFAR) low-velocity channel of the ocean itself. Recently, these have been used for water thermometry over long spatial and temporal baselines (Wu et al., 2020), but for the purposes of imaging the deep Earth, they are unwanted. Last, the ocean is full of sound (Dahl et al., 2007) that also must be filtered out. Examples are ship propellers, volcanic eruptions, glacial calving, rain, mysterious plane crashes, and, of course, sounds of biological origin. Adaptations targeting rather than avoiding such sources are straightforward. Acoustic packages tailor-made for whale census research (Matsumoto et al., 2013) and meteorology (Riser et al., 2008) are part of MERMAID's extended family.

The Second Coming

MERMAID's breakthrough came in the form of the second-generation model (Hello et al., 2011) that reported data via

Figure 4. *Seismic events detected at a 700 m depth offshore of San Diego, CA, during the recovered deployments of MERMAID-001.* ***a:*** *Only the large (magnitude [mag] 6) event is from a distant source 5,170 km from the epicenter as measured along the surface of the Earth and is thereby suited to map seismic wave speed variations in the Earth's mantle.* ***b:*** *a nearby (144 km epicentral distance) smaller (magnitude 2.7) crustal earthquake.* ***Left column:*** *filtered pressure records aligned on the first-arriving seismic "P" wave.* ***Right column:*** *Fourier spectrograms. These reveal how earthquake propagation over long distances filters out the high frequencies. Pressure conversions due to the close-by earthquake remain prominent in the range of 0-10 Hz, whereas the distant quake registers as a relatively small blip of power around 0.5 Hz. MERMAID's onboard processing unit recognizes these differences and is now tuned to preferentially report large earthquakes. The horizontal bands of energy are caused by nonseismic oceanic acoustic noise. Reproduced from Simons et al., 2009, with permission.*



satellite in near real time. That all-important autonomy enabled a series of science deployments. Signal-processing algorithms for sound decision making again proved to be critically important. Detection and discrimination routines became probabilistic (Sukhovich et al., 2011) such that MERMAID now has an evaluation and scoring system that confidently picks out segments of seismological interest and reports them to the receiving data centers.

In this context, one often wonders whether MERMAID technology could be useful for tsunami warning. The ascent from MERMAID's current parking depth of 1,500 m takes a few hours. Such a delay is immaterial for global earthquake seismology, but the instrument would need to wait even longer before surfacing until a tsunami can be confidently detected, which it would need to do at even lower frequencies than is now typical for earthquake recording (Joubert et al., 2015). Alternatively, MERMAID could be programmed to dive at a shallower depth or reengineered to rise to the surface faster. However, because tsunami waves caused by an earthquake in, for example, Chile, reach Tahiti, Hawaii, and Japan about 10, 15, and 22 hours, respectively, after the main event, Masayuki Obayashi from the Japan Agency for Marine-Earth Science and Technology (Yokosuka) calculates that there may well be an opportunity for a worldwide array of MERMAID floats to fulfill this important societal function.

Across the Mediterranean Sea, the Indian Ocean, and the Pacific, second-generation MERMAID established itself as a reliable purveyor of signals from earthquakes large and small. Although noise environments vary vastly among oceans and with the seasons, a large fraction of global earthquakes with magnitudes greater than 6.5 can be recorded, as can many smaller ones (Sukhovich et al., 2015). For example, over the course of one month in 2013, one of the floats unexpectedly reported hundreds of small earthquakes following a magnitude 5.1 shock in the Indian Ocean. Even the closest island stations recorded only a handful of the largest ones, all within a brief interval after the main shock. Hence, although mantle seismologists continue to focus on large and distant earthquakes, scientists interested in the oceanic crust will find MERMAID perfectly capable of being optimized for the study of smaller earthquakes near the instrument.

MERMAID's first coordinated scientific experiment was dedicated to imaging the mantle roots of the Galápagos volcanic hot spot. For two years, nine floats sampled seismic ray paths that illuminated mantle corridors that had never before been accessed directly. Tomographic modeling of the new data combined with data from land stations revealed that the Galápagos archipelago is underlain by a deep-seated mantle plume, with rocks buoyed up by excess temperature carrying an unexpectedly large heat flux toward the surface (Nolet et al., 2019). Those are the types of findings that MERMAID was designed to enable, that is, provocative new observations from previously inaccessible areas, leading to models that stimulate further thinking by the geophysical community.

In making the 10-year leap from prototype to scientific workhorse, the low-cost and nimble MERMAID instrument became a vital partner in the seismic exploration of the Earth's deep interior. Freely drifting midwater hydrophones fit in an Earth-observing strategy that must also contain increased ocean-bottom sensor coverage among permanent networks of (is)land-based sensors and possibly even more exotic types of data gathering (e.g., Sladen et al., 2019). Autonomous hydrophones will not replace ocean-bottom seismometers as the backbone of an ocean-wide observing system, at least in the foreseeable future. But although global arrays of three-component ocean-bottom sensors remain dreams of the future, MERMAID rules in the ocean today.

Third Is the Charm

Yann Hello at Géoazur in Valbonne, France, and a team at French engineering firm OSEAN SAS in Le Pradet, France, solved the last of the sticking points, longevity. Although data returns are variable depending on seismicity, MERMAID's life expectancy is now five years. Moreover, at every surfacing, MERMAID not only transmits seismograms but also takes instructions, for example, to update mission parameters or tweak filter settings. A glass sphere now encapsulates the batteries, electronics, and hydraulic components to achieve neutral buoyancy in the water column (**Figure 5**). On its first day-long deployment out of Kobe, Japan, a third-generation MERMAID was again so lucky as to catch a first earthquake, which arrived in the form of a local magnitude 5.2 event, dutifully reported over the IRIDIUM satellite network.

In the current commercial version, MERMAID can maintain acoustic operability down to about 3,000 m.

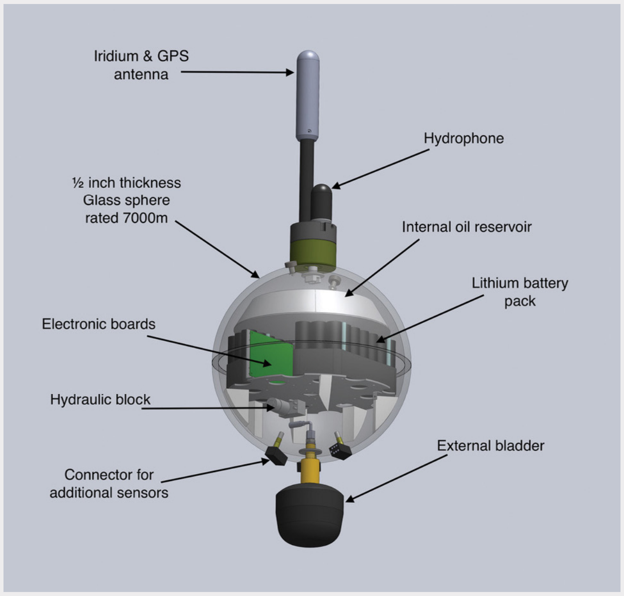


Figure 5. *Design schematic of the third-generation MERMAID float. Image courtesy of Yann Hello and OSEAN SAS.*

Future versions will sustain performance to full-ocean depths and may be equipped with "landing" capabilities such that MERMAID can become a temporary ocean-bottom hydrophone. This will allow some researchers to shift their focus from the global recording of distant earthquakes to monitoring local and regional events and listening for landslides, cracking glaciers (Deane et al., 2019), and other nonseismic signals.

Five Years

With Yongshun John Chen and his team from SUSTECH in Shenzhen, China, in the lead, the French, Japanese, and US partners joined forces. Their attention has turned to the volcanic islands of Polynesia including Tahiti, Samoa, and Marquesas among many others. What lies beneath them? A broad region of anomalously slow-wave velocities in the mantle deep under the South Pacific may feed these volcanoes via conduits of hot uprising rock that may stretch all the way from the core-mantle boundary to the surface (French and Romanowicz, 2015). High-resolution tomography is needed to understand the fine-scale nature of this planetary hot-rock plumbing system. The 50 MERMAIDs launched so far (**Figure 6**) will give scientists the large-aperture array necessary to perform detailed imaging at depth.

We have arrived at the point where acoustics ends and seismology begins. The analysis pipeline (Simon et al., 2020), focuses on matching the seismograms reported by MERMAID to known earthquakes such that seismic wave speeds can be measured. **Figure 7** shows seismograms from two distant earthquakes recorded in the Pacific. The solid travel-time curve is a prediction, based on a reference Earth model that contains only depth-based subdivisions of wave speed and no lateral variations. The seismic waves arrive around the predicted times, but the signal of the three-dimensional Earth with its internal wave speed variations lies in precisely how closely these measurements agree with the predictions. Seconds matter!

One Year of Noise

MERMAID is a low-cost solution to instrumenting the oceans for seismology, most of all because deployment is extremely straightforward. No specialized equipment or personnel is required, and recovery is possible but not mandatory if it is not cost effective. Hours after deployment at sea, the data files start accumulating on the scientists' desktop computers. A running buffer of one year is maintained, and, thanks to two-way communication capability, requests

Figure 6. *Launch of a MERMAID in the waters around Tahiti. No specialized equipment is needed. Once waterborne, MERMAID is completely autonomous and reports earthquake records via satellite, on average every 6.25 days. Photograph courtesy of Frederik J. Simons.*

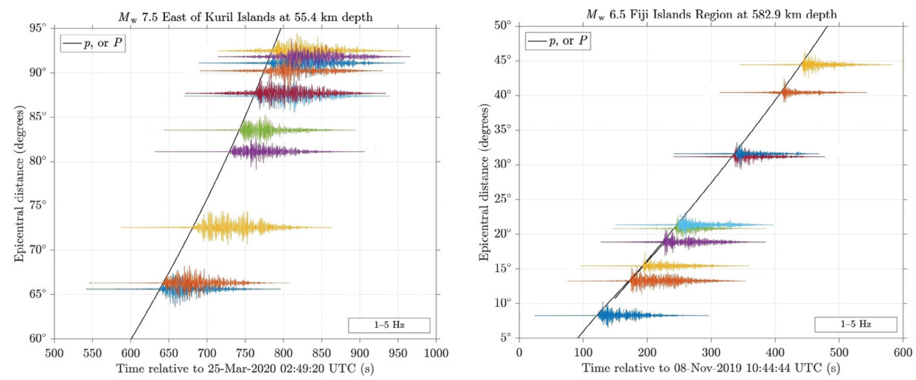


Figure 7. *Seismograms reported by MERMAIDs in the Pacific. Graphs correspond to two different earthquakes, identified by the titles.* M_w *is a measure of earthquake magnitude. The time (in seconds), is since the earthquakes' origin time. The source-receiver, or epicentral, distance, is measured in decimal degrees. Every degree is about 111 km measured along the surface of the Earth. The seismograms are drawn centered at the distance between the earthquakes' epicenter and the individual MERMAIDs, which are distinguished by arbitrary colors. The acoustic pressure records are scaled to show only relative differences in amplitude.* ***Slanted lines:*** *predictions (*p *or* P*) for when the seismoacoustic compressional waves from the earthquakes should arrive, made in simple reference Earth models. Lowercase p waves travel up from the earthquake; uppercase P waves propagate down into the Earth before curving back to the surface. When the seismic waves arrive later than predicted, as they do in this region, the mantle through which they propagate before conversion to acoustic pressure at the ocean bottom is slow and, by inference, hot, which is in line with the idea that deep zones of buoyant material feed the abundant volcanoes in this area of the Pacific.*

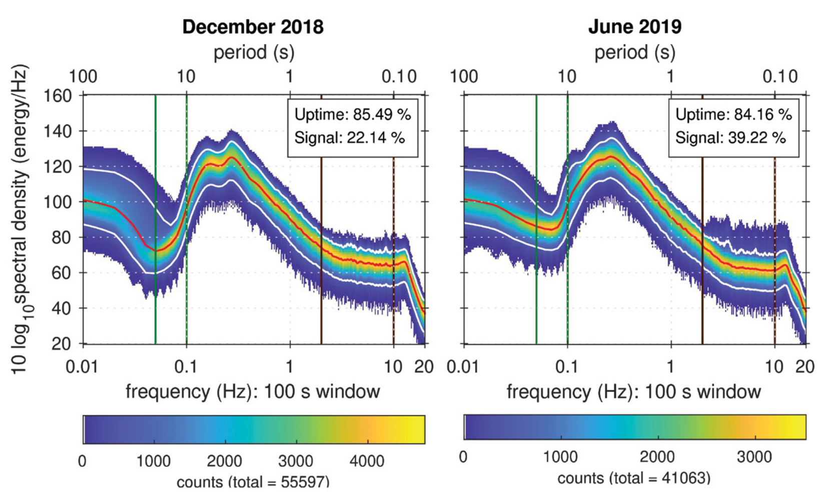


Figure 8. *Distribution of energy per frequency interval, or spectral density, of acoustic noise at a 1,500 m depth in the Pacific as captured by MERMAID's hydrophone. In the months shown, the instrument was turned on for close to 85% of the time (uptime); 22% and 39%, respectively, (signal) of the record contained earthquakes and other "signals" that were removed so as to leave only the ambient "noise" of the ocean itself. The stored 1-year record was divided in 100-second-long segments whose spectral densities were calculated, and their collective distribution is rendered as a color density map.* ***Red curves****, median spectral densities for each month, and their white envelope marks the 5th and 95th percentiles.* ***Vertical lines****, frequency intervals of interest for earthquake (****green curve****) and hydroacoustic (****black line at bottom****) observations, respectively. Seasonality is most apparent in the frequency range of 0.08-0.8 Hz and can be clearly linked to a mechanism whereby wind-generated surface water waves couple to acoustic waves at double the driving frequency. Newly modified MERMAIDs will specifically target and report these sources of ambient noise for studies of the marine environment.*

can be made to complement and extend the triggered and automatically reported datasets.

The spreading out of MERMAID deployments did allow for a unique opportunity. After about one year of continuous operation in the Pacific, one MERMAID was recovered and its buffer was read out. Access to the continuous time series helps us understand detection sensitivity and evaluate the performance of the triggering algorithm. The complete record includes the first-arriving seismoacoustic *P* waves of our primary interest but also later arriving wave types such as the purely hydroacoustic, or *T*, waves. The *P* waves mostly travel in the mantle before being converted to acoustic energy in the ocean. The *T* waves for the most part travel in the water layer itself, and they are thus not useful for imaging of the solid Earth.

Excising all those "signals," we are left with the "noise" soundscape of the marine environment at 1,500 m depth, which enables us to study its seasonal variability. **Figure 8** shows two noise power-spectral densities for different months. The sensitivity of the hydrophone decreases steeply below 0.1 Hz, and, in **Figure 8**, filtering has removed the signal above 10 Hz. The very low frequency (VLF) acoustics band above 5 Hz largely contains human-made noise, mainly from shipping. The broad peak of power is caused by wind and wave action at the ocean surface. Such noise is also observed at the ocean floor and even through reverse conversion of acoustic pressure to elastic waves on distant land stations. It constitutes the dominant "secondary microseismic" noise contribution that Bradner set out to observe in situ back in the 1970s. We have come full circle. A group of MERMAIDs modified to report ambient noise spectra rather than earthquake signals was commissioned by Lucia Gualtieri at Stanford University (Stanford, CA) for deployment in the Mediterranean and the Atlantic in the year to come.

United We Dive: EarthScope Oceans

The MERMAID project evolved from a single prototype to a fledgling fleet of promising newcomers to a now 50-strong array of robust third-generation units with a lifetime of 5 years that is currently floating about, collecting acoustic data for seismological science. The story of how we got there is one of selfless collaboration across generations, between individuals, institutions, and nations. The EarthScope Oceans consortium (see www.earthscopeoceans.org) was founded to coordinate efforts worldwide. It intends to shepherd projects into the international arena where globally relevant, and mutually agreed upon, decisions can be made on instrument development, science objectives, data management, and outreach activities, much like the land-based seismological academic community is doing today. Indeed, EarthScope Oceans already deposits data and metadata with the Data Management Center of the Incorporated Research Institutions for Seismology (IRIS) in Seattle, WA.

The Fourth Generation and the Great Beyond

MERMAID's fourth generation will carry more than just acoustic sensors, and the instruments will become fully programmable, even reprogrammable, midmission. The computer language developed for this purpose, MeLa (Bonnieux et al., 2020), is the bridge between engineers worried about hardware constraints, computer scientists specialized in the design of low-power embedded systems, and the multiple end users who will simply want to focus on maximizing scientific data return. Observation modes will be able to flexibly switch between, for example, earthquake observation, noise recording, whale call identification, and profiles of salinity or biogeochemical measurements. A mobile app, Adopt-A-Float, exists to animate classroom outreach activities. By including seismologists and acousticians, biologists and bioacousticians, physical and chemical oceanographers, meteorologists and climate scientists, and others, EarthScope Oceans will become even more multidisciplinary. Collaboration with other ocean-observing programs will enable cost-effective instrument deployment and opportunistic recovery by nonspecialized vessels, such as cruise ships or pleasure yachts.

In the years to come, MERMAID will carry more instrumental payload, dive deeper, travel farther, and live longer. Many hands (on few decks) will make light work. Consider yourselves invited to join the community. Sound, after all, is an Essential Ocean Variable (see acousticstoday.org/ocean-soundscapes).

Acknowledgments

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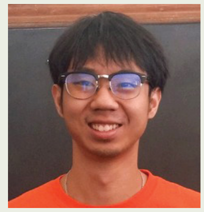

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