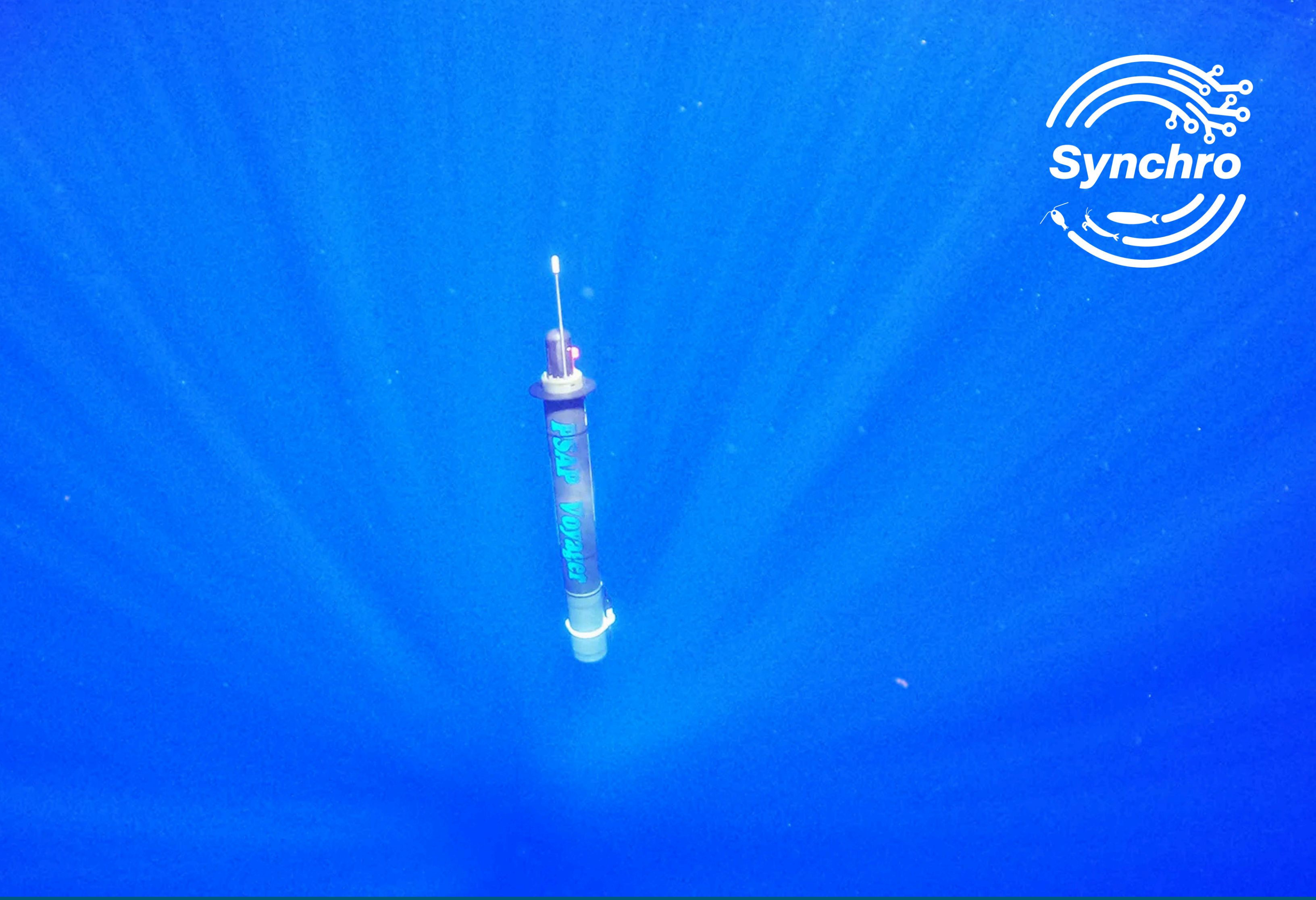

Testing & Evaluation Report:

InfiniTE™ Float: Energy-Harvesting Acoustic Profiling for Long-Term Ocean Soundscape Monitoring

SEATREC

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infiniTE™ Float: Energy-Harvesting Acoustic Profiler for Long-Term Ocean Soundscape Monitoring

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Introduction

The Persistent Smart Acoustic Profiler (PSAP) is a new autonomous oceanographic and passive acoustic sensing platform designed to provide scientists with a long-endurance monitoring capability, particularly useful for monitoring ocean soundscapes [1]. PSAP is built on the infiniTE™ profiling float developed by Seatrec, Inc. located in Vista, California. The infiniTE™ float is powered by the energy harvested from the temperature gradients in the ocean [2]. With the unlimited energy from the ocean, the raw acoustic data can be processed onboard to extract the essential information to be transmitted to satellites. This soundscape data can quantify biological and ecosystem variables such as the occurrences and behaviors of marine life, including marine mammals and fish, along with data on oceanographic conditions from temperature, salinity, chlorophyll-a and more. PSAP can be easily handled by two people, making it easy to deploy and recover from a small boat. It uses a buoyancy engine to move up and down through the water column. Like a hot-air balloon that uses wind shear to steer it, PSAP can use current shear at different depths to keep it near a preferred location. Because PSAP can tap into an endless supply of energy and is able to process data onboard and transmit the products to shore in near real-time, the profiler can be deployed once and not require recovery, providing monitoring of the soundscape for an extended period. This mode of operation reduces operating expenses significantly since there are no costs associated with recovery, refreshing or replacing the system.

Passive acoustic monitoring (PAM) is gaining traction for quantifying several information user needs for place-based management. This includes understanding the dynamics of protected and managed species in relation to tourism, commerce, and energy development; National Marine Sanctuaries and marine protected area management, and variables tracked to inform stock assessments such as with the Integrated Ecosystem Assessments conducted by the National Oceanographic and Atmospheric Administration (NOAA). Moreover, the increase in ocean energy industry development is also driving the need for greater access to PAM data in both the United States, such as with the Bureau of Ocean Energy Management (BOEM), and internationally. This novel PSAP system, when parked at 400 meters, has been shown to detect the same soundscape as a cable-powered hydrophone anchored at 900 meters (see Figure 2; also in [2]). Now, PSAP can be deployed anywhere in the world to monitor soundscapes in the ocean. Work has been conducted using this novel PSAP system to evaluate the questions 1) What is the performance of this system when compared to a fixed station with the same hydrophone, and 2) What are the platform performance characteristics in terms of net daily power loss or gain, compared to a solely battery driven profiler?

The System

PSAP is 2 m tall, 30 cm in diameter and weighs approximately 50 kg. An icListen hydrophone by Ocean Sonics is attached to a mount located at the bottom of the profiler with its cable running the length of the profiler body. The icListen is programmed prior to deployment to sample at a set rate. The sampling rate determines the maximum frequency which can be resolved in the data which, in turn, determines which soundscape contributors will be observed.

Image 1. PSAP deployment off NOAA's RV Fulmar in Monterey. The icListen hydrophone is circled in red.

Near the top of the PSAP, a Conductivity-Temperature-Depth (CTD) sensor made by RBR Global collects oceanographic information that is sent back to shore. The temperature difference between the upper ocean and the parking depth the float is programmed to achieve is critical to the energy harvesting process. The temperature difference causes phase-change material (PCM) to freeze and melt. As the PCM melts, it expands, forcing high-pressure hydraulic fluid to turn a generator that, in turn, charges a battery for energy storage. This process is repeated as needed to keep the float in a healthy state.

An Iridium antenna is located at the very top of the PSAP. As the profiler reaches the ocean surface, the antenna stands approximately 30 – 50 cm above the water. Once it locks on to satellites, PSAP passes location information, system health data, and both oceanographic and acoustic product files to shore while also downloading new instructions, as needed. It should be pointed out that the Iridium satellite has a very limited bandwidth of less than 2 kbps using RUDICS (Router-based Unrestricted Digital Internetworking Connectivity Solution) with Point-to-Point Protocol (PPP). Time at the surface is minimized to a few minutes as rough sea conditions may cause damage to the topside sensors and antennas, and strong surface currents may push the PSAP in an undesirable direction.

The PSAP is limited to a maximum 900 m diving depth simply because the icListen RB9 hydrophone is rated for 900 meters, although the infiniTE™ float has a depth rating of 1,000 meters. Vertical temperature gradients are weak at these depths and therefore there is little incentive in going deeper for energy harvesting purposes. Acoustically, the PSAP is already well into the deep sound channel while at or above 900 meters. Therefore, there is no acoustic advantage to dive deeper. Also, by having the PSAP park at deeper depths for long periods, this minimizes the accumulation of biofouling during long-endurance missions.

The PSAP has three distinct modes of operation that enables it to function like no other soundscape monitoring system – (a) an energy-harvesting mode, (b) a listening mode and (c) a communications mode. To harvest energy from the local environment, the profiler moves up-and-down through the thermal gradient of the water column using its energy-efficient buoyancy engine. This operation is typically conducted every 6-8 hours to sustain the energy budget but can be conducted as often as needed to ensure PSAP remains sufficiently powered. In listening mode, the PSAP is parked at a target depth typically in the range of 400-600 m. In midlatitude environments, sound is refracted downward from near-surface sources such as marine mammal vocalizations and ship passages [3]. By having PSAP drift at depth, there is no flow noise induced by the movement of the hydrophone through the water and there are no other system noises generated from the buoyancy engine or energy harvesting system. Without self-noise from the PSAP, the hydrophone is able to receive sounds from a wide acoustic aperture without frequency masking. During listening mode, data processing is occurring on a small form-factor Linux board, preparing the files that will be eventually transmitted to shore. It should be noted that in the current system configuration, acoustic recording occurs during defined intervals within each dive cycle rather than continuously, with the duty cycle determined by the available energy budget.

When the profiler surfaces, it goes into communications mode setting up a two-way communication path by linking to Iridium satellites. PSAP passes GPS position information, system engineering data, temperature profiles and soundscape acoustic information to shore. It also downloads any new mission commands, as needed. Operators can adjust mission parameters, including the acoustic recording sample period and duty cycle, while the float is deployed, based on diagnostic data transmitted from the instrument. Currently, PSAP transmits processed data products including spectral probability density (SPD) statistics and spectrogram images. Raw acoustic data are stored onboard and can be retrieved upon float recovery. The capabilities and limitations of onboard processing and data transmission are discussed in further detail below.

PSAP has a unique advantage over moored receivers or ocean gliders which require recovery, regular battery replacement and redeployment to continue working. The cost of parts, labor and ship time to support continuous operations of those systems grows significantly with time. In order to continue monitoring coverage with expendable systems, replacement and redeployment costs also become significant over time. Autonomous profiling floats already used in the Argo programme have partly addressed this problem. However, Argo floats powered by primary batteries have a finite battery life, typically cycling once every 10 days and supporting only low-power sensors like CTD and BGC (Biogeochemical) sensors. The Seatrec infiniTE™ floats have completely solved this problem by harvesting energy from the ocean's natural temperature gradient for battery recharging throughout the float mission. Because the float continuously harvests energy from the ocean, there is no power penalty for more profiles, enabling profiling as frequent as every 6 hours to 1,000 meters. By eliminating power bottlenecks, PSAP can now carry both a hydrophone and oceanographic sensors such as a CTD and BGC simultaneously.

The energy harvesting module uses phase change materials (PCMs), which change phases between solid and liquid state across the phase change temperature. When the float is parked at 1,000 meters, the ocean temperature is usually cold (e.g., 4-8 degrees Celsius) and the material exists as a solid state. As the float ascends to warmer surface waters (>15 degree Celsius), the material melts into a liquid. This phase change from solid to liquid induces a volume increase that will generate a hydraulic pressure to spin a motor and generator to generate electricity to charge the internal batteries of the float. Different PCMs with different phase change temperatures can be selected for different geographic regions. The stronger the temperature gradient from deep ocean to the surface promotes a more rapid phase change. Therefore, it is more advantageous to operate the float in regions of warmer surface waters as opposed to temperate or arctic regions (<15 degrees Celsius).

With sufficient energy remaining, PSAP carries a commercial off-the-shelf (COTS) Linux computer for onboard processing to reduce acoustic data volume for near real-time satellite transmission. Users can purchase this COTS Linux computer and develop the data processing algorithms in the laboratory environment. Once developed, the processing codes are uploaded to PSAP for ocean testing. During the early stage of the algorithm development, PSAP floats can be deployed with multiple surfacing events to transmit the processed data to satellites in real-time and recovered for a selected period of time (e.g., one week) assuming within reach of a recovery vessel.

Once the PSAP float is recovered, the raw hydrophone data can be retrieved. By comparing the onboard processed data against the raw data, users can improve the onboard data processing algorithms. Multiple algorithms can be loaded on PSAP floats. When floats are at the surface, users can pick a particular algorithm (e.g., switching from a power spectra to monitor ambient noise to a detector to monitor Rice's whale). PSAP floats can be deployed and recovered multiple times to further iterate and improve the onboard data processing algorithms. Once the data processing algorithm is finalized, the PSAP float can be deployed for a long-endurance (e.g., multiple years) mission without the need of recovery.

Field Tests

Three PSAP field tests have been conducted off the California coast, two in Monterey Bay in central California and one in southern California near Oceanside, California. The first two were 24-hour tests consisting of three 8-hour dives to around 400 m. They were primarily shakedown tests to ensure sensors worked properly and acoustic receptions were clean without any significant interference from system self-noise. For all three tests, the float was recovered and the raw hydrophone data were retrieved. This raw data allows us to develop the onboard processing algorithms as required for future missions when floats will not be recovered.
In the first test at Monterey Bay on 17 - 18 Aug 2023, PSAP was deployed in the vicinity of the Monterey Accelerated Research System (MARS) cabled observatory, which is operated by the Monterey Bay Aquarium Research Institute (MBARI) in Moss Landing, California. MARS has an icListen hydrophone identical to the PSAP hydrophone that is installed at the ocean bottom in 900 m water depth. PSAP soundscape data for the full deployment are shown in Figure 1.

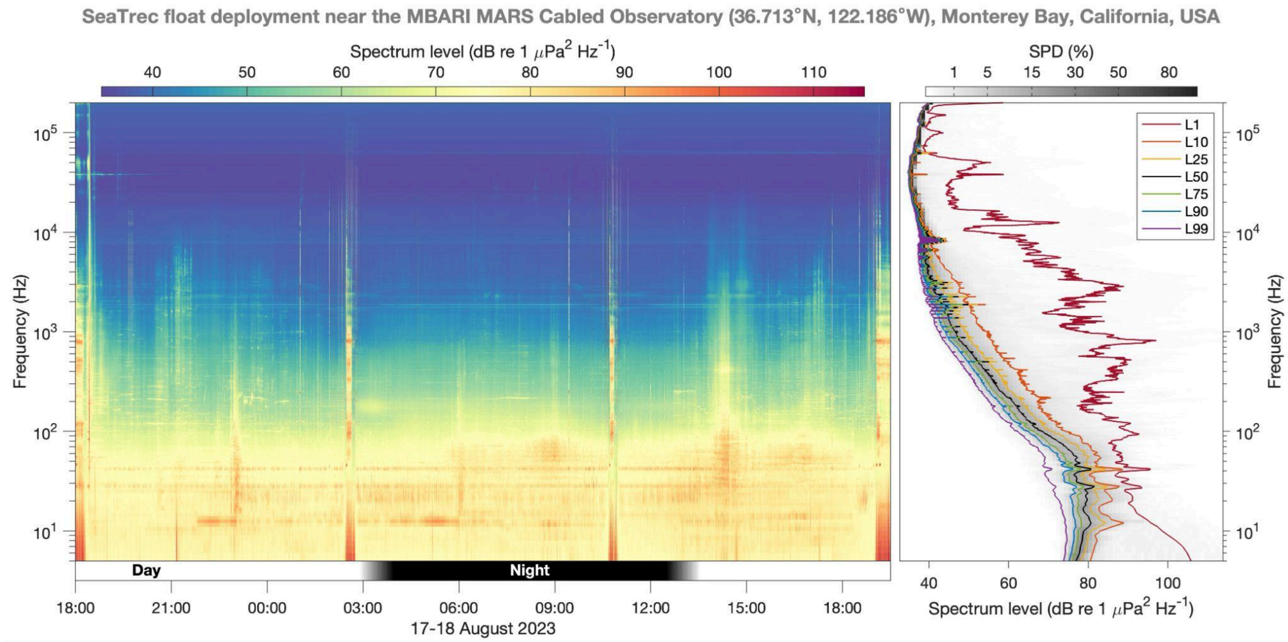

Figure 1. (left) A 24 hour period of sound spectral data taken from the August 2023 deployment near the MARS cabled observatory. (right) SPD is spectral probability density and L* spectra are exceedance levels from the full deployment.

Direct comparison of recordings from PSAP and MARS illustrate the clarity of signal capture from two endangered species – blue and fin whales – using an acoustically quiet float platform (Figure 2). At the time of the spectrograms, the two hydrophones were about 3 km apart and the PSAP at 400 m depth. At both locations, calls from fin whales (20 Hz) and blue whales (28 and 42 Hz) are evident. The details of the two spectrograms show both hydrophones were clearly listening to the same soundscape. The track of the PSAP during this test was driven primarily by currents at 400 m. It is not uncommon for the currents in Monterey Bay to have a generally circular pattern, which kept the PSAP in the general vicinity of the MARS site through the entire test.

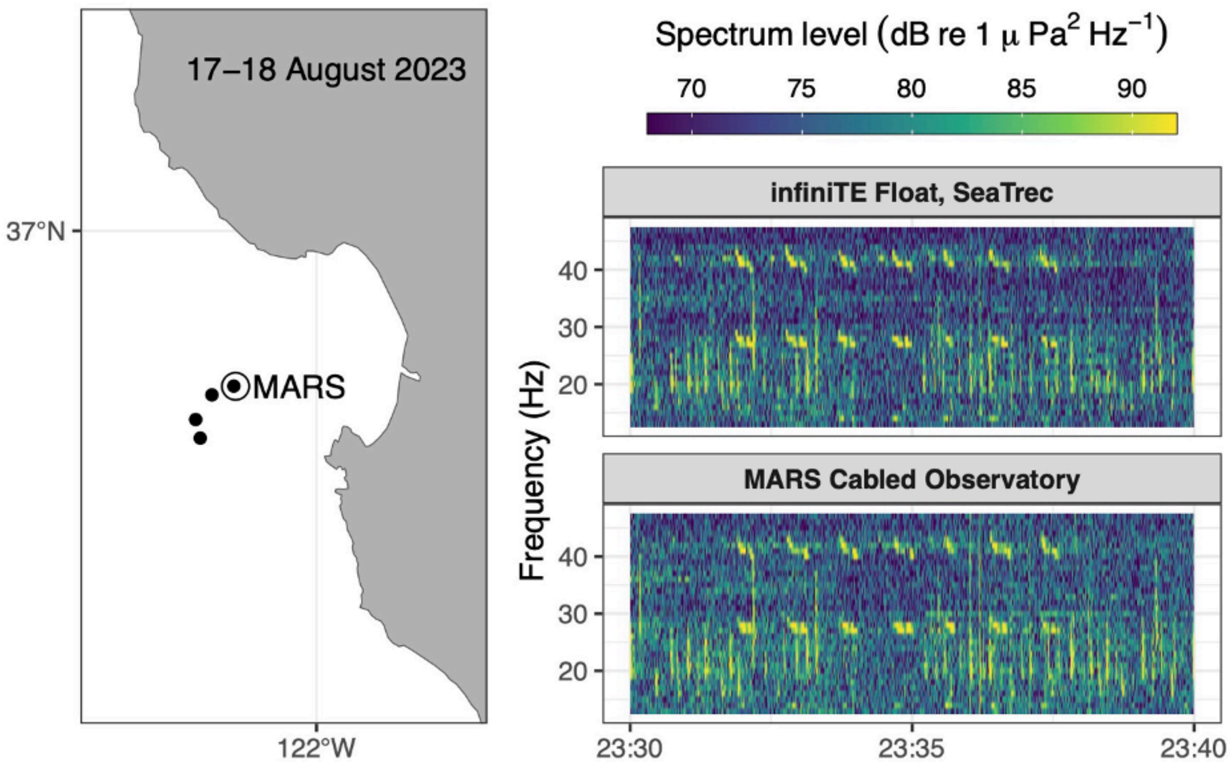

Figure 2. Ground truth comparison. The map shows the location of the MARS cabled observatory (open circle) and the deployment and surfacing locations of the infiniTE™ float (solid circles) during 17-18 August 2023. The spectrograms are from 17 August and were aligned in time to facilitate comparison of signals across the recording platforms. Each recording was made using an Ocean Sonics icListen HF hydrophone.

The second test was conducted near Oceanside. The goal was to minimize self-noise that was identified during the first test. Besides meeting that goal, two other notable outcomes were observed from this test. First, the warmer waters of southern California were much more efficient for energy harvesting purposes and second, the acoustic environment near the test site was much noisier due to naval activities taking place nearby during the test.

The third test was conducted in Monterey Bay from 17 April – 02 May 2024 supported by Synchro. This 10-day experiment was designed to demonstrate the system's unique attributes of using energy harvesting to sustain the profiler's energy budget while capturing soundscape signals of interest, processing the data onboard and transmitting related products over satellite communication to shore with each PSAP surfacing. Examples of 10-minute spectrograms display the acoustic signatures of a humpback whale song while PSAP was in listening mode at 500m (Figure 3a and 3b). Both plots show the presence of a singing humpback and ship noise, rendered on the same intensity scale, with the April 17 recording (Fig. 3a) showing considerably brighter signals indicating both sources were in close proximity to the PSAP. In the April 17 recording, the humpback whale abruptly ceases singing at ~7 minutes, a behavioral change possibly associated with the nearby vessel. Additional weak signals are also identifiable in the spectrogram, including a probable fin whale call near 20 Hz at ~5:10 minutes and probable blue whale A and B calls near 40 Hz at ~6:10 and ~7:05 minutes, respectively. The April 25 recording (Fig. 3b) captures the same sources at greater range, with wind-generated broadband noise above ~100 Hz more clearly visible. The humpback vocalizations were simultaneously recorded on the nearby MARS hydrophone and an acoustic recorder mounted on a Spray ocean glider operating in the vicinity, validating the acoustic performance of the PSAP (Figure 4). Due to the relatively cool surface waters of Monterey Bay, especially during upwelling episodes, the PSAP was set to only record during the first 30 minutes of each 8-hour dive. Future development work will focus on finding efficiencies in the energy budget, data collection and signal processing that will enable continuous recording while in listening mode and passing all the soundscape information to shore in near real-time.

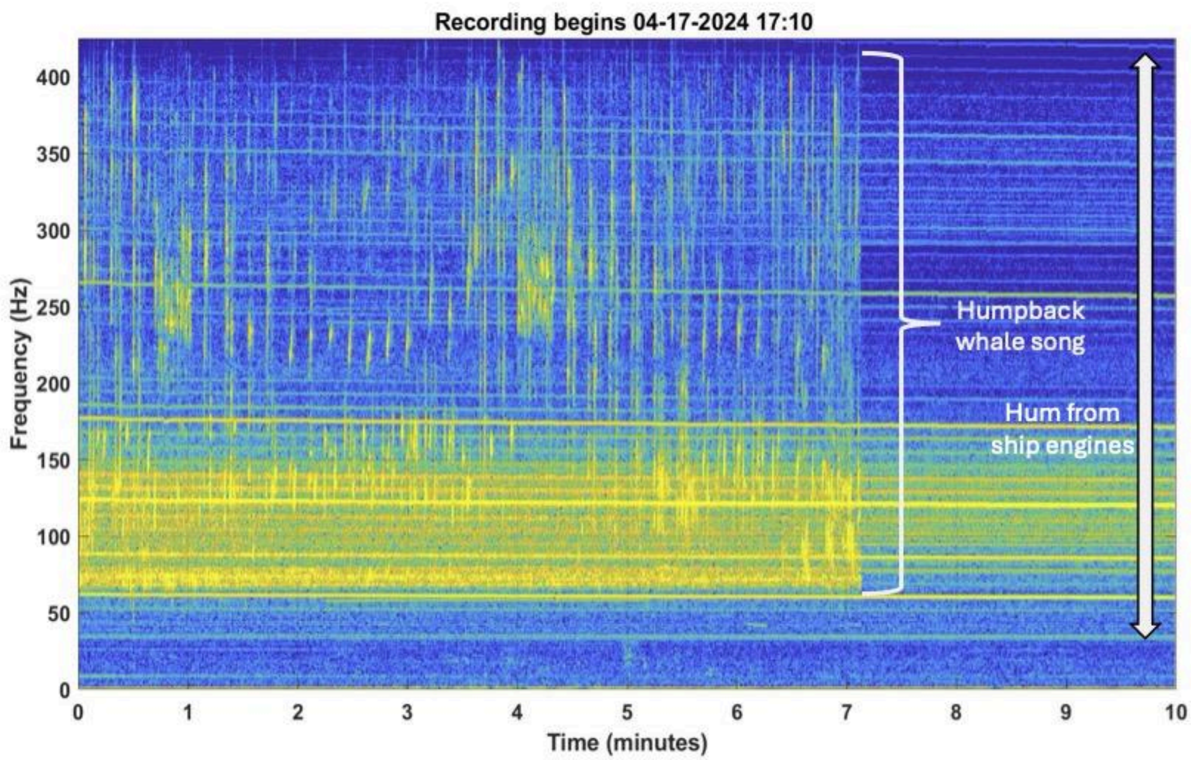

Figure 3a. A 10-minute spectrogram collected by PSAP on April 17, 2024 near Monterey Bay showing humpback whale song and ship noise in close proximity to the PSAP. The whale abruptly ceases singing at ~7 minutes. Weak signals consistent with fin whale (~20 Hz) and blue whale A and B calls (~40 Hz) are also identifiable.

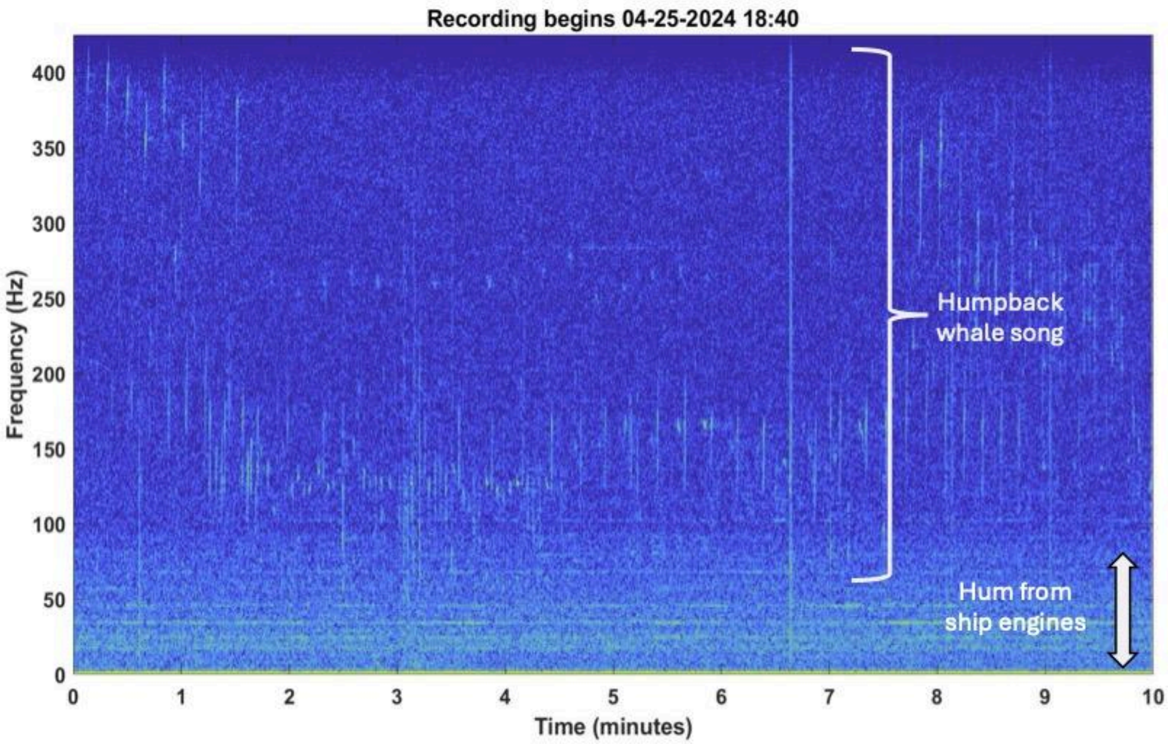

Figure 3b. A 10-minute spectrogram collected by PSAP on April 25, 2024 near Monterey Bay showing humpback whale song and ship noise from a more distant source. Wind-generated broadband noise above ~100 Hz is more clearly visible compared to Fig. 3a.

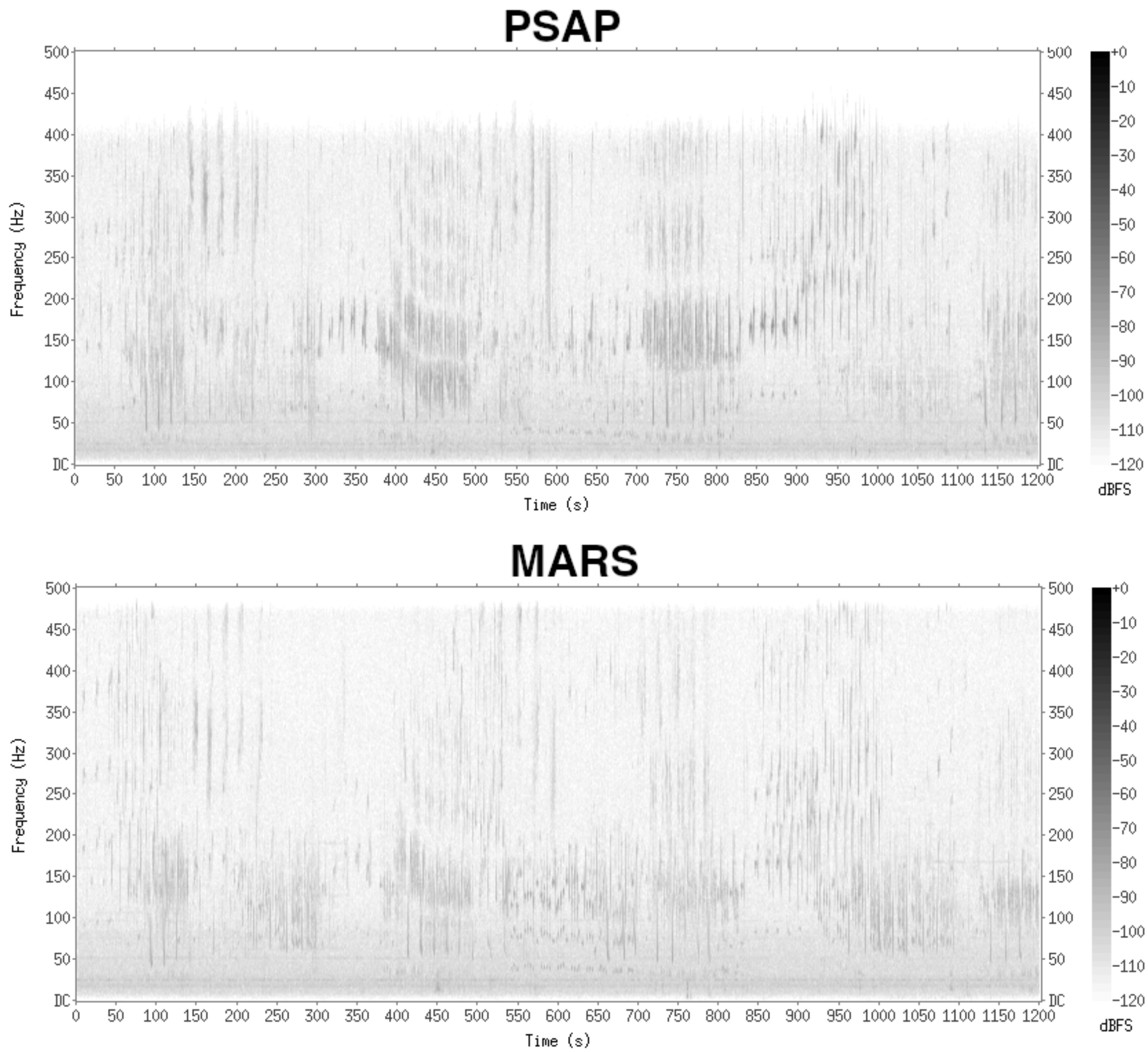

Figure 4. Song from multiple humpback whales, simultaneously recorded on PSAP and the MARS cabled observatory, demonstrating that PSAP is capable of picking up clean acoustic signatures to identify various components of the soundscape. Start time is 17:40 UTC on 25-Apr-2024. At the time of these recordings, PSAP was ~4.5 km ESE of MARS (bearing 116 degrees from MARS).

Additional Field Testing

The three previous short-term tests ensured PSAP was ready to perform a multi-month demonstration. In November 2024, the PSAP Voyager was deployed a few miles off the Kona Coast of Hawaii’s Big Island to evaluate its end-to-end functionality, including its ability to maintain a balanced energy budget throughout a multi-month operation. Once deployed, it was intended to let the PSAP drift with the currents without further at-sea support for recovery. Upon release from a small fishing vessel, the float followed the flow of a clockwise gyre west of the

Big Island and traveled due south along the coast until it came out of the lee of the island, after which the PSAP followed a meandering path generally to the south of the island in a box bounded by 14.8ºN to 18.8ºN between 157.4ºW and 172.2ºW. After more than 8 months of flawless operation, PSAP conducted over 1000 dives to 700m depth on a 6-hourly cycle. As it became clear that the energy harvesting was maintaining a strong net-positive energy budget, the listening time was increased from two 10-minute periods per dive to three and sometimes four 10-minute periods per dive while drifting at depth in the deep sound channel. On this deployment, a new onboard data processing method was implemented on an internal Linux board executing a Python-based hybrid millidecade spectral [5] analysis algorithm that distilled the raw acoustic data to spectral probability density (SPD) statistics from each 10-minute recording. Given the short communications window that PSAP has at the surface (~15 minutes) to pass science and engineering data ashore and receive new instructions, it was not feasible to pass all raw acoustic data files to shore over the low Iridium bandwidth. However, the SPD files were only on the order of a few kilobytes each and were easily transmitted to shore. This test successfully demonstrated all the key functionality that PSAP was designed for: (a) operating independently of other assets, (b) providing a continuous stream of real-time standardized ocean-acoustic data products to shore, (c) unlimited endurance and (d) reliable 2-way communication from remote locations.

Future Work

The first iteration of PSAP has demonstrated a new concept of operation – that is a small autonomous soundscape monitoring system that can be deployed once and provide information about the soundscape in near real-time for extended periods without expensive refreshing or replacement support costs. As is the case for many first attempts, there is room for improving PSAP performance. Three primary areas of focus are reducing energy use, increasing communication bandwidth, and delivering more complete information about the entire soundscape without overloading the processing or communications throughput.

To reduce energy usage, new smart hydrophone technology that uses less power is being developed. By reducing the energy demand on the order of a factor of 5 – 6, the goal of having continuous recording while the hydrophone is in listening mode is achievable and may be available within a year. Furthermore, a lower-power hydrophone would enable acoustic recording during energy-harvesting mode, when the float is actively moving through the water column.

Affordable high-bandwidth satellite communication plans that can be utilized on small autonomous systems like PSAP are forthcoming. This will allow more soundscape information to be transmitted ashore in real-time without extending the surface time of the profiler.
The primary soundscape product files sent ashore during the latest PSAP test were images of 10-minute spectrograms that a trained analyst could use to identify useful soundscape features such as humpback whale calls, small vessel operations (likely whale watching boats) and

variable wind-generated noise [4]. These products were a proof of concept that acoustic signals collected on the profiler could be processed and transmitted to shore in near real-time in a useful format. The new products can be compressed into files that are a few tens of kilobytes in size and are practical to transmit over current Iridium links during PSAP surfacing. These statistics will characterize the soundscape in much greater detail based on the attributes of sounds produced by various soundscape contributors. Periodic float recovery also provides access to the full raw acoustic record, enabling analysis of vocalizations not yet assigned to a species and for which no automated detectors currently exist. These analyses can inform the development of new onboard detectors, progressively expanding the range of soundscape contributors that PSAP can identify and report in near real-time.

Deploying a passive acoustic system on a profiling float can meet several key information needs for agencies such as NOAA's National Marine Sanctuaries, the Bureau of Ocean Energy Management (BOEM), and Integrated Ecosystem Assessment (IEA) programs. For National Marine Sanctuaries, PAM detects and monitors marine life including mammals, fish, and invertebrates; characterizes visitation and other human uses of sanctuary waters; supports the development of ecological baselines; identifies drivers of and measures change including recovery; tracks the status and trend of resources over time; and provides insight into anthropogenic noise impacts from vessel traffic, construction, military activities, and offshore industry. BOEM can use acoustic data to assess the environmental impacts of offshore energy development by monitoring underwater noise, detecting the presence of protected species in lease areas, establishing pre-construction acoustic baselines, and post-construction monitoring. For IEA programs, PAM enhances ecosystem-based management by contributing indicators of biological activity, such as fish choruses or predator-prey interactions, and by supporting integrated assessments of spatial and temporal ecosystem trends. Across all stakeholders, PAM-equipped profiling floats can offer real-time or near-real-time insights into species distributions, shifting ocean soundscapes due to climate change, and even the detection of illegal activities in protected zones, making them a valuable tool for marine resource management and conservation.

Acknowledgements

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