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Immersive Underwater Audio Capture Using a Wideband Spatial Hydrophone Array

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ABSTRACT

Immersive audio continues to expand beyond traditional studio and terrestrial field-recording environments, yet underwater soundscapes—particularly those involving marine mammals—remain largely documented in mono or stereo formats. This paper presents a practical and low-cost approach for capturing immersive underwater audio using a newly developed wideband hydrophone and a multichannel array optimized for marine environments. The hydrophones, designed by the author, feature a low noise floor, extended frequency response exceeding 100 kHz, and direct compatibility with standard P48 phantom-powered audio recorders, enabling deployment without specialized underwater preamplifiers or power systems.

To translate established immersive recording techniques into the ocean environment, an array architecture was developed based on a compact eight-element cube geometry. Two variants of the array were constructed to account for the significantly higher speed of sound in water compared to air, allowing the spatial characteristics of underwater sources to be captured with appropriate inter-element spacing. Field recordings were conducted off the coast of Hawaii in January during the peak season for humpback whale song. Recordings were made at multiple depths and positions to explore variations in reverberation, propagation, and ambient biological activity.

Preliminary results indicate that the system captures detailed spatial cues from humpback whale vocalizations while simultaneously preserving the rich ambient marine soundscape. The extended ultrasonic response further allows slowed or pitch-shifted playback to reveal fine temporal structures not typically audible. This work demonstrates a feasible method for immersive underwater recording and provides a foundation for both scientific research and creative content production.

1 Introduction

Immersive audio has experienced significant growth in recent years, both in the development of spatial audio formats and in the ability to reproduce those formats in multichannel loudspeaker systems. Portable multichannel field recorders such as the Zoom F8n Pro and Sound Devices MixPre-10 II have made it practical to capture large numbers of microphone channels simultaneously. These devices provide up to eight high-quality microphone inputs, operate from battery power, and can run for many

hours in remote recording environments.

While immersive recording techniques are now well established for terrestrial sound capture, underwater immersive recording remains a relatively unexplored area. A review of the literature reveals only a limited number of examples. One paper describing the adaptation of stereo techniques to underwater recording [1] notes that during production of the film *The Hunt for Red October*, underwater audio was reportedly captured by placing a pressure zone microphone (PZM) inside a metal can and submerging it. Other field recordists have improvised

by wrapping inexpensive dynamic microphones in plastic and lowering them into the water.

More recently, the sound team for the documentary *My Octopus Teacher* reportedly deployed waterproof action cameras on the kelp bed primarily to capture the associated underwater audio environment. These approaches demonstrate the interest in underwater sound capture, but they also highlight the lack of purpose-built tools for spatial underwater recording.

One notable exception is a paper describing an underwater spatial recording system [2]. Delikaris-Manias *et al.* describe using a tetrahedral hydrophone array to create a first-order Ambisonic microphone. While this work demonstrates the feasibility of underwater spatial recording, practical systems suitable for field deployment remain limited.

This paper presents a practical approach to immersive underwater recording based on a newly developed wideband hydrophone and a compact multichannel array geometry. Specifically, this work describes:

- A phantom-powered wideband hydrophone compatible with modern field recorders
- A compact immersive hydrophone array geometry suitable for marine deployment
- Field recordings of humpback whale vocalizations captured in immersive format
- Practical observations on underwater spatial recording techniques

The system was deployed during field recordings conducted off the coast of Hawaii during the humpback whale breeding season, providing an opportunity to evaluate immersive recording techniques in a biologically active underwater environment.

2 Background: Underwater Acoustics and Hydrophones

2.1 Acoustic Properties of Water

Sound propagation in water differs significantly from that in air, primarily because water is far less compressible. This property corresponds to a much larger bulk modulus, which leads to a higher speed of sound according to

$$c = \sqrt{\frac{K}{\rho}} \quad (1)$$

where

$$\begin{aligned} c &= \text{speed of sound in the medium m/s} \\ K &= \text{the bulk modulus of the medium Pa} \\ \rho &= \text{density of the medium Kg/m}^3 \end{aligned}$$

Although water is also much denser than air, the increase in bulk modulus dominates. As a result, typical values are:

$$\begin{aligned} c_{\text{air}} &\approx 345 \text{ m/s} \\ c_{\text{water}} &\approx 1500 \text{ m/s} \end{aligned}$$

For a given frequency, the resulting acoustic wavelength is therefore approximately 4.4 times longer in water than in air. This has important implications for hydrophone array design, particularly in determining appropriate sensor spacing and spatial sampling requirements.

Another key difference arises from the much higher acoustic impedance of water, defined as

$$Z = \rho c \quad (2)$$

where

$$\begin{aligned} Z &= \text{acoustic impedance (Rayl)} \\ Z_{\text{Air}} &\approx 4.1 \times 10^2 \text{ Rayl} \\ Z_{\text{Water}} &\approx 1.5 \times 10^6 \text{ Rayl} \end{aligned}$$

Because the acoustic impedance of water is several thousand times greater than that of air, sound energy couples very poorly between the two media. This is why most airborne sound reflects strongly from the surface of water. Within the water itself, however, the higher acoustic impedance results in efficient pressure transmission and relatively low attenuation, particularly at low frequencies.

Hydrophones measure acoustic pressure rather than particle velocity, making them well suited for underwater environments where pressure fluctuations dominate the acoustic field and can propagate over very long distances. Low-frequency sounds can travel hundreds or even thousands of kilometers in the ocean, enabling species such as humpback whales to communicate across vast distances.

The underwater acoustic environment is further complicated by strong reflections from both the water–air interface at the surface and the water–seafloor interface below, creating a complex and highly reverberant sound field.

The ocean noise floor also differs substantially from that of the atmosphere. The classic work by Wenz [3] characterizes the dominant noise sources in the ocean as a function of frequency. These include turbulence, shipping, wind-driven surface noise, and biological activity. One important reference used throughout underwater acoustics is sea state, which describes the background noise level of the ocean generated primarily by wind-driven surface motion. These noise levels will later be used as a reference when evaluating the self-noise and dynamic range of the hydrophone system presented in this paper.

2.2 Hydrophone Transducers

The mechanisms used to sense sound in water differ significantly from those used in air.

In airborne acoustics, microphones are typically based on capacitive transducers, such as condenser microphones, or on velocity-sensitive transducers, such as ribbon microphones. These devices respond either to absolute pressure or to pressure gradients across a diaphragm.

Hydrophones, in contrast, most commonly employ piezoelectric transducers. Piezoelectric hydrophones were first developed during World War I for submarine detection and have remained the dominant sensing technology for underwater acoustics.

The hydrophone described in this paper uses a piezoelectric ceramic cylinder as its sensing element. When exposed to acoustic pressure in water, the resulting mechanical stress in the ceramic material generates an electrical charge proportional to the applied pressure. This piezoelectric effect produces a voltage that directly represents the acoustic pressure fluctuations in the surrounding water.

To protect the piezoelectric element and ensure reliable underwater operation, the transducer is typically embedded in a casting resin or similar encapsulating material. This resin provides waterproofing, mechanical protection, and electrical insulation.

The acoustic properties of the encapsulating material are also important. Ideally, the encapsulant should have an acoustic impedance close to that of water. This maximizes acoustic energy transfer into the transducer while minimizing reflections at the boundary between materials.

Property	Microphone	Hydrophone
Transducer Type	Capacitive	Piezoelectric
Acoustic Impedance	Low	High
Sensitivity (Typical)	mV/Pa	μ V/Pa
Frequency Response	20 Hz-20Khz	>100kHz

Figure 1: Microphone Hydrophone Comparison

3 Phantom Powered Hydrophone Design

Most commercially available hydrophones are intended for scientific monitoring applications, such as long-term environmental measurements or oil-rig monitoring. As a result, they are typically designed to interface with specialized instrumentation rather than standard audio equipment. These devices are priced and engineered accordingly.

My search for a hydrophone design that could interface directly with modern audio recorders led me to a NOAA technical paper [4]. The authors described a hydrophone front-end based on the Analog Devices AD743 BiFET operational amplifier, a device that is now obsolete. While the electronics described in the paper are no longer practical to reproduce directly, the paper provided valuable guidance regarding the use of piezoelectric cylinders as hydrophone transducers and their mechanical construction.

Based on this work and additional experimentation, the following design goals were established:

- Compatibility with standard field recorders
- Low noise floor
- Wide bandwidth
- Rugged deployment
- Operation from standard 48 V phantom power without external supplies

3.1 The Transducer

Based on the NOAA paper and further research, a PZT-4 piezoelectric ceramic cylinder was selected as the sensing element. The device used in this design measures 26 mm outer diameter, 22 mm inner diameter, and 13 mm height. The manufacturer's

datasheet specifies a capacitance of approximately 6600 pF.

PZT-4 refers to a particular formulation of piezoelectric ceramic that is widely used in ultrasonic and underwater transducer applications due to its high mechanical strength and stability.

The specific supplier originally used for this project (STEMINC, Florida) is no longer in business; however, equivalent PZT-4 cylinders in similar dimensions are available. Testing by the author has also shown that moderate variations in cylinder size have minimal impact on the overall performance of the hydrophone, provided the ceramic material remains PZT-4 or an equivalent formulation.

3.2 The Electronics

The electronics design builds upon previous work by the author using operational amplifiers as impedance converters for condenser microphones [5]. Much of the circuitry from that work was reused, with two important modifications required for the piezoelectric transducer. The first modification involves the bias resistor across the piezo element. In the condenser microphone design this resistor was 1 G Ω , but for the hydrophone it was reduced to 1 M Ω . In combination with the measured capacitance of the piezo cylinder of 6.3nF, this produces a low-frequency roll-off of approximately 25 Hz.

$$f_c = \frac{1}{2\pi(1.0 \times 10^6)(6.30 \times 10^{-9})} \approx 25\text{Hz}$$

which is well suited for underwater recording.

The second modification was discovered through field experience. Piezoelectric elements can generate extremely high voltages when subjected to mechanical shock. Several early prototypes failed when finished hydrophones were accidentally dropped or struck during handling. Measurements performed by connecting the piezo cylinder directly to an oscilloscope showed that a simple finger tap could generate transient voltages exceeding 100 V.

To prevent damage to the input stage, Schottky protection diodes were added to clamp the input voltage to the supply rails.

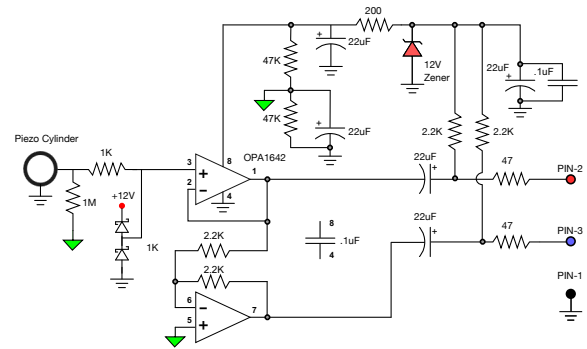


Figure 1: Hydrophone Electronics

The circuit connects directly to a recorder microphone input and is powered entirely from the 48V phantom power supplied by the recorder.

The incoming phantom power is applied through the standard 6.8 k Ω feed resistors within the recorder and appears on pins 2 and 3 of the XLR connector. Inside the hydrophone, this DC supply is filtered by a 22 μ F capacitor and a 0.1 μ F bypass capacitor supplied by a pair of 2.2 k Ω resistors

Voltage regulation is provided by a 12 V Zener diode, followed by additional filtering through a 200 Ω resistor and a 22 μ F capacitor.

Operational amplifiers require a split-rail power supply, which is synthesized in this design using a virtual ground. Two 47 k Ω resistors form a voltage divider that creates a mid-supply reference, which is then stabilized with a 22 μ F capacitor. A .1uF capacitor is placed across the opamp supply rails.

The active device used is the Texas Instruments OPA1642, a dual low-noise JFET-input operational amplifier with specifications well suited for hydrophone applications:

- 5.1 nV/ $\sqrt{\text{Hz}}$ input noise density
- 1.8 mA quiescent current per channel
- Near rail-to-rail output swing
- 0.00005% THD+N at 1 kHz

The first amplifier stage operates as a unity-gain non-inverting buffer, presenting a high impedance to the piezo element while providing a low-impedance output.

The buffered signal is AC-coupled through a 22 μ F capacitor and a 47 Ω series resistor to pin 2 of the

XLR connector, forming one side of the balanced output.

The same signal is also routed to a unity-gain inverting amplifier, implemented using the second op-amp stage and two 2.2 k Ω resistors. This stage generates an inverted version of the signal, which is AC-coupled through another 22 μ F capacitor and 47 Ω resistor to pin 3 of the XLR connector.

The result is a fully balanced output stage capable of driving long microphone cables to the recorder while maintaining excellent common-mode noise rejection.

The piezo element is connected to the input stage through a 1 k Ω series resistor, which limits current during transient events. Two Schottky diodes connect the input node to the supply rails, clamping excessive voltage and protecting the operational amplifier.

3.3 The Complete Hydrophone

Integrating the transducer, electronics, and mechanical structure into a complete hydrophone required several design iterations.

Key lessons learned during development included the importance of:

- Providing a direct electrical ground reference to the surrounding water
- Selecting an appropriate potting resin
- Developing reliable molding techniques

A compact PCB was designed with dimensions closely matching the piezo cylinder so that both components could be embedded together. A 3D-printed alignment frame holds the PCB and transducer in the correct position during the molding process.

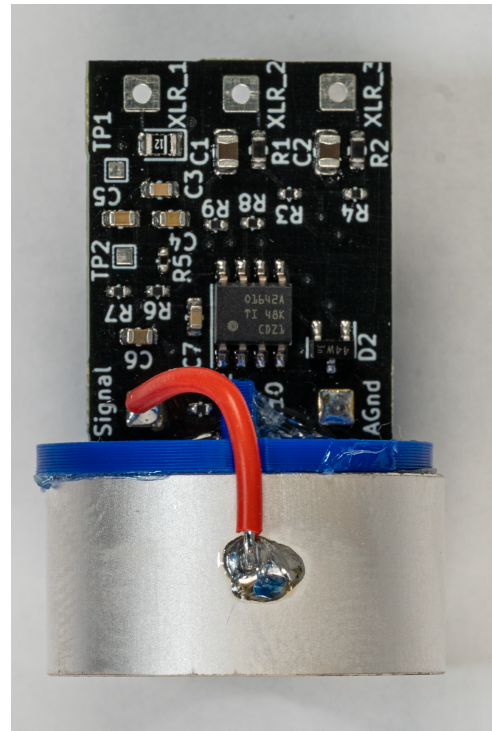


Figure 2: Complete Transducer and PCB

The encapsulation material used is Smooth-Cast 65D polyurethane resin. Several alternative resins were evaluated during development, but this material proved the easiest to work.

Smooth-Cast 65D has a density very close to that of water, and the speed of sound in most polyurethane resins is approximately 1500 m/s. As a result, the acoustic impedance of the resin closely matches that of water, which minimizes reflection at the water–resin interface. This means:

- The resin is nearly acoustically transparent to water
- Very little signal loss occurs at the boundary
- The piezo element experiences nearly the full acoustic pressure field

The design uses standard flexible microphone cable, which performs well for portable deployments. One challenge unique to hydrophones is cable handling noise, which can easily dominate recordings if the cable is too stiff or mechanically noisy.

For this reason, flexible cables such as Mogami microphone cable are recommended. Some manufacturers offer cables designed for direct burial or permanent underwater installation, but these tend

to be significantly stiffer and can introduce more handling noise.

It should also be noted that the hydrophone presented here is intended for portable recording applications, not permanent underwater installations. Commercial hydrophones that cost significantly more are typically engineered for long-term deployment in harsh marine environments, sometimes remaining submerged for six months or more before retrieval. Designing for that level of durability represents a very different engineering challenge.

Detailed construction instructions for the hydrophone described here are available in [6] where the project was originally published as an Instructables article. Since that publication, the design has been replicated by builders around the world and has been used to capture a wide variety of marine sounds.

3.4 Dynamic Range and Noise Performance

Both air and water exhibit a fundamental noise floor arising from the thermal (Brownian) motion of the particles in the medium. In the ocean, this thermodynamic limit lies far below the ambient noise levels typically encountered in practice, which are dominated by environmental sources first characterized by G. M. Wenz and further elaborated by Peter H. Dahl [7].

Calculation of the hydrophone noise floor and dynamic range requires knowledge of the transducer sensitivity. This is one parameter that was not directly measured for the present design. Accordingly, the sensitivity value adopted in this paper,

$$M_v = 178 \mu\text{V}/\text{Pa}$$

is treated as a practical engineering estimate rather than a direct calibration of the specific element used. This value is based on published free-field sensitivities of comparable cylindrical ceramic hydrophones, including values near

$$-195 \text{ dB re } 1 \text{ V}/\mu\text{Pa}$$

which corresponds to

$$M_v \approx 1.78 \times 10^{-4} \text{ V}/\text{Pa}.$$

This estimate is also consistent with the expected behavior of a circumferential-mode piezoelectric cylinder. Unlike a simple slab model, a cylindrical

element develops significant hoop stress under acoustic loading, increasing the effective strain in the ceramic and resulting in higher sensitivity.

The measured capacitance of the transducer used in this work, approximately 6300 pF, further supports this assumption, as it is consistent with a high-capacitance piezoelectric cylinder operating in a circumferential mode.

A detailed derivation of the hydrophone electronic self-noise and its conversion to equivalent acoustic noise is presented in Appendix A. The resulting values are summarized in Table 2, with the full analysis provided for reference in the appendix.

Frequency	p_n ($\mu\text{Pa}/\sqrt{\text{Hz}}$)	N_{eq} (dB re 1 $\mu\text{Pa}/\sqrt{\text{Hz}}$)
100 Hz	185	45.3
1 kHz	36.5	31.2
10 kHz	30.8	29.8

Figure 3: Hydrophone Self Noise

Once the hydrophone self-noise is established, the system dynamic range can be determined. A maximum hydrophone output level of $3V_{RMS}$ was selected, representing a conservative limit for the circuit while remaining above the maximum input level of the recorder used in this work.

The acoustic dynamic range of the ocean environment is defined as the difference between Sea State 1 ambient noise and the level of a nearby humpback whale vocalization.

The complete derivation of these values is presented in Appendix B, with a summary of the results provided in Table 3.

System	Dynamic Range (dB)
Ocean Environment	86
Hydrophone Electronics	129.5
Zoom F8n Pro	131

Figure 4: Dynamic Range Comparison

4 Array development and deployment

The initial array geometry selected for this work was a cubic configuration. Immersive array designs using omni microphones such as those detailed by Hyunkook Lee [8] commonly employ a cube with approximately 1 m spacing between elements. When scaled for use in water, this spacing must increase

proportionally with the higher speed of sound, resulting in an equivalent cube dimension of approximately 4.4 m. For this work, a practical implementation of this concept resulted in a cube of approximately 15 ft (4.6 m) per side.

The initial array design consisted of a 15 ft square frame constructed from PVC, suspended in the water column. Hydrophones were positioned at each corner of the square to form the upper (height) layer, with four additional hydrophones suspended approximately 15 ft below these positions to form the lower layer. This configuration created a vertically spaced eight-element cubic array.

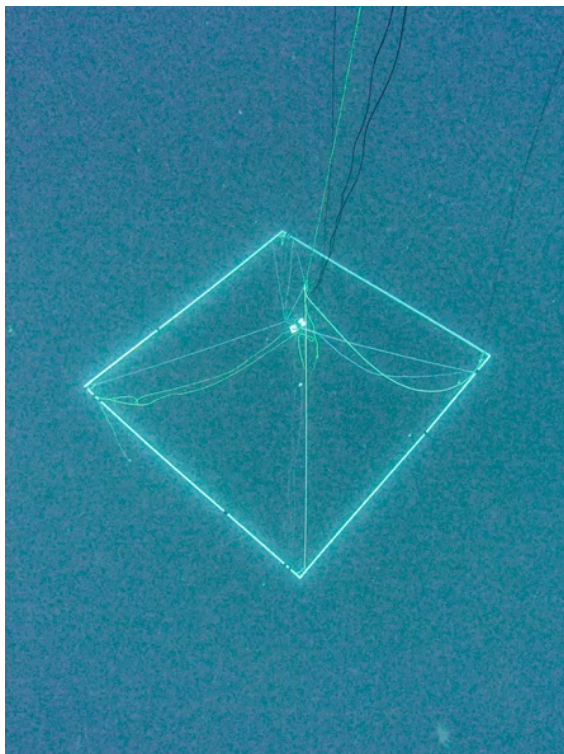


Figure 5: PVC Pipe Array

Two custom submersible snake cables were constructed to support this layout. Each snake combined four hydrophones per layer into a single 100 ft run of direct-burial Cat5 cable. The underwater junctions were molded at the hydrophone end, while the surface end provided four breakout cables terminated in XLR connectors for direct connection to the recorder. Two complete arrays were fabricated to provide redundancy in the field.

The system was tested in a local lake prior to deployment and then shipped to Hawaii. In addition to the array systems, several individual 100 ft

hydrophones from previous builds were brought as backups, which ultimately proved to be valuable. A vessel with an experienced captain was chartered for five days of recording off the coast of the Island of Hawaii.

Structurally, the PVC frame incorporated eye bolts at each corner and a rope harness system designed to maintain orientation in the water and allow controlled deployment and retrieval. While the concept was sound in principle, practical deployment in open water proved significantly more challenging than anticipated. One hydrophone failure occurred during initial deployment, and while several hours of recording were obtained with the PVC array, issues such as cable handling noise, tangling, and general deployment complexity limited its effectiveness.

Following this initial attempt, the array configuration was revised. The PVC frame was abandoned in favor of a simpler and more robust deployment method. Four hydrophones were suspended directly from the corners of the vessel to form the upper layer, while four additional hydrophones were deployed independently to a depth of approximately 100 ft to form the lower layer. This approach produced a rectangular volumetric array with substantial vertical separation, providing strong height discrimination while significantly simplifying deployment.

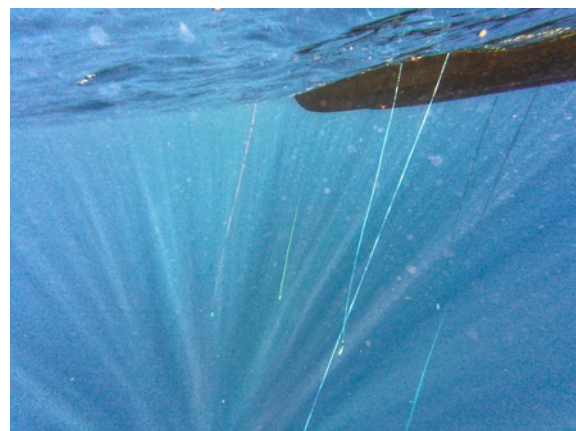


Figure: 6 Top layer of the hydro array

The revised configuration proved reliable and was used for the remainder of the recording sessions.

5 Humpback Whale Vocalization

Male humpback whales produce complex vocalizations during the winter breeding season.

These songs were first widely documented in the 1970s with the release of *Songs of the Humpback Whale* by Roger Payne and Katy Payne, bringing attention to their structured and repetitive nature.

Humpback vocalizations typically span a frequency range from approximately 100 Hz to 24 kHz or higher, with individual sounds capable of propagating over distances on the order of 10 km or more, depending on ocean conditions. Complete song cycles can last from approximately 4 to 30 minutes and are composed of repeating phrases organized into hierarchical structures, including units, subphrases, and themes. The statistical distribution of these vocal elements has been observed to follow patterns similar to Zipf's law [9], suggesting structural parallels to human language.

The vocal mechanism in cetaceans differs significantly from that of terrestrial mammals. Sound production occurs without the expulsion of air; instead, air is recycled between the lungs and specialized structures within the nasal cavity. This mechanism allows for sustained vocalization without loss of buoyancy or the need to surface.

Groups of male humpback whales often produce similar song patterns within a region, though individual variations are present. When combined with the highly reverberant underwater environment, including reflections from both the surface and seafloor, these vocalizations create a dense and spatially complex acoustic field.

Capturing this environment using an immersive hydrophone array reveals spatial characteristics that are not apparent in traditional mono or stereo recordings. Playback over a multichannel system with height reproduction further emphasizes the three-dimensional nature of the sound field, providing a more complete representation of the acoustic environment.

6 Field Recording and Results

To facilitate deployment and channel identification, the array was color-coded such that each hydrophone corresponded to a matching color-coded XLR connector. Following the transition from the suspended PVC frame to the "side-of-boat" configuration, hydrophone positions were documented during setup to maintain spatial consistency across recordings.

Recordings were made using a Zoom F8n Pro configured for 32 bit float at a 192 kHz sample rate. Multiple recording locations were selected to capture a range of acoustic environments, including both near-shore and deeper offshore positions.

Near-shore recordings were characterized by a high density of impulsive broadband noise, primarily attributed to snapping shrimp activity. In contrast, recordings made in deeper water exhibited a distinct separation between surface and depth layers. Surface-generated wave noise was prominent in the upper hydrophones, while the deeper elements remained relatively unaffected. During immersive playback, this produces a compelling spatial effect in which wave activity appeared to move above the listener.

In addition to the primary array, a compact stereo drop rig was constructed using two hydrophones connected to a self-contained recording system consisting of a Zoom F3 and battery housed in a modified Pelican enclosure. This unit was deployed near a coral reef environment and successfully recorded approximately 24 hours of continuous audio. The recordings revealed significant high-frequency snapping shrimp activity, including ultrasonic content captured by the wideband hydrophones. The system was lost after the second day of deployment.

7 Improvements

Post-session evaluation led to a simplified and more robust deployment approach. A revised design utilized stereo microphone cable with two hydrophones per line: one at the distal end and a second positioned approximately 15 ft above. This configuration allowed rapid deployment from the four corners of a vessel, enabling a single operator to deploy a full eight-element array efficiently.

Multiple sets of these cables were constructed with color-coded XLR connectors and heat-shrink tubing depth markers to ensure repeatable positioning. This revised system was subsequently deployed in Tahiti, where it enabled comparative recordings of whale populations in a different geographic region.

The updated array demonstrated improved reliability and ease of use, with one system operating continuously for 10 days without failure.

8 Conclusions

This work demonstrates that a low-noise, wide-

bandwidth hydrophone suitable for immersive recording can be constructed using readily available components and straightforward fabrication techniques. The design provides performance sufficient for high-quality audio capture while maintaining a cost structure that enables the deployment of multiple elements in array configurations. The resulting system supports immersive recording of marine soundscapes, capturing both the spatial complexity of environmental noise and the detailed structure of biological sources such as humpback whale vocalizations.

Future work will focus on refinement of array geometries, improved calibration methods, and development of decoding techniques to more fully characterize and reproduce the complex three-dimensional acoustic environment of the ocean.

Of note we did not document the directional orientation of the ship and we drifted during the recordings to minimize surface noise.

9 Acknowledgments

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10 Appendixes

Appendix A: Hydrophone Self-Noise

The hydrophone sensitivity used throughout is

$$M_v = 178 \mu\text{V}/\text{Pa} = 1.78 \times 10^{-4} \text{ V}/\text{Pa} \quad (1)$$

A.1 Electrical Model

The piezoelectric element is modeled as a capacitance

$$C_p = 6.3 \times 10^{-9} \text{ F} \quad (2)$$

with bias resistance

$$R_b = 1.0 \times 10^6 \Omega \quad (3)$$

yielding a high-pass corner frequency

$$f_c = \frac{1}{2\pi R_b C_p} \approx 25.3 \text{ Hz} \quad (4)$$

A series input resistor is present:

$$R_s = 1.0 \times 10^3 \Omega \quad (5)$$

A.2 Noise Sources

The OPA1642 input voltage noise is

$$e_{n,op} = 5.1 \times 10^{-9} \text{ V}/\sqrt{\text{Hz}} \quad (6)$$

Two op-amp stages are used (buffer and unity-gain inverter). Assuming uncorrelated noise:

$$e_{n,op,tot} = \sqrt{2} e_{n,op} \quad (7)$$

Thermal noise of the bias resistor:

$$e_{n,R0} = \sqrt{4kTR_b} \approx 1.27 \times 10^{-7} \text{ V}/\sqrt{\text{Hz}} \quad (8)$$

This noise is filtered by the piezo capacitance:

$$e_{n,R}(f) = \frac{e_{n,R0}}{\sqrt{1 + (2\pi f R_b C_p)^2}} \quad (9)$$

Thermal noise of the series resistor:

$$e_{n,s} = \sqrt{4kTR_s} \approx 4.1 \times 10^{-9} \text{ V}/\sqrt{\text{Hz}} \quad (10)$$

Total input-referred noise:

$$e_{n,tot}(f) = \sqrt{e_{n,op,tot}^2 + e_{n,s}^2 + e_{n,R}(f)^2} \quad (11)$$

Input protection diodes are present but are reverse-biased during normal operation and do not contribute significantly to the noise floor.

A.3 Equivalent Acoustic Noise

$$p_n(f) = \frac{e_{n,tot}(f)}{M_v} \quad (12)$$

$$N_{eq}(f) = 20 \log_{10} \frac{p_n(f)}{1 \mu\text{Pa}/\sqrt{\text{Hz}}} \quad (13)$$

A.4 Results

Frequency	p_n ($\mu\text{Pa}/\sqrt{\text{Hz}}$)	N_{eq} (dB re 1 $\mu\text{Pa}/\sqrt{\text{Hz}}$)
100 Hz	185	45.3
1 kHz	36.5	31.2
10 kHz	30.8	29.8

Interpretation: The hydrophone self-noise is dominated by bias resistor noise at low frequency and by op-amp and series resistor noise at higher frequencies. The resulting noise floor remains below typical ocean ambient noise levels for Sea State 0-1 across the audio band.

Appendix B: Dynamic Range

B.1 Definition

$$DR = 20 \log_{10} \frac{V_{max}}{V_n} \quad (1)$$

B.2 Hydrophone

Assume

$$V_n = 1.0 \times 10^{-6} \text{ V} \quad (2)$$

$$V_{max} = 3.0 \text{ V} \quad (3)$$

$$DR_{\text{hyd}} \approx 129.5 \text{ dB} \quad (4)$$

Using

$$M_v = 1.78 \times 10^{-4} \text{ V/Pa} \quad (5)$$

Noise pressure:

$$p_n = \frac{V_n}{M_v} \approx 5.62 \times 10^{-3} \text{ Pa} \quad (6)$$

$$L_n \approx 75.0 \text{ dB re } 1 \mu\text{Pa} \quad (7)$$

Maximum pressure:

$$p_{max} = \frac{V_{max}}{M_v} \approx 1.69 \times 10^4 \text{ Pa} \quad (8)$$

$$L_{max} \approx 204.6 \text{ dB re } 1 \mu\text{Pa} \quad (9)$$

B.3 Recorder

$$EIN \approx -127 \text{ dBu} \quad (10)$$

$$V_n \approx 3.46 \times 10^{-7} \text{ V} \quad (11)$$

$$V_{max} \approx 1.23 \text{ V} \quad (12)$$

$$DR_{\text{FS}} \approx 131 \text{ dB} \quad (13)$$

B.4 Ocean Environment

$$L_{\text{sea}} \approx 94 \text{ dB re } 1 \mu\text{Pa} \quad (14)$$

$$L_{\text{whale}} \approx 180 \text{ dB re } 1 \mu\text{Pa} \quad (15)$$

$$DR_{\text{ocean}} \approx 86 \text{ dB} \quad (16)$$

B.5 Summary

Table 1: System dynamic range

System	Dynamic Range (dB)
Ocean Environment	86
Hydrophone Electronics	129.5
Zoom F8n Pro	131

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