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Prototype Low-Cost Hydrophone for the Ocean of Things Program

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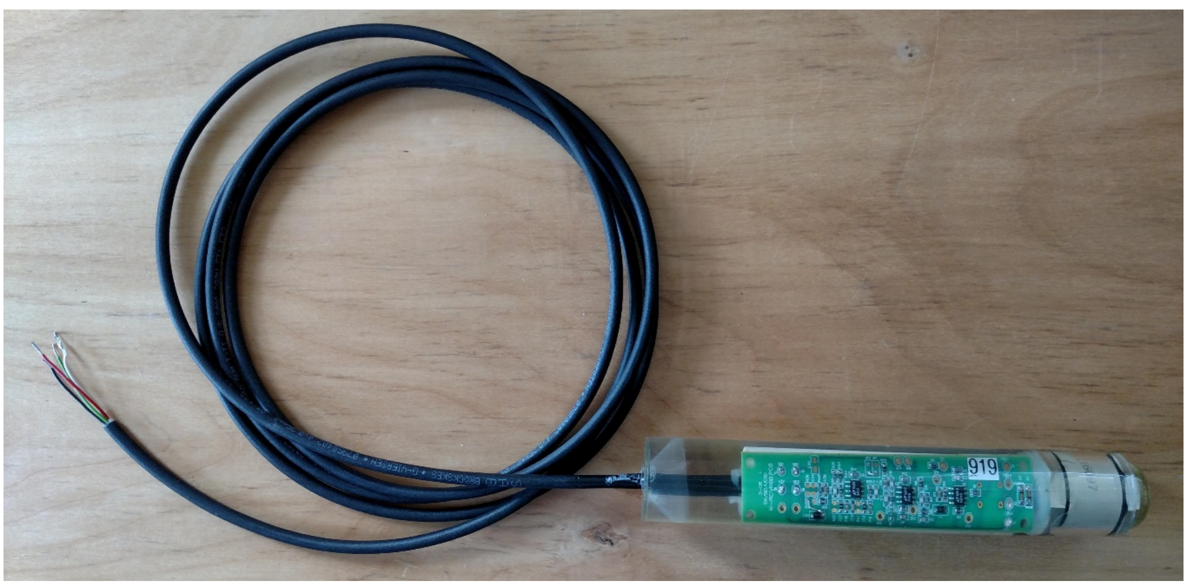

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Executive Summary

The Defense Advanced Research Projects Agency (DARPA) Ocean of Things (OOT) program seeks to expand maritime awareness by development of a distributed network of small, low-cost, smart floating sensors, including hydrophones. We evaluated both commercial and military hydrophones and incorporated our own scientific hydrophone designs into a prototype low-cost, high-fidelity, durable hydrophone design. The 7” long x 1.25” diameter prototype consists of a cylindrical PZT ceramic transducer and signal conditioning electronic circuit board encapsulated in a polyurethane elastomer mated to a flexible 0.20” diameter cable. Our estimate is that the prototype hydrophone could be put into large-scale production at a price that would meet the $100-150 specification for use in the OOT platform.

Introduction

The Defense Advanced Research Projects Agency (DARPA) Ocean of Things (OOT) program seeks to expand maritime awareness across open seas by supporting development of ocean-based Internet of Things (IOT) made of a distributed network of thousands of small, low-cost, smart floating sensors. Each float is envisioned to consist of a suite of commercially available sensors to collect environmental data such as water temperature, meteorological parameters, location, and light levels in addition to underwater sounds to detect, for example, calling marine mammals, vessel traffic, and potential port threats. The floats would transmit sensor data via satellites to cloud networks for storage and real-time analysis (https://www.darpa.mil/news-events/2017-12-06).

The Palo Alto Research Center (PARC) was awarded a contract to develop a network and fleet of small multi-sensor floats for the OOT program. Their float design consists of rechargeable batteries, electronic circuit boards, solar panels, sensors, and antennas packaged in a thin-walled hemispherical dome convex downward with its equator parallel to the sea surface. The material properties of the PARC hemisphere allow it to be robust for packaging as an ocean float, but also easily destroyed for planned jettisoning of the float as per the program's requirements. The design also includes a hydrophone hanging from a cable attached to the underside of the smart float dome.

Our effort in this project was to investigate and advise on low-cost options for a hydrophone design. We evaluated both commercial and military hydrophone devices and incorporated our own scientific hydrophone designs into a low-cost, high-fidelity, durable hydrophone design and prototype. The 7" long x 1.25" diameter prototype consists of cylindrical lead zirconate titanate (PZT) ceramic transducer and signal conditioning electronic circuit board encapsulated in a polyurethane elastomer mated to a flexible 0.20" diameter cable. Hydrophone calibration and self-noise were measured in addition to laboratory-based measurements using an ocean acoustic recorder. The following details the investigation, design, fabrication and testing of the low-cost prototype hydrophone.

Investigation

Three approaches for a low-cost hydrophone were evaluated: (1) commercially available hydrophones, (2) single-use military hydrophones, and (3) custom scientific hydrophones.

(1) Commercial hydrophone

There are a wide range of commercially available hydrophones with varying trade-offs in price, quality, and performance. PARC OOT identified a manufacturer of low-cost, readily available hydrophones from Aquarian Audio (http://www.aquarianaudio.com/). Two hydrophone models were purchased and evaluated: H1C and the H2C (with powered impedance buffer amp); $139 and $169, respectively. Both are similar construction with a thin sensing layer deposited on a metal disk, mounted on a stainless steel threaded mount, elastomer sensor boot, and polyurethane cable (Appendix A1 – top photo).

While the H1C generated a voltage response to sound, its sensitivity appeared to be both highly directional (highest across flat of boot face) and non-uniform with frequency. The H1C also requires addition signal conditioning to amplify and filter ocean sounds. Upon removing the sensor boot, the sensor was found to be a diaphragm disk (0.5" diameter x 0.04" thick) construction suggesting the sensitivity is depth and pressure dependent. We did not investigate this sensor further.

(2) Single-use military hydrophone

The militaries around the world have deployed large-numbers of single-use hydrophones on sonobuoys for several decades. The mature, well-proven design of passive acoustic sonobuoys and their similarity to this project's smart float with a hydrophone dangling from a sea surface float and wireless data transfer led us to evaluate their design.

We investigated an SSQ-53F sonobuoy which includes hydrophone sensors and signal conditioning electronics. We disassembled the SSQ-53F deep omni-directional hydrophone and signal conditioning electronics (Figure 1).

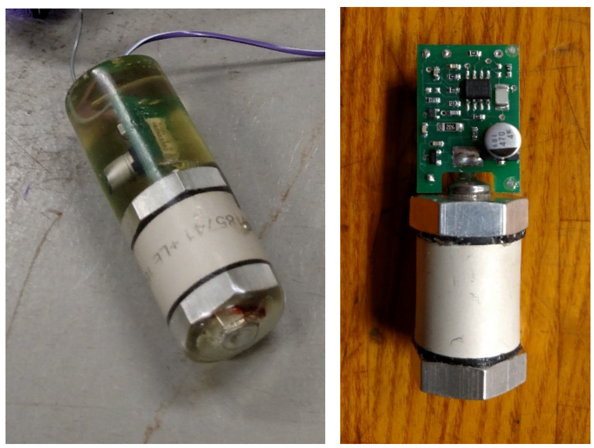


Figure 1. Sonobuoy SSQ-53F deep omni-directional hydrophone. The white cylindrical PZT sensor is capped on each end by aluminum hexigonal nuts with the signal conditioning electronics circuit board attached to one end. Left: polyurethane encapsulated. Right: encapsulation removed.

The sonobuoy hydrophone construction was evaluated and documented including sensor size and electronics board layout and components. The cylindrical PZT ceramic transducer sensor measures 0.75" long x 0.75" diameter x 0.063"wall thickness providing an internal air-backed cavity when both ends are sealed as with the aluminum nuts/endcaps and gaskets. The air-backed cavity provides good sensitivity at low frequencies, but the PZT size and geometry limit its high-frequency sensitivity to sounds arriving perpendicular to the sensor's circumference, making it omni-direction to only about 10 kHz. The PZT cylinder capacitance was measured to be about 8.5 nF.

While sonobuoys use 18 V saltwater batteries to power their signal conditioning electronics, we used a dual power supply to provide +5 V and -5 V to the circuit so that we could evaluate its performance. The low-noise JFET operational amplifier used for the pre-amplifier as the first stage of the circuit has a typical voltage self-noise of 18 nV/sqrt(Hz) at 1 kHz and a typical low current draw of 1.4 mA. The signal conditioning electronics sensitivity frequency response was measured by sending a known signal from a function generator to the circuit input through a 9 nF capacitor to emulate the transducer's frequency response (Figure 2). Over 70 dB of gain was observed along with a high-pass filter (HPF) corner frequency (-3 dB) around 1.5 kHz and a low-pass filter (LPF) corner around 25 kHz.

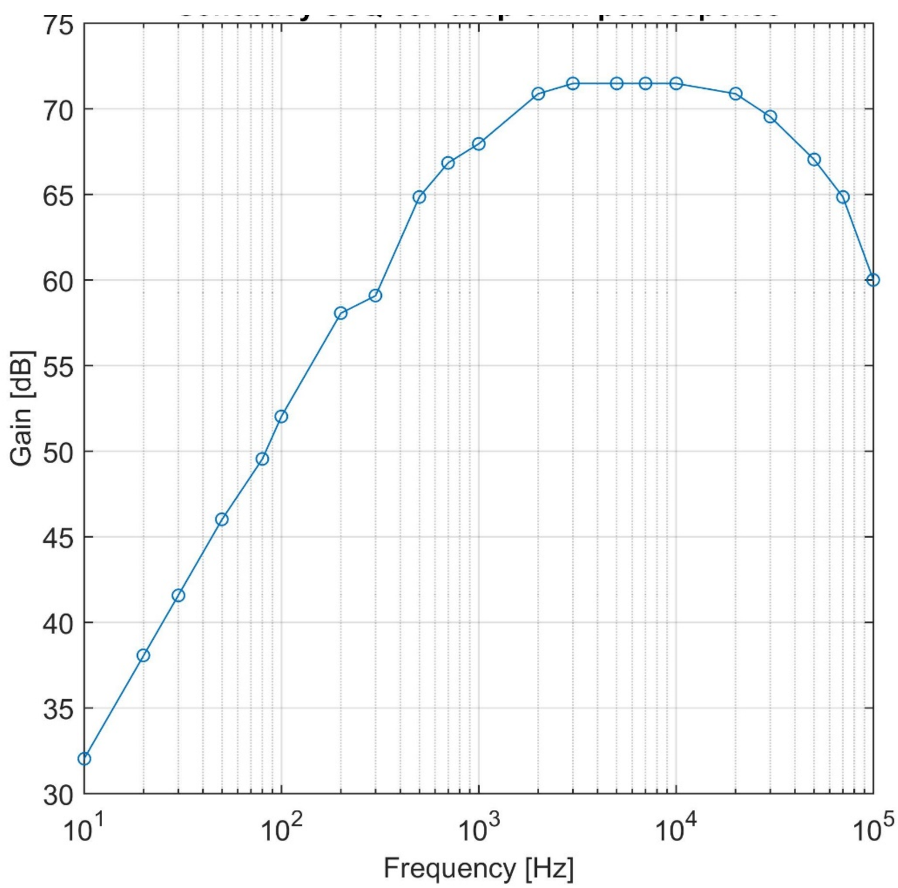


Figure 2. Sonobuoy SSQ-53F signal conditioning electronics frequency response through a 9 nF capacitor on the circuit's input.

Since sonobuoys are produced in large quantities for the Department of Defense, it was recommended that PARC OOT contact Sparton (https://sparton.com/engineered-products/sonobuoys/), a primary manufacturer of sonobuoys, about purchasing these hydrophones directly; however, the price quote for standard SSQ-53F deep omni-directional hydrophones was well above the target hydrophone budget.

PARC OOT also identified a Sparton commercial hydrophone product (Appendix A2), which we evaluated as having excellent specifications, but noting that PARC would need a very large price discount to meet their budget requirements with an online price of $995 (https://www.spartonnavex.com/product/phod-1-hydrophone/).

(3) Custom high-fidelity scientific hydrophone

Our group has been developing and using custom hydrophones for scientific studies of sound in the ocean for over 30 years. Typically, we connect our hydrophones to long-term autonomous recorders for deep sea deployments or incorporate them into arrays for towing behind ships or autonomous vehicles. Our standard configuration hydrophone includes a spherical PZT ceramic transducer to allow for high sensitivity at high frequency in all directions. Spherical ceramic elements have superior characteristics to cylindrical geometries at high frequencies, but at much higher costs. In addition, our signal conditioning electronics can be configured many ways, including dual sensor input for very wide-band response, but this flexibility is not needed for a large fleet of consistently manufactured smart floats, thus requiring modifications to our hydrophone design approach.

Since PARC OOT plans to sample the smart float hydrophone at ~ 20 kHz, a spherical PZT ceramic is not needed for true omni-directional sound measurements allowing a cylindrical PZT to be used, reducing cost. Initial search from 12 manufacturers for raw (non-encapsulated, non-wired) PZT ceramics ranged from $100 - $300, but a manufacturer – APC International (https://www.americanpiezo.com/) was found that provided similar size ceramic as used for the sonobuoy hydrophone with a cost of ~ $50 (Appendix A3 - Catalog # 42-1021). Costs may be reduced further when purchasing these ceramics in large quantities.

We provided our hydrophone signal conditioning electronics design to PARC OOT, and discussed the details of the circuit design with a PARC OOT electronics engineer to evaluate if this design would be viable for their system. We further assessed our hydrophone circuit design and found ways to minimize the number of components and to simplify the design without a significant impact on the signal conditioning performance required for this project's hydrophone. The frequency response of the circuit was modified to be similar to that measured for the sonobuoy hydrophone (Figure 2), but for sampling at 20 kHz (10 kHz Nyquist frequency) and with 20 dB less gain because the PARC OOT float hydrophone will be nearer to the noisy sea surface and likely not include the motion decoupling mechanisms employed in the sonobuoy system due to reliability and cost. This new design provided the basis for a prototype hydrophone to be built, calibrated and tested.

Prototype low-cost hydrophone

Signal conditioning electronics

Using a one of our existing hydrophone circuit boards, we modified and populated it with components. Providing 5 V power results in about 6 mA current draw or 30 mW power consumption. The signal conditioning electronic circuit was calibrated similarly to the sonobuoy electronics by providing a known signal through a capacitor to the circuit input and measuring the output response (Figure 3). Overall nominal gain is 50 dB and the -3 dB corner frequencies for the HPF and LPF are at 300 Hz and 8 kHz, respectively. The next step would be to make a new circuit board layout with a smaller footprint for a more compact hydrophone design.

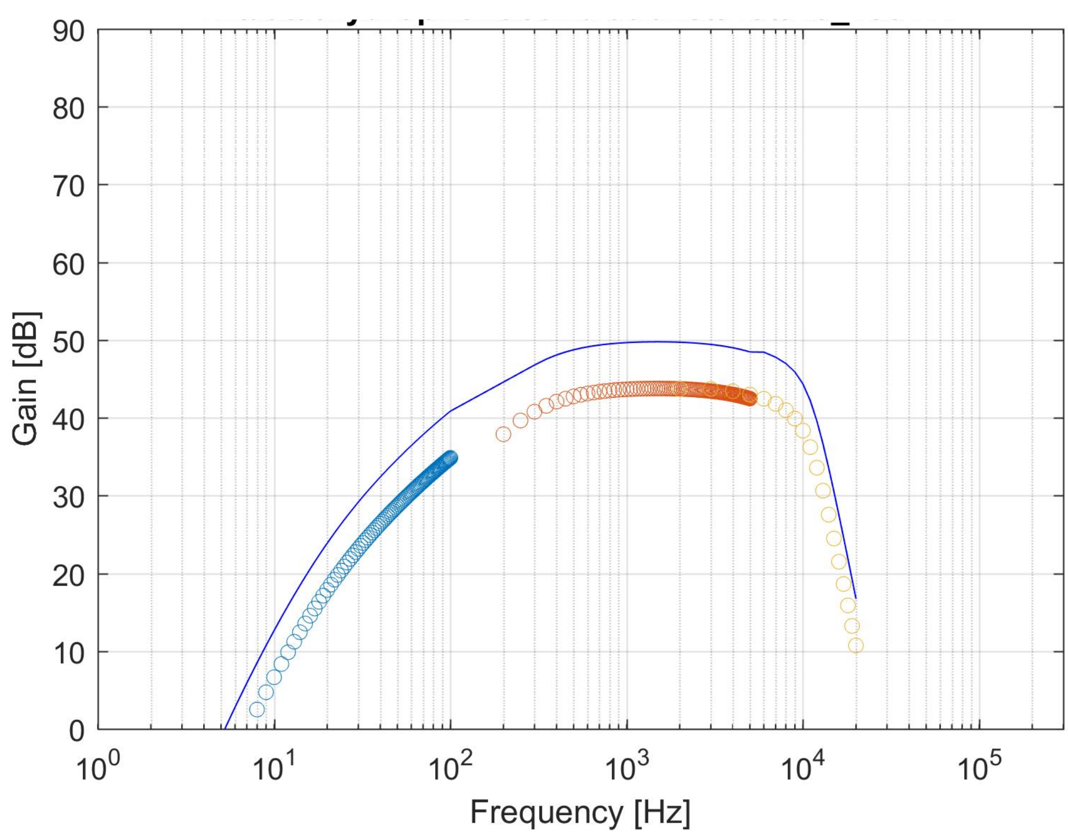


Figure 3. Prototype hydrophone signal conditioning electronics frequency response through a 9 nF capacitor on the circuit's input. Solid blue line is total gain, open circles are one side of the differential output (-6 dB below total gain).

PZT ceramic transducer

While we identified and received one sample of a cost-effective, high-quality transducer with the same dimensions as used in the sonobuoy hydrophone, for the prototype we used the SSQ-53F deep omni-directional transducer because it was already fitted with end caps providing an air-backed space internal to the cylinder for good low frequency sensitivity. The sensor was connected to the input for the signal conditioning electronics, near the circuit board, and the output was connected to a durable 4-wire continuous-flex polyurethane cable for 5 V power, ground, and two differential output signals (Figure 4). The hydrophone assembly prior to encapsulation was tested with one of our standard long-term acoustic recorders and it performed well during tests involving various sounds such as impulses and tones, and showed low self-noise.

Encapsulation

To keep sea water from damaging the hydrophone electronics, the hydrophone assembly was fitted into a clear PVC Tygon tube (1" ID x 1/8" wall) and encapsulated in a water-clear flexible (shore 70A) polyurethane elastomer (Figure 5). The polyurethane elastomer (BJB Enterprises WC-575; https://bjbenterprises.com) is a durable thermoset and is resistant to degradation in sea water in addition to many other chemicals. The water-clear property allows for inspect of internal components and of potential problems such as water ingress due to poor encapsulation processes. We chose a flexible encapsulation to allow for better long-term adhesion during continuous flexing of the cable when deployed from a float constantly move at the sea surface.

At-Sea Testing

We propose that the next step will be to conduct at-sea tests of the prototype hydrophone, as well as conducting a complete calibration of system response versus frequency at the Navy's TRANSDEC or similar facility.

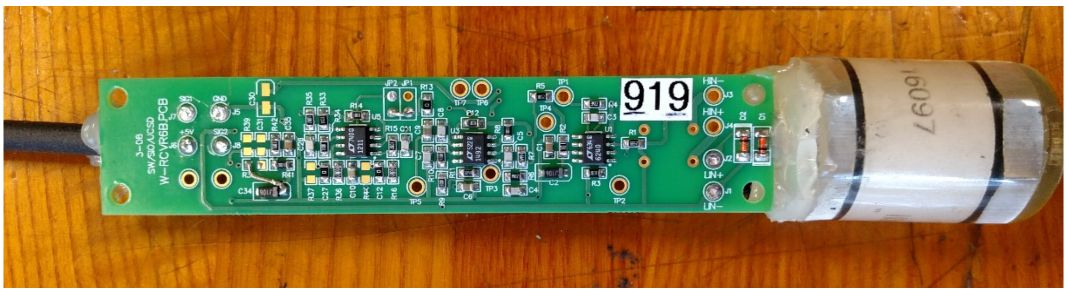


Figure 4. Prototype hydrophone assembly prior to encapsulation. Cylindrical transducer with end caps for internal air-backing on right is from an SSQ-53F sonobuoy hydrophone. Signal conditioning electronics (#919) has been modified for one input sensor only, 5 V power for all components, and frequency response similar to what was found for the sonobuoy hydrophone. A continuous-flex polyurethane jacketed cable is used for durability and to connect power, ground and two differential output signals.

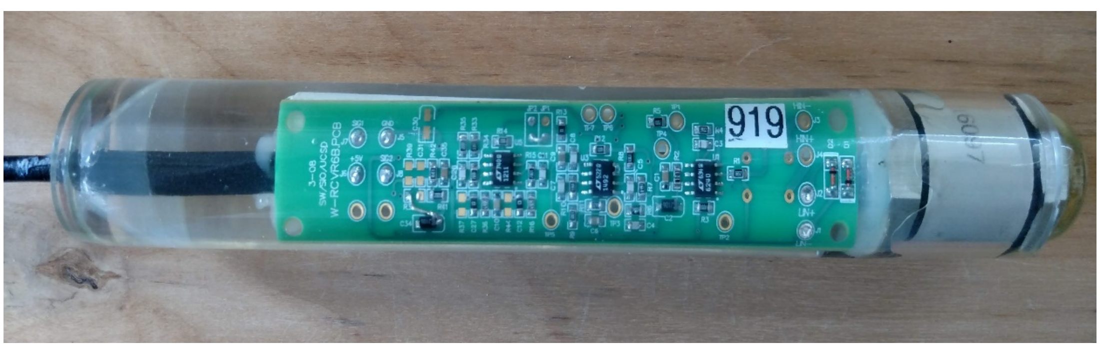


Figure 5. Prototype hydrophone assembly encapsulated in water-clear polyurethane elastomer.

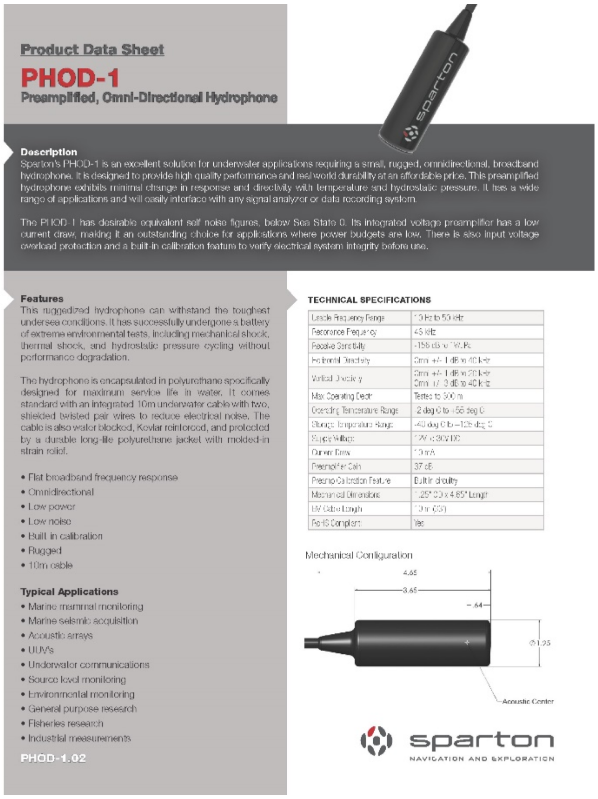
Conclusion

Our estimate is that the prototype hydrophone could be put into large-scale production at a price that would meet the $100-150 specification for use in the OOT platform.

Appendix

A1. Aquarian Audio Hydrophone H1C/H2C (top photo), and disassembled H1C with sensor boot removed displaying thin disk sensor (bottom photo).

A2. Sparton pre-amplified omni-directional hydrophone PHOD-1 product sheet (2 pgs).



Product Data Sheet

PHOD-1

Preamplified, Omni-Directional Hydrophone

Description

Sparton's PHOD-1 is an excellent solution for underwater applications requiring a small, rugged, omnidirectional, broadband hydrophone. It is designed to provide high quality performance and real world durability at an affordable price. This preamplified hydrophone exhibits minimal change in response and directivity with temperature and hydrostatic pressure. It has a wide range of applications and will easily interface with any signal analyzer or data recording system.

The PHOD-1 has desirable equivalent self noise figures, below Sea State 0. Its integrated voltage preamplifier has a low current draw, making it an outstanding choice for applications where power budgets are low. There is also input voltage overload protection and a built-in calibration feature to verify electrical system integrity before use.

Features

This ruggedized hydrophone can withstand the toughest undersea conditions. It has successfully undergone a battery of extreme environmental tests, including mechanical shock, thermal shock, and hydrostatic pressure cycling without performance degradation.

The hydrophone is encapsulated in polyurethane specifically designed for maximum service life in water. It comes standard with an integrated 10m underwater cable with two, shielded twisted pair wires to reduce electrical noise. The cable is also water blocked, Kevlar reinforced, and protected by a durable long-life polyurethane jacket with molded-in strain relief.

- Flat broadband frequency response
- Omnidirectional
- Low power
- Low noise
- Built in calibration
- Rugged
- 10m cable

Typical Applications

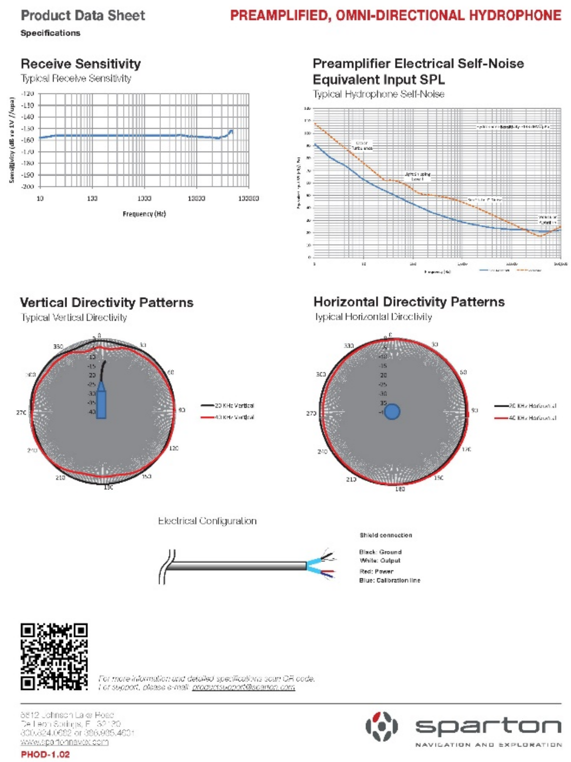
- Marine mammal monitoring
- Marine seismic acquisition
- Acoustic arrays
- UUV's
- Underwater communications
- Source level monitoring
- Environmental monitoring
- General purpose research
- Fisheries research
- Industrial measurements

PHOD-1.02

TECHNICAL SPECIFICATIONS

Usable Frequency Range	10 Hz to 50 kHz
Resonance Frequency	45 kHz
Receive Sensitivity	-156 dB re 1V/uPa
Horizontal Directivity	Omni +/- 1 dB to 40 kHz
Vertical Directivity	Omni +/- 1 dB to 20 kHz Omni +/- 3 dB to 40 kHz
Max Operating Depth	Tested to 300 m
Operating Temperature Range	-2 deg C to +55 deg C
Storage Temperature Range	-40 deg C to +125 deg C
Supply Voltage	12V to 30V DC
Current Draw	10 mA
Preamplifier Gain	37 dB
Preamp Calibration Feature	Built in circuitry
Mechanical Dimensions	1.25" OD x 4.65" Length
UW Cable Length	10 m (33')
RoHS Compliant	Yes

Mechanical Configuration



Product Data Sheet **PREAMPLIFIED, OMNI-DIRECTIONAL HYDROPHONE**

Specifications

Receive Sensitivity

Typical Receive Sensitivity

Preamplifier Electrical Self-Noise Equivalent Input SPL

Typical Hydrophone Self-Noise

Vertical Directivity Patterns

Typical Vertical Directivity

Horizontal Directivity Patterns

Typical Horizontal Directivity

Electrical Configuration

For more information and detailed specifications scan QR code.
For support, please e-mail: productsupport@sparton.com

5812 Johnson Lake Road
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[illegible] or 386.985.4631
www.spartonnavex.com

PHOD-1.02

A3. APC international ceramic PZT cylinder quotes.

APC International, Ltd.
Piezoelectric Ceramics & Piezo Components

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3	1	C-19.00mm-16.00mm-20.00mm-Type II (ID +) **Cat. # 42-1021**	54.000	54.00
4	1	C-6.35mm-4.90mm-6.35mm Type II (ID +) **Cat. # 42-1001**	54.000	54.00

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