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The Development of a Low-Cost Hydrophone for Passive Acoustic Monitoring of Dolphin's Vocalizations

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Abstract: Passive acoustics are widely used to monitor the presence of dolphins in the marine environment. This study aims to introduce a low-cost and homemade approach for assembling a complete underwater microphone (i.e., the hydrophone), employing cheap and easy to obtain components. The hydrophone was assembled with two piezo disks connected in a balanced configuration and encased in a plastic container filled with plastic foam. The hydrophone's performance was validated by direct comparison with the commercially available AS-1 hydrophone (Aquarian Hydrophones, Anacortes, U.S.) on different underwater acoustic signals: artificial acoustic signals (ramp and multi-tone signals) and various dolphin vocalizations (whistle, echolocation clicks, and burst pulse signals). The sensitivity of the device's performance to changes in the emission source position was also tested. The results of the validation procedure on both artificial signals and real dolphin vocalizations showed that the significant cost savings associated with cheap technology had a minimal effect on the recording device's performance within the frequency range of 0–35 kHz. At this stage of experimentation, the global cost of the hydrophone could be estimated at a few euros, making it extremely price competitive when compared to more expensive commercially available models. In the future, this effective and low-cost technology would allow for continuous monitoring of the presence of free-ranging dolphins, significantly lowering the total cost of autonomous monitoring systems. This would permit broadening the monitored areas and creating a network of recorders, thus improving the acquisition of data.

Keywords: passive acoustic monitoring; underwater acoustic signals; low-cost hydrophone; bottlenose dolphins

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1. Introduction

The detailed characterization of marine soundscapes may contribute to a better understanding of the environmental factors that influence the life conditions of marine fauna, shedding light on the behaviors of different marine species and their interactions with human activities [1–3]. One of the primary goals of marine monitoring activities is to collate data to store, study, and interpret underwater bioacoustic signals [4–6]. In particular, the assessment of spatial and temporal patterns in these signals could aid description of the behavior of most species in their natural environment [7].

Passive Acoustic Monitoring (PAM) is widely acknowledged as a suitable technique to identify possible sources of underwater acoustic signals. PAM involves deploying passive acoustic devices into water (the sea, oceans, and pools) to capture and identify sounds from the surrounding environment [8]. This technique is usually employed to monitor the presence and behavior of marine mammals in the open sea, with minimal intrusion into their daily lives [9]. One of the most studied species of marine mammals is the common bottlenose dolphin (*Tursiops truncatus*), a species with a worldwide distribution in tropical and temperate latitudes. These cetaceans are known for their advanced communicative and cognitive skills, making this species particularly notable in the field of acoustic communication [10,11].

Each species of dolphin produces distinct sounds. The typical acoustic emissions generated by bottlenose dolphins can be grouped into three different categories: (i) narrow-band frequency-modulated whistles [12], (ii) trains of highly directional echolocation clicks [13], and (iii) various typologies of broadband (mainly ultrasonic) burst pulsed sounds [14]. The whistles are interpreted as communication and social interaction signals. They are typically emitted for individual identification, contact between individuals, and coordinating group activities and transfers [15]. A large inter-individual variability is typical of these signals. The characteristics of whistles are usually quantified by assessing typical acoustic parameters such as temporal duration and frequency content [16]. Specifically, the frequency spectrum of dolphin whistles is highly informative and easy to compute, thus facilitating the creation of many quantitative studies focused on the analysis of this signal. The click trains are functional for echolocation. However, echolocation clicks are considered hard to classify in acoustic recordings due to their distinctive features: they are highly directional signals formed by a high-frequency acoustic content, which entails amplitude attenuation over relatively short distances [13]. It was reported that energy in echolocation clicks is narrowly focused along the longitudinal axis of the echolocating dolphin. As the axis–hydrophone angle increases, the signal is increasingly attenuated. Furthermore, high frequencies attenuate faster than low frequencies as the distance increases [13]. Thus, the assessment of the attenuation distance could depend on many factors. However, echolocation signals have been detected at distances of up to 650 m [17]. Moreover, dolphins are used to moving in large groups and vocalizing at the same time, thus superimposing individual sounds. The concomitance of these aspects increases the clicks' variability, which makes the identification of these signals very complex. Finally, burst pulse signals are primarily detected during foraging and feeding events, alarm and danger, aggressive behavior, and pre-copulatory interactions [18,19]. However, the specific purpose of these signals is still the subject of debate.

PAM usually employs underwater microphones to capture marine bioacoustic signals, known as hydrophones [20]. Hydrophones are sound-to-electricity transducers that can be submerged in water to record underwater sounds. A wide selection of hydrophones is currently available on the market. In normal conditions, most of these commercial devices are user-friendly and able to provide high-quality audio performances. Nevertheless, their cost could be considerable, especially when more hydrophones are concurrently needed for PAM analysis. This should be considered a limitation, particularly for research groups from emerging countries interested in conducting research in this field.

Therefore, the purpose of this study is to propose a novel low-cost homemade hydrophone called the CoPiDi (Common Piezo Disk) hydrophone. More specifically, the hydrophone has been developed and optimized to simultaneously reduce device costs and preserve the trustworthiness of the measurement of free-ranging dolphin vocalizations. A preliminary attempt has already been proposed in [21]. That approach has been expanded in this paper, increasing the acquisition of experimental data, improving the processing of acquired signals, detailing the technical description of the hardware, and strengthening the procedure for the validation of the device and interpretation of results. Two experimental tests were conducted to evaluate the hydrophone's performance. The first experimental test assessed the CoPiDi hydrophone's sensitivity to the signal emitted by two different signal generators placed in a round pool. Since PAM-analysis quality may worsen when vocalizations originate from multiple directions, the sensitivity of hydrophone's performance to changes in the position of emission sources was also tested. The second experimental test evaluated the proposed hydrophone's capability of delivering a high-quality signal to assess the echolocation clicks emitted by seven bottlenose dolphins recorded in a pool.

In both experimental phases, the CoPiDi hydrophone was tested against a commercially available hydrophone, which served as a reference.

2. Materials and Methods

2.1. Hardware Architecture

The proposed low-cost acoustic device is composed of two main hardware components: the hydrophone and the signal preamplifier to raise the level of the original signal, which is measurable in a few millivolts. Both component prototypes were built, assembled, and then utilized in the experimental trials. Details are provided in the following sections.

2.1.1. The Hydrophone

The CoPiDi hydrophone is mainly composed of common piezoelectric disks [22], which are widely used in several commercial applications such as alarm clocks, small audio devices, etc. The proposed prototype uses a single-face piezo capsule disk with a diameter of 27 mm. The hydrophone is assembled with two piezo disks encased in a plastic container (37 × 37 × 67 mm) filled with plastic foam. The disks are connected in a balanced configuration and placed on opposite sides. An aluminum rectangle (23 × 28 × 2.5 mm) was glued between each piezo disk and the plastic surface. At this level of experimentation, the total cost of this homemade hydrophone is estimated to be around $10.00. A description of this device is provided in Figure 1.

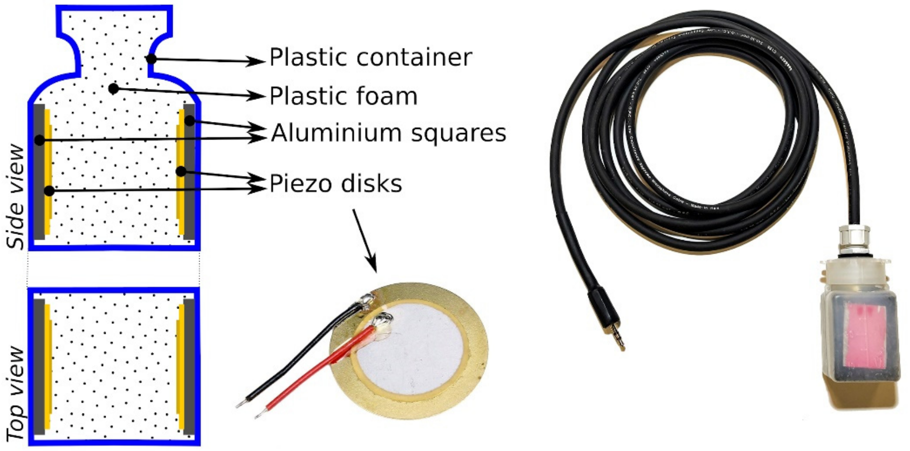

Figure 1. The proposed CoPiDi hydrophone.

2.1.2. The Preamplifier

Typically, the signal preamplifier is the complementary component to the hydrophone, and it is frequently housed in the same casing. Two different preamplifiers were used in this experimental project: a homemade preamplifier and the TritonAudio FetHead preamplifier. The features of both preamplifiers are described below. The homemade preamplifier is based on the circuit shown in Figure 2. It is a common differential JFET amplifier working with a phantom power source [23]. The circuit's design is based on an original idea by Alexander Rice and further improved in successive implementations [24].

Three 2N3819 JFETs (Q1, Q2, and Q3) are incorporated in the circuit (Figure 2): Q1 and Q2 are the differential pair, and Q3 is the current source, and also Q1 and Q2 are matched pairs. This preamplifier features an advantageously small size (it fits inside a 3-cm-diameter circle). The calculated gain is around 15 dB. At this experimental stage, the total cost of this homemade preamplifier is approximately $5. The TritonAudio FetHead is a professional low-noise and in-line microphone preamplifier with a stated gain of 27 dB [25]. Similarly to the proposed homemade preamplifier, the TritonAudio preamplifier also utilizes phantom power and FET technology. The output of both preamplifiers is a standard XLR male connector.

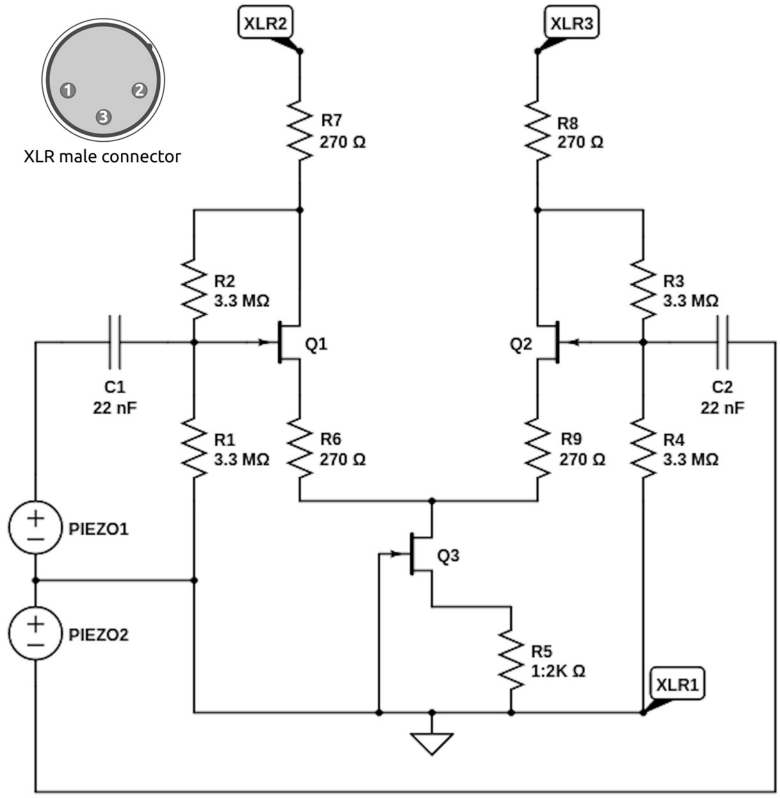

Figure 2. Schematic representation of the proposed homemade preamplifier.

2.2. Experimental Validation

The low-cost hydrophone's performance was evaluated using acoustic signals acquired in two different environments: a round-shaped pool that enables the testing of the hydrophone's sensitivity to specific signals emitted by two controlled artificial sound sources and a dolphin pool containing seven bottlenose dolphins. In both cases, the proposed hydrophone was validated by comparison to the commercially available AS-1 hydrophone (Aquarian Hydrophones, Anacortes, U.S. [26]). The AS-1 hydrophone has a linear range response of between 1 Hz and 100 kHz (±2 dB) and a receiving sensitivity of –208 dBV re 1 µPa (40 µV/Pascal). A standard laptop equipped with Audacity software (version: 2.4.2~dfsg0-5) was used throughout these experimental trials. Acquired data were stored on the local hard disk. Each timestamped wave file was recorded at a sample rate of 192 kHz and a 16-bit resolution. High performance acquisition was ensured by using the Focusrite Scarlet 2i2 at the USB audio interface, which provided a 24-bit resolution and a high sampling rate of 192 kHz for the AD-DA converters.

2.2.1. Recording of Artificial Acoustic Signals

In November 2022 we conducted an experimental session of acoustic recordings at Università Politecnica delle Marche, Ancona, Italy. There we evaluated the performance of the CoPiDi hydrophone in recording underwater signals. Furthermore, we tested the sensitivity of the devices to changes in the position of emission sources. Experiments were conducted in the round-shaped pool with a 16-m diameter. Both the CoPiDi and reference AS-1 hydrophones were immersed in water on the west side of the pool at a depth of 70 cm and a mutual distance of 100 cm (Figure 3c).

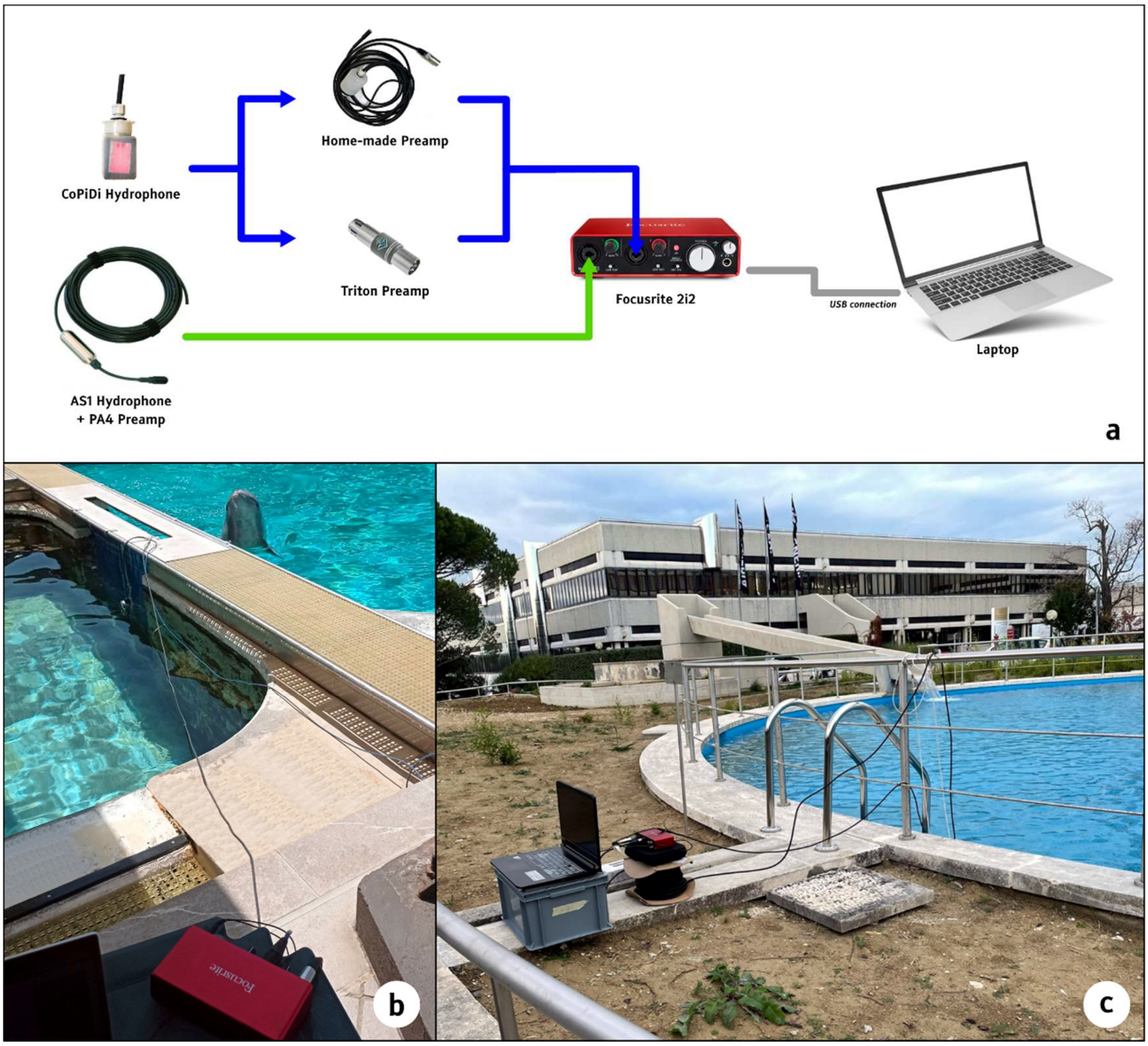

Figure 3. (**a**) Connection scheme of the devices used in the experimental trials. The reference AS-1 hydrophone is closely coupled with a PA4 preamp and the CoPiDi hydrophone has been connected to two different preamplifiers near to the audio device. (**b**) Experimental arrangement in the dolphin pool. (**c**) Multitone and ramp signals trials configuration.

Two different sound sources were utilized, both immersed in the opposite side of the pool (east side) at a distance of approximately 16 m from the hydrophones:

1. A homemade signal source device consisting of a piezo disk mounted inside a floating metallic can (diameter 7 cm and height 4 cm) and powered by a Tektronix CFG253 signal generator. This device generates cyclically variable 20-Vpp sine waveform signals with a frequency in the interval between 0 and 100 kHz (ramp signal). The cycle duration is 1.7 s;
2. An acoustic deterrent device or "pinger" (DDD, manufactured by S.T.M. Products, Italy) with remote wired activation, emitting sounds within the frequency range of 5 to 500 kHz with an emission power of 165 dB (1 µPa @ 1 m) and operating at a depth of 70 cm. The device produces multiple sweeping signals and a 30-s cycle of multitone impulses (Figure 4). The multitone impulses were analyzed in the experimental activities.

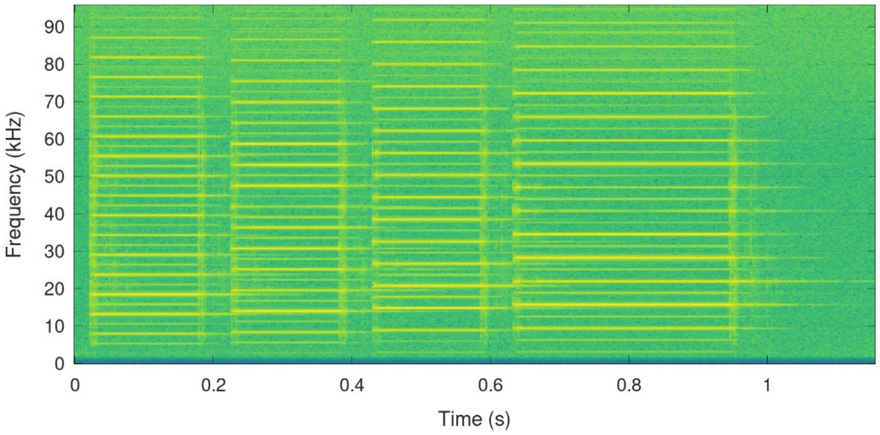

Figure 4. Portion of the multitone source signal produced by the STM DDD pinger.

The comparative analysis of the response at the two different sources can help to identify potential resonance issues in the frequency domain. The experimental activity was also designed to test the proposed hydrophone's sensitivity to positional changes with respect to emission sources. Four different positions were tested, as described below. It is worth recalling that the CoPiDi hydrophone is assembled with two piezo disks encased in a plastic container filled with plastic foam (Figure 1). The relative positions of the hydrophone with reference to these two piezo disks are as follows:

- The first piezo disk is orthogonal to the direction of the emission; the other disk is on the opposite side of the device—position 0°;
- Both piezo disks are parallel to the direction of the emission—position 90°;
- The second piezo disk is orthogonal to the direction of the emission and the other disk is on the opposite side of the device—position 180°;
- The sound emission strikes the bottom part of the hydrophone orthogonally–horizontal (H).

The same protocols are used to describe the reference hydrophone's positions. The two preamplifiers described above were used in these trials in all positions.

The acquisition session consisted of 18 different trials. Each recording session lasted about 2 min. The first 16 rows in Table 1 report the details of each acquisition trial, including the sound source typology, the orientation of the tested hydrophone with respect to the emitting source, and the preamplifier used. The last two rows in Table 1 describe two further trials that were carried out just to collect underwater background noise.

Table 1. Details of experimental activity.

Trial	Source	Orientation	Preamplifier
1	Ramp signal	0°	Triton
2	Ramp signal	90°	Triton
3	Ramp signal	180°	Triton
4	Ramp signal	H	Triton
5	Ramp signal	0°	Homemade
6	Ramp signal	90°	Homemade
7	Ramp signal	180°	Homemade
8	Ramp signal	H	Homemade
9	Multitone signal	0°	Triton
10	Multitone signal	90°	Triton
11	Multitone signal	180°	Triton
12	Multitone signal	H	Triton
13	Multitone signal	0°	Homemade
14	Multitone signal	90°	Homemade

Table 1. *Cont.*

Trial	Source	Orientation	Preamplifier
15	Multitone signal	180°	Homemade
16	Multitone signal	H	Homemade
17	Environmental noise	0°	Triton
18	Environmental noise	0°	Homemade

2.2.2. Recording Dolphin Vocalizations

Two experimental acoustic signal acquisition campaigns were held in November 2021 and May 2022 at the Oltremare marine park in Riccione, Italy, to test the performance of the proposed hydrophone in acquiring underwater dolphin vocalizations. For each campaign, 30-min acquisition sessions were conducted in the pool housing seven free-ranging bottlenose dolphins; signals were stored in 5-min-long segments. Acquisitions were obtained in the Oltremare dolphin lagoon during the dolphins' daily training activities, which included feeding. The proposed hydrophones and the reference AS-1 hydrophone were immersed in water at a depth of 120 cm and a mutual distance of 100 cm, as shown in Figure 5. The homemade preamplifier described in Section 2.1.1 was utilized in all the trials.

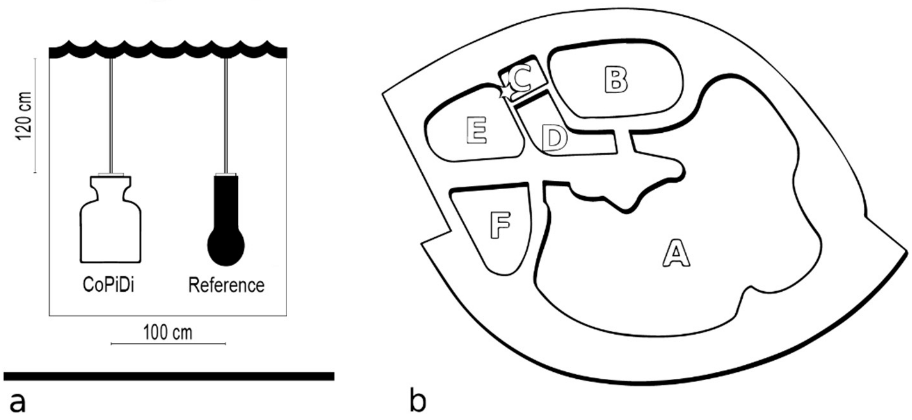

Figure 5. (**a**) The haul scheme used in experimental dolphin trials: the CoPiDi and reference AS-1 hydrophones were placed at a distance of 100 cm and at the same depth of 120 cm. (**b**) A map of the Oltremare marine park. The star indicates the location of the hydrophones.

The configuration of the Oltremare dolphin lagoon can be altered by removing gates between adjacent areas. Figure 5b is a map outlining the different areas. The hydrophones were placed in basin C close to the gate (the star in Figure 5b). The dolphins were not allowed to enter area C in order to avoid undesirable direct interactions with the devices. During the recordings, two male bottlenose dolphins were free to roam in areas D and E, while five females roamed freely in areas A, B, and F. Since the gates are built with a large metal mesh grid, sound can flow with negligible attenuation between adjacent areas and hydrophones.

2.3. Data Analysis

2.3.1. Artificial Acoustic Signals

Signals were stored in two-channel wave files, with the left channel containing data from the CoPiDi hydrophone and the right channel containing AS-1 reference data. Ambient noise from vehicular traffic near the pool during the trials was eliminated from both channels using a 2 kHz high-pass filter (48 dB cut-off). A stereo normalization filter was then applied. All the above operations were performed using Audacity audio software. Two different approaches were adopted for signal processing in order to extract specific information from the two different sources:

- For ramp signals, the Fourier Transform (FFT, size = 1024) was computed in 7-ms windows in order to provide the power spectral density (PSD). A 7-ms window was chosen because the frequency is considered stable in this interval. The CoPiDi hydrophone's performance was evaluated by comparing its PSD to that of the reference. Wave files were processed using GNU Octave software;
- For multitone signals, 30 s of the recorded signal were processed in order to extract a series of single multitone segments of variable length as follows: the signal was scanned to identify the samples where the signal amplitude is $\approx$0 dB (no signal) in the whole frequency range (0–96 kHz). These no-signal areas were then used to split the whole signal in the multitone segments. Each segment is composed of consecutive signal-area samples (signal amplitude > 0) included between two successive no-signal areas. The Fourier transform (FFT, size = 1024) and PSD were then computed in each single segment. PSD values exceeding the empirically identified threshold of 3.50×10^{-3} dB/Hz (used to filter out noise) were compared between the proposed and reference hydrophones. The GNU Octave software was used for this processing.

2.3.2. Dolphin Vocalizations

The dolphins' acoustic signals (the frequency-modulated whistles, the echolocation clicks, and the burst pulse signals) were analyzed to extract the three types of acoustic emissions and validate the CoPiDi hydrophone. Clicks were identified by means of an algorithm-based approach; whistles and burst pulse signals were both assessed using PAM analysis.

Click Identification

Each 5-min segment containing the dolphin vocalizations was split into sixty 5-s segments. The approach presented in [27] (chapter 4) was utilized to detect and compare the number of peaks recorded by the CoPiDi and reference hydrophone signals. These peaks were interpreted as dolphin echolocation clicks. In detail, the signals were high-pass filtered (cut-off frequency = 10 kHz); the signal-to-noise ratio (*SNR*) for the acquired signal *S* was then computed in a 2-ms window using the following Equation (1):

$$SNR = \frac{signal}{noise} \tag{1}$$

where *signal* is the filtered signal after constant offset removal,

$$signal = S - mean(S) \tag{2}$$

and *noise* is the noise level assessed as reported in Equation (3):

$$noise = \sqrt{mean\ (N^2)} \tag{3}$$

where *N* is the noise computed in a specific 60-s segment where no dolphin vocalizations were detected.

Then, an SNR threshold, Th, was empirically set to a constant value of Th = 4.5, in line with what is reported in [27]. An echolocation click was assessed each time the SNR value exceeded this Th value within the 2-ms window. This approach was applied to the signals recorded by both hydrophones using GNU Octave software. The performance of the low-cost hydrophone in identifying the correct number of echolocation clicks was tested versus the chosen reference. A statistical analysis of the results was also performed. Specifically, the normality of the distributions was first evaluated through the Shapiro–Wilk test. Given that at least one of the distributions was not normal, the Mann–Whitney test was used to test the significance of the statistical difference. The threshold for the test significance was set at 5%.

Identification of Whistles and Burst Pulse Signals

The low-cost hydrophone performance was further evaluated based on the quality of the recorded signal in detecting the two additional dolphin emissions, i.e., the whistles (W) and the burst pulse signals (BPS). To this end, a trained and experienced PAM operator used a spectrogram viewer (adopting 1024 points FFT with a 50% overlap and Hann window) to visually identify W and P signals from both the CoPiDi and reference hydrophones. Each detected vocalization was marked, and the number of events was used for comparison and validation.

2.4. Preamplifier Validation

A secondary objective of this study was to conduct a preliminary evaluation of the suitability of the proposed homemade 3-JFET-based preamplifier. To this end, the performance of the homemade preamplifier coupled with the CoPiDi hydrophone was compared to that of the commercial TritonAudio FetHead preamplifier coupled with the same hydrophone. Multiple trials were conducted to test the sensitivity of the preamplifier's performance to the emission sources' different locations, as described in Table 1 (four different positions: 0°, 90°, 180°, and horizontal and two different signals: ramp and multitone signals).

3. Results

The results of the analysis of the acoustic signals are described in the following sections. They are presented separately for artificial acoustic signals and dolphin vocalizations in order to provide a clearer presentation of the outcomes.

3.1. Artificial Acoustic Signals

As discussed in Section 2.2.1, two different signals were analyzed: the ramp signal and the multitone signal. The spectrogram (in green) and the power spectral density (PSD) of the ramp signal in a frequency range of 0 kHz to 96 kHz were computed in each one of the 1.7-s segments. An example of the results is shown in Figure 6 for the proposed (panel a) and reference (panel b) hydrophones.

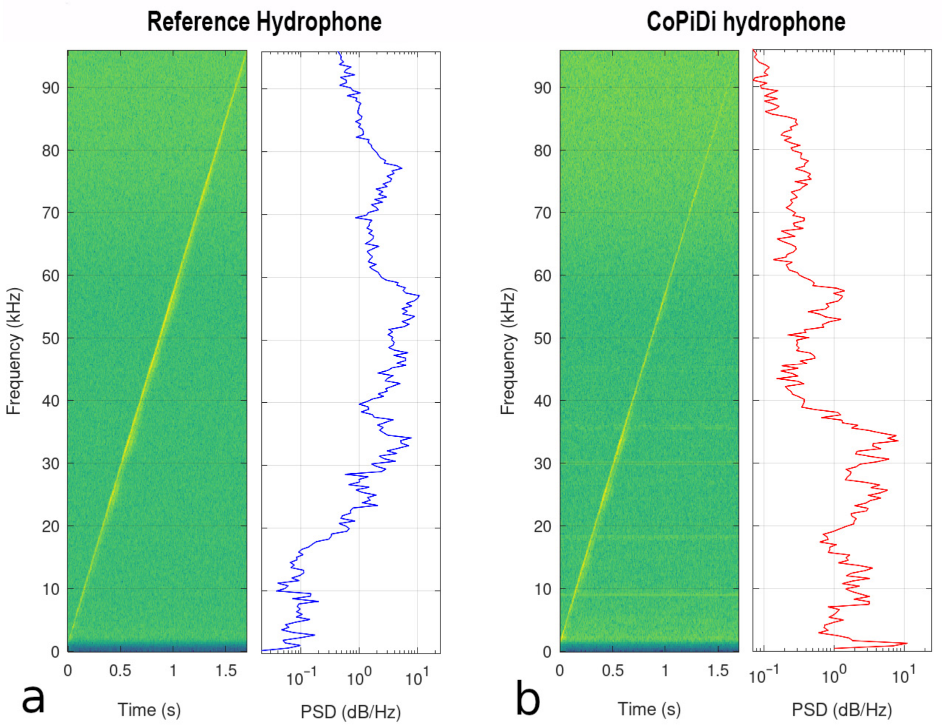

Figure 6. Example of a single ramp signal spectrogram (in green) and PSD analysis comparison. (**a**) Response of the Reference Hydrophone (**b**) Response of CoPiDi Hydrophone.

Figure 7a depicts a comparison of the average PSD computed over all segments between the proposed hydrophone coupled with both the homemade preamplifier (orange curve) and the Triton preamplifier (red curve), and the reference hydrophone coupled with the Triton preamplifier (light blue curve). This comparison highlights that the proposed device has a better response below ≈20 kHz, a substantial approximation up to 35 kHz, and a discernible deterioration in performance at higher frequencies.

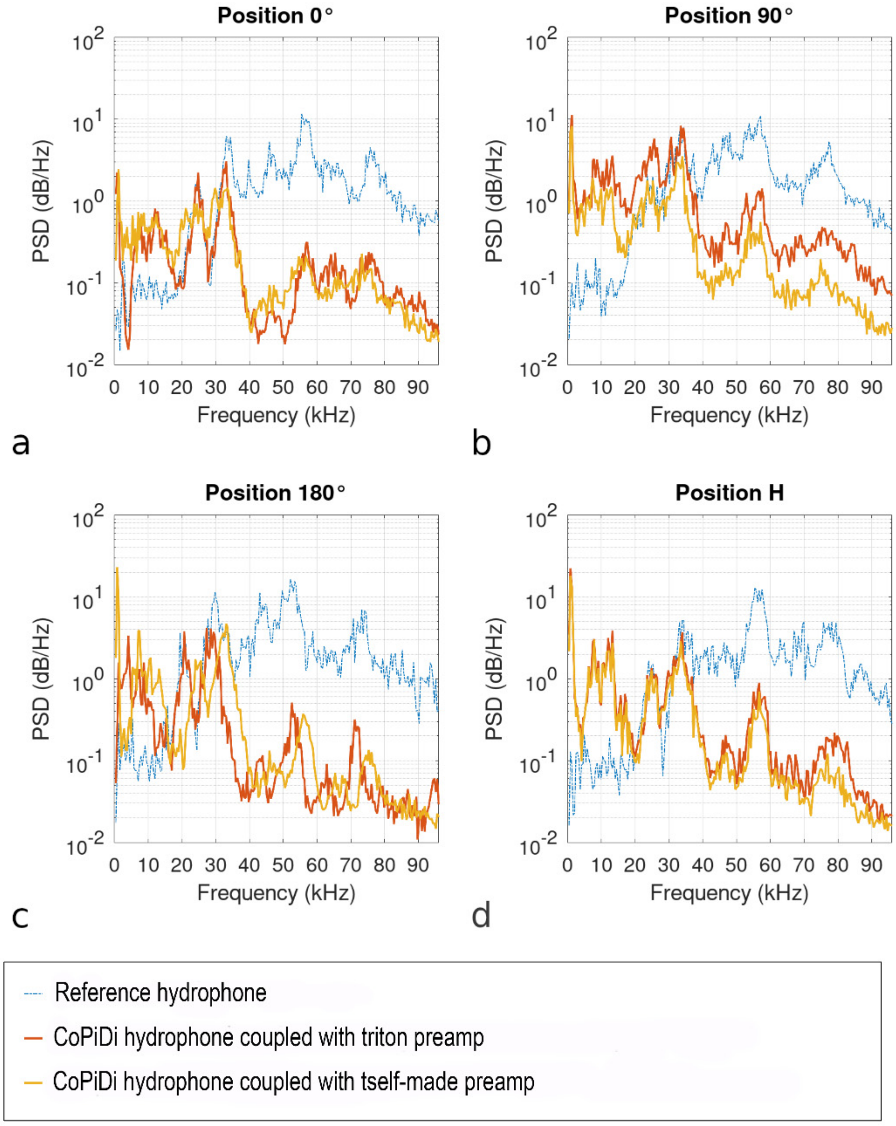

Figure 7. Comparative analysis of PSD in the frequency domain between the proposed hydrophone and the reference hydrophone. Four different orientations and two different preamplifiers were tested (**a**) Signal source at 0°. (**b**) Signal source at 90°. (**c**) Signal source at 180°. (**d**) Hydrophone in orizontal position.

The remaining three panels in Figure 7 depict the sensitivity analysis of the proposed hydrophone's performance to changes in the emission source direction. The three other positions (90°, 180°, and H), were tested in addition to the initial position (0°). For the 180° and H positions, the relative trend of the CoPiDi hydrophone curves (orange and red) remained practically unaltered when compared to the reference curve (light blue). Otherwise, an improvement in the performance of the CoPiDi hydrophone above 35 kHz was observed for the 90° position (panel b). Nevertheless, the enhancement of the low-frequency response (0–20 kHz) and the concomitant deterioration of high-frequency behavior (>35 kHz) observed for the CoPiDi hydrophone in the 90° position were also confirmed in the other three positions. The four panels in Figure 7 also enable a direct comparison of the performance of the recording technique utilizing the two different preamplifiers (orange curve for the homemade preamplifier and red curve for the Triton preamplifier). The two curves are practically superimposed in three positions (0°, 180°, and H) in all the frequency ranges, particularly below 35 kHz. In the 90° position, a reduction in PDS values can be observed in the orange curve, mainly above 35 kHz.

The multitone analysis was conducted on a single recording lasting 30 s with the emission source in the 0° position. In order to only test hydrophone performance, the proposed device was coupled with the commercial Triton preamplifier. The processing isolated 99 multitone signals along the entire cycle. A matrix (512 columns and 99 rows) for both the CoPiDi and reference hydrophones, containing PSD peak values exceeding the threshold level (3.50×10^{-3} dB/Hz), was computed in the frequency domain. Each individual row in the matrix contains a single multitone signal. Figure 8 displays the full results for both hydrophones, enabling a direct comparison of their performances.

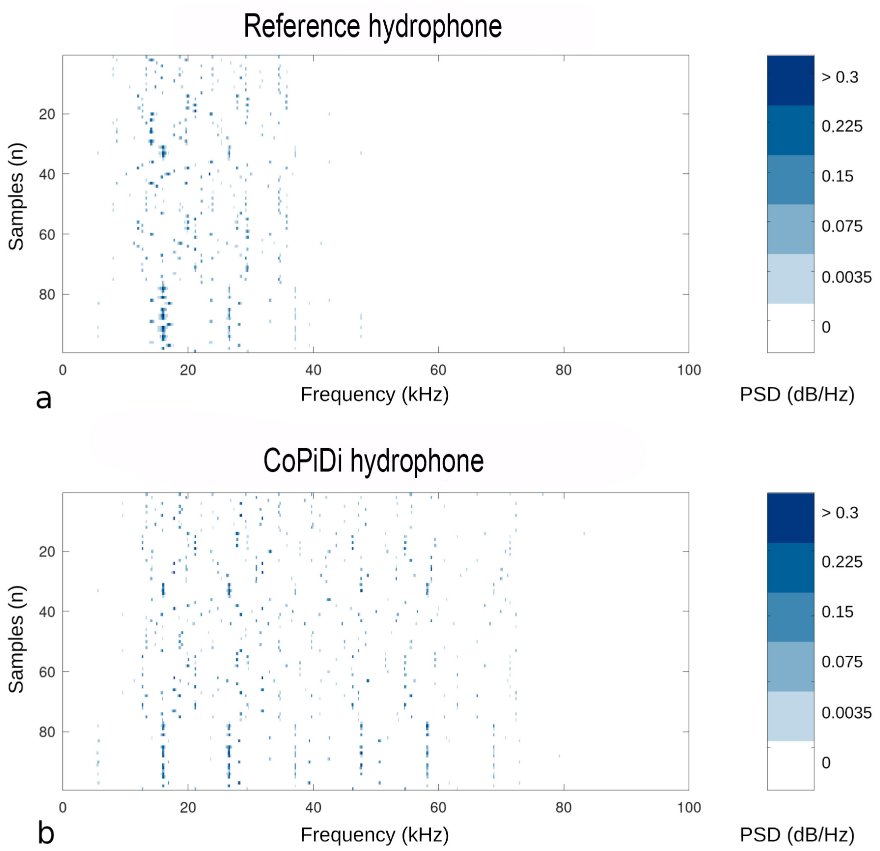

Figure 8. Comparison of the results of the multitone signal analysis between the CoPiDi (panel **a**) and the reference (panel **b**) hydrophones. The blue points represent PSD peak values detected by the two hydrophones on a single 30-s recording.

Figure 8a highlights the reduced capability of the proposed hydrophone to identify PSD peaks for high frequencies (>40 kHz) compared to the reference device, which can detect PSD peaks up to 70 kHz.

3.2. Dolphin Vocalizations

The first parameter extracted from dolphin vocalization signals was the number of echolocation clicks. Figure 9 illustrates an example of the hydrophone's performance in terms of this parameter using the current approach (panel b) compared to the reference approach (panel d) in a selected 5-s segment of the signal. Visual inspection suggests that outcomes are comparable between the two approaches.

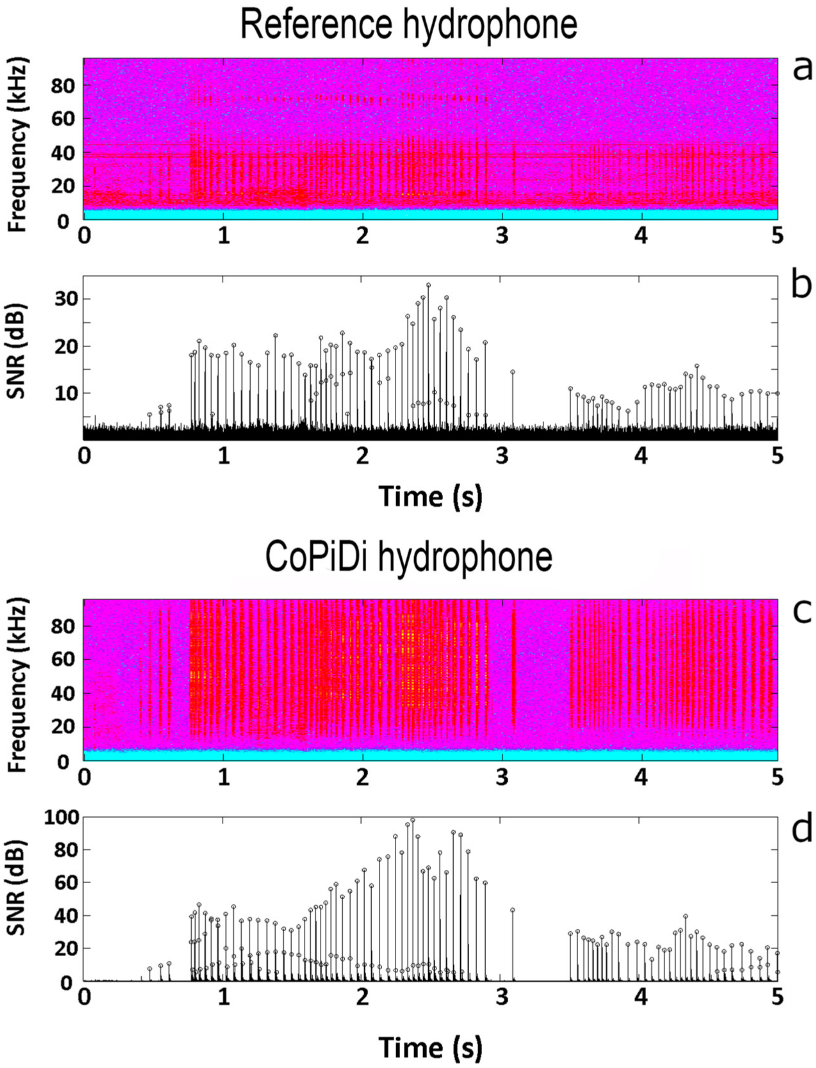

Figure 9. Hydrophone performance in a representative 5-s segment using the proposed low-cost approach (spectrogram in panel **a** and click detection in panel **b**) as compared to the reference approach (spectrogram in panel **c** and click detection in panel **d**). Detected clicks are highlighted with a circle. SNR is signal-to-noise ratio.

The low-cost approach detected a total of 8797 clicks in all the 60 5-s segments of the signal. The reference approach identified 9065 clicks in the same signals. The difference between the 2 approaches is 268 clicks, corresponding to 2.97% of the total clicks identified using the AS-1-based approach. The median values of the number of clicks detected over the 60 segments are 140.5 ± 77.7 for the CoPiDi hydrophone and 155.5 ± 73.2 for the reference hydrophone. The difference between median values (non-normal distributions) is not statistically significant ($p > 0.05$).

Two further parameters were used to validate the hydrophone's quality: the number of whistles and burst pulse sounds detected in the dolphin vocalization signals by visual inspection during PAM analysis. Figure 10 shows an example of hydrophone performance achieved in terms of these two parameters. The measurements of the low-cost approach for a selected segment of the signal are reported in panel a while measurements of the AS-1-based reference approach are shown in panel b. A visual inspection suggests that the outcomes of the two approaches are comparable.

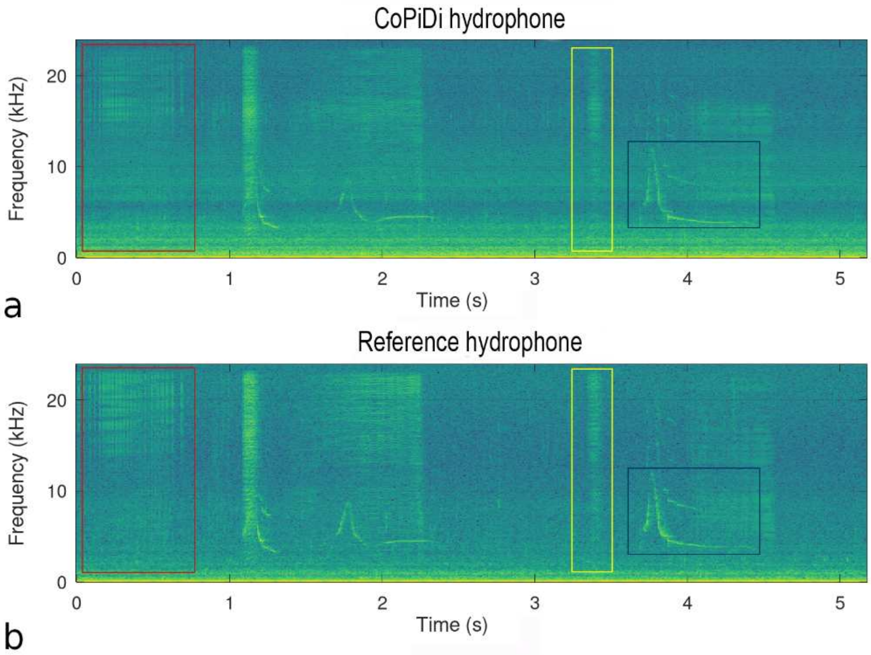

Figure 10. Example of a comparison between CoPiDi hydrophone (**a**) and the reference hydrophone (**b**) by visual inspection during PAM analysis between the waveforms of click sounds (red box), feeding buzzes (yellow box), and whistles (blue box) detected by means of the two different approaches.

Quantitatively, the PAM expert detected 11 whistles and 133 burst pulse sounds in the signal recorded by the low-cost approach. The same expert was able to identify the same number of whistles (11) and burst pulse sounds (142) in the signal recorded by the reference approach. The difference between the two methodologies is 9 BPS, corresponding to 6.34% of the total BPS identified by the reference approach.

4. Discussion

Passive acoustic monitoring of marine fauna is severely hampered by the high costs of recording devices. Although the hydrophone may be considered the primary component of the recording system, it is merely a single sensor that has to be coupled with a recorder and power source. Moreover, all these devices have to be waterproofed or at least kept partially out of water. This contributes to a marked increase in the global cost with respect to equivalent terrestrial devices. A recent literature review indicates that the price of commercial underwater recording units is on average five times that of their terrestrial counterparts [28]. This is particularly true for the cheapest systems, where prices can be up to 40 times higher than terrestrial systems. These inflated prices frequently compel researchers to use a lower number of systems (sometimes only one), thus creating undesirable limitations to the experimental project, including a reduction in the number of monitored areas and the inability to create a network of recorders. The risk of losing the device owing to involvement with other human activities (e.g., boating or fishing) also makes this recording procedure more complex. Therefore, the development of low-cost recording systems for underwater monitoring is a priority in order to facilitate the widespread utilization of PAM in aquatic environments. The hydrophone is crucial for sound acquisition. Reducing the cost of this main sensor should be the first step in this direction.

This study is a modular component of a wider project to develop an autonomous low-cost device for detecting the acoustic presence of cetaceans, as described in [21]. Specifically, the study focuses on the concept of a novel homemade hydrophone for acquiring underwater sounds that is capable of minimizing costs while maintaining the practicability of the recordings. This proposed hydrophone is very cheap (approximately €10), making it very competitive in comparison to commercially available models, including the AS-1 hydrophone used as a reference in this work. A secondary objective of this study is to propose and then conduct a preliminary evaluation of the suitability of a homemade 3-JFET-based preamplifier coupled to the proposed hydrophone.

To evaluate the practicability of the CoPiDi hydrophone, it was tested against the commercially available AS-1 hydrophone which served as the reference. Trials were conducted in different phases, sampling artificial sound signals and bottlenose dolphin vocalizations. Two different artificial acoustic signals were analyzed in the first phase of hydrophone validation: ramp signals and multitone signals. On average, the PSD analysis seems to indicate that the response of the two hydrophones to ramp signals is comparable to frequency values below 35 kHz (Figure 7). Particularly for the 0–20 kHz frequency range, the self-made hydrophone appears to be even more sensitive than the AS-1 hydrophone (Figure 7). Low-frequency high performance is also confirmed by the multitone signal analysis depicted in Figure 8. For frequency values higher than 35 kHz, both ramp and multitone analyses indicate that the AS-1 hydrophone seems to work better than the proposed device. The size of the active element of a hydrophone (piezo disk in CoPiDi hydrophone) is an important parameter. Indeed, when a typical hydrophone is placed in a real acoustic field, it must cause less influence on the original acoustic field. However, hydrophones may suffer from unwanted noise created as a result of their presence in real fields [29]. Starting from this consideration, it is likely that the observed attenuation starting at 35 kHz could be due to the piezo disk dimensions. Specifically, a diameter of 27 mm would be considered too big. The aluminum plate thickness and the density of the plastic foam could also play a role in the frequency response. Further studies will be focused on the effect of varying those dimensions and using an air cavity instead of plastic foam on the frequency response.

Although it is acknowledged that peak frequencies of bottlenose dolphin vocalization could extend up to 150 kHz [13,30], the appropriate frequency range for characterizing bottlenose dolphin vocalizations is still open to discussion. Indeed, it is important to take into account limitations and challenges associated with recordings with a wide frequency range, such as high equipment cost and larger data storage requirements. The choice of the frequency range to record can vary depending on the type of vocalization. Different studies reported that the frequency content of signature whistles ranges from 1 up to 30 kHz [31,32]. Thus, a frequency range of 0–35 kHz is suitable to identify and classify dolphin whistles based on their spectral features. Concerning bottlenose dolphin echolocation clicks, a study by Baumann-Pickering et al. focused on spectral characteristics of the acoustic signal and reported that median peak frequencies range between 27.2 and 35.6 kHz [33]. Furthermore, it was reported that high-frequency echolocation signals occur primarily when vocalizations are recorded along the axis of the transmitting beam of the dolphin [34]. Outside the beam, the low-frequency components suffer less attenuation and appear in the frequency spectrum [35]. Thus, low-frequency components are expected to be predominant when free-ranging dolphin vocalizations are recorded since they are mainly off-axis of the transmitting beam [36]. It is worth recalling that the CoPiDi hydrophone was developed with just the main aim of measuring free-ranging dolphin vocalizations. Moreover, based on the abovementioned analyses, a study by Romeu et al. showed that a sampling frequency of 48 kHz (and thus recorded bandwidth = 24 kHz) may be effective for recording the entire acoustic repertoire of Turpsiops truncatus when employed in studies analyzing and quantifying the presence/absence of the single animal or a population of cetaceans in a specific location [36]. For all the situations described above, the proposed hydrophone appears to be a suitable tool for recording dolphin’s vocalization, especially considering its low cost. However, for different goals where the recording of the full bandwidth is recommended, more expensive commercial hydrophones should be considered.

The direction of an incoming signal could impact the quality of the recording process. Consequently, the sensitivity of hydrophone performance to four different emission source locations was also evaluated. Figure 7 demonstrates that the high performance of the CoPiDi hydrophone in the frequency range <35 kHz is maintained regardless of the emission source’s location. Performance deterioration for higher frequencies is also confirmed.

However, an incoming signal from a specific 90° position appears to boost hydrophone performance above 35 kHz. This may be a result of the direct incidence of sound waves on both piezo capsules, as opposed to one single piezo capsule as in the other three positions.

In addition to the analysis of the artificial acoustic signal, the practicability of the low-cost hydrophone was also tested on real dolphin vocalizations. In a preliminary step, a comparison with the AS-1 reference was undertaken to quantify the capability of the two hydrophones to provide a high-quality signal to assess the echolocation clicks emitted by dolphins. The detection of clicks was adopted as an evaluation task because click characteristics (highly directional; high-frequency acoustic content) make this assignment very challenging and highly significant [13]. A simple but reliable SNR-based algorithm for click assessment was applied to a series of sixty 5-s segments extracted from the signals recorded by the two hydrophones [27]. The results reveal that there is no significant difference ($p > 0.05$) in the average number of clicks identified by the two approaches. The global number of assessed clicks is also comparable (8797 clicks for the low-cost hydrophone and 9065 clicks for the AS-1 hydrophone) since their difference is below 3%. This suggests that, despite the deterioration in high-frequency performances detected by analyzing artificial acoustic signals (Figures 7 and 8), the CoPiDi hydrophone also appears to be competitive in click detection. These results are reinforced by a visual examination of Figure 9, in which the echolocation clicks assessed by the two hydrophones are compared directly in the same segment of the signal (panel b vs. panel d).

In order to compare the hydrophone's ability to acquire different vocalization typologies, a second validation stage was deemed necessary. To this end, PAM analysis was undertaken by visual inspection to quantify and compare the number of whistles (W) and burst pulse sounds (P) identified by a trained human expert in the signal measured concomitantly by means of the two devices (Figure 10). The number of whistles detected in the low-cost hydrophone and reference hydrophone signals is the same (11 whistles). The detection error of burst pulse sounds in the signal of the low-cost hydrophone is less than 7% (133 vs. 142 BPS). The concordance of the results on dolphin vocalizations suggests that the deterioration in performance produced by the cheap technology used in the low-cost device is limited compared to the significantly more expensive reference device. This supports the promising results achieved through the analysis of artificial acoustic signals. As stated previously, the objective of this study is not to conduct a comprehensive evaluation of acoustic monitoring of dolphin presence; rather, the study is the preliminary approach to this task in order to test the hydrophone's performance. Nevertheless, the quantitative results of the processing are really promising and warrant further in-depth research to refine and optimize the hardware design and algorithms used to detect the clicks. A secondary objective of this study is to carry out a preliminary assessment of the homemade 3-JFET-based preamplifier's practicability. The comparative analysis of the commercial-grade and homemade preamplifiers yielded commendable results, with the two PSD curves practically superimposed across the entire frequency range. This would enable further cost reductions for the underwater recording system.

The overall results of the experimental trials clearly demonstrate that common and cheap piezo disks can be used to develop a low-cost hydrophone suitable for recording dolphin vocalizations during PAM activities. This provides the opportunity to drastically reduce the costs of monitoring activities while enhancing the quality of the analysis of the interaction between cetaceans and fishing activities. Indeed, this favorable cost reduction in underwater recording systems would facilitate the inclusion of more systems in PAM analysis, making it possible to extend monitored areas and create a network of recorders, thereby boosting the quantity and quality of gathered data. Cheaper systems would also enable more emerging countries to participate in this field of research and provide their contributions.

The monitoring of set nets is one potential scenario where the CoPiDi hydrophone could be highly useful [3]. The set net is a piece of widely used fishing gear with a length that can exceed six kilometers. This length significantly increases the likelihood that the gear may engage with depredating cetaceans. The use of a single hydrophone/recorder/detector would result in a coverage area that is too narrow or too wide. In the former case, the PAM analysis may be influenced by possible false negatives, while in the latter, by possible false positives. Monitoring the set net with multiple devices enables more accurate sampling, thereby reducing both false positive and false negative detections. The low cost of the proposed hydrophone (and preamplifier) can boost the use of multiple devices to improve the sampling process.

Further potential developments are currently under investigation. Particularly, (1) to produce a 3D-printed casing housing piezo disks and the preamplifier, (2) to adopt a 3D-printed air cavity behind each piezo disk, and (3) to develop a new preamplifier design using operational amplifiers. An autonomous recorder using the proposed hydrophone and preamplifier will be tested in the Life DELFI project's monitoring activities.

5. Conclusions

Overall, the current study proposed a novel approach for creating a low-cost hydrophone device suitable for recording underwater sounds during PAM activities. Its validation on both artificial acoustic signals and dolphin vocalizations revealed that the significant cost savings associated with cheap technology minimally impacted the recording device's performance in the frequency range of 0–35 kHz. At this stage of experimentation, the hydrophone's global cost is estimated to be around €10.00, making it very competitively priced when compared to commercially available models. Due to its low cost, the proposed device can be combined with widely used smartphones and suitable software to create a basic PAM system at a very affordable price. This could stimulate and support research activities in developing countries, as well as facilitate public participation in studies. With an eye toward the future, the low cost of these components may enable the creation of autonomous devices deployed in a network of marine recorders that will: (a) foster the continuous monitoring of marine mammal presence over large areas and (b) more generally, facilitate the efficient monitoring of noise pollution in the marine environment.

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Data Availability Statement: The data analyzed in the present study are currently available for research purposes by contacting the corresponding authors.

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