METHOD ARTICLE

Assembling cheap, high-performance microphones for recording terrestrial wildlife: the Sonitor system [version 1; referees: 2 approved, 1 approved with reservations]

Kevin Darras [1], Bjørn Kolbrek[2], Andreas Knorr[3], Volker Meyer[4]

[1]Department of Agroecology, University of Göttingen, Göttingen, Niedersachsen, 37077, Germany
[2]Celestion, Ipswich, Suffolk, IP6 0NL, UK
[3]Mess-, Steuerungs-, und Regeltechnik, University of Göttingen, Göttingen, Niedersachsen, 37077, Germany
[4]Konstruktion, Geräte- Neuentwicklung, Schreinerei, Schlosserei, University of Göttingen, Göttingen, Niedersachsen, 37077, Germany

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Abstract

Passive acoustic monitoring of wildlife requires microphones. Several cheap, high-performance open-source solutions currently exist for recording sounds, but all of them are still reliant on commercial microphones. Commercial microphones are relatively expensive, specialized on particular taxa, and often have opaque technical specifications. We designed Sonitor, an open-source microphone system to address all needs of ecologists that sample terrestrial wildlife acoustically. We evaluated the cost of our system and measured trade-offs that are seldom acknowledged but which universally limit microphones' functions: weatherproofing versus sound attenuation, windproofing versus transmission loss after rain, signal loss in long cables, and analog sound amplification and directivity with acoustic horns. We propose three microphone configurations suiting different budgets, sound qualities, and flexibility requirements, which all cover the entire sound frequency spectrum of sonant terrestrial wildlife at a fraction of the cost of commercial microphones.

Keywords

autonomous sound recorders, passive acoustic monitoring, signal-to-noise ratio, self-noise, acoustic horn, Song Meter, Swift recorder, Bioacoustic recorder

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1 **Sarab S. Sethi**, Imperial College London, UK

2 **Holger Klinck**, Cornell University, USA

3 **Catharina Karlsson**, National University of Singapore, Singapore

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Corresponding author: Kevin Darras (kdarras@gwdg.de)

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Introduction

Passive acoustic monitoring of terrestrial wildlife is nowadays a firmly established field of study. It has many advantages over classical human observation methods[1] and bears considerable potential for further development[2]. Birds, bats, amphibians, insects, and primates are often surveyed using autonomous sound recorders. A wide range of open-source devices and commercial products exists for recording sound in terrestrial habitats (Table S1)[3]. Established manufacturers offer products to cover all needs, and non-profit organisations also build and sell autonomous sound recorders. Raspberry-Pi based solutions, as well as dedicated autonomous sound recorders offer cheap alternatives to commercial products[4].

As transducers of mechanical energy into electrical signals, microphones are the most important components of a sound recorder. They are the first step in the sound recording process, and through their frequency response, they determine which animals can be recorded. A recent meta-analysis demonstrated the crucial importance of microphone specifications and underlined how microphone signal-to-noise ratio, a measure of its inherent noise level, affected the sound detection space[5], which is also determined by external factors[6].

Despite the many different sound recorders that are available, their owners are usually restricted to the microphones of the manufacturers or the recommendations of recorder builders due to compatibility or warranty issues. Outdoor microphones rapidly degrade as they are exposed to rain ingress, animal damage, ultraviolet radiation, and wide temperature ranges[7]. Users usually only have the choice of expensive microphone replacements as repair instructions are not available, components are unknown, and the design is not disclosed. Microphone specifications are rarely complete, and sensitivity is stated more often than the more important signal-to-noise ratio. In many cases, the microphone element that is used is unknown. In some cases, microphone signals are filtered at the source only for commercial reasons, to enable either bird or bat recordings and sell multiple specialised products. Currently, no microphone is available to record both bats and birds, although the recorders that can record ultrasound theoretically could sample the entire frequency range of interest.

To provide alternatives to the sound-recording community of ecologists, we designed a cheap, open source, high-performance, and modular microphone system called Sonitor. The system can be used to record all terrestrial wildlife. We first present the basics of microphone parts, then present the Sonitor system, and assess its performance. We show the trade-offs between weatherproofing and transmission loss, between wind-proofing and drying time, between cable length and signal loss, between directivity and analog amplification, and evaluate the temporal and financial cost of assembly. We built microphones for the most common audio connector system used in current recorders of established manufacturers: Wildlife acoustics (Song Meter), FrontierLabs (Bioacoustic recorder), and Cornell University (Swift). We present three different microphone configurations for different needs and budgets.

Methods

Microphone design basics

Sound consists of pressure waves travelling through a medium, in our case air. Audible sound makes the air vibrate at frequencies between 20 Hz and 20 kHz. Ultrasound, which is not audible for humans, extends beyond 20 kHz. Insects and bats can emit and perceive ultrasound up to 200 kHz[8]. Microphones are transducers of mechanical energy (pressure waves) into electrical energy (a voltage). A variable voltage is created as sound waves move mechanical parts of microphones, which can be a polarized membrane (electret condenser), or a piezoelectric element. The role of the recorder is mainly to increase the minimal voltage differences with amplifiers, digitize them with analog-to-digital converters, and record them to a digital storage medium (mostly solid-state memory secure digital cards).

Outdoor microphones are electrical devices which need to be protected against water ingress, and climatic and mechanical shocks. Protection comes from solid housings, often metal tubes in which the microphone element is inserted. The microphone element (often ambiguously called simply "microphone") is the centerpiece of the microphone and consists only of the acoustic sensor which transduces sound to a variable voltage, and it is not usable as is. Microphone housings need to be open to allow sound to reach the microphone element through their acoustic port. Since an opening would allow water to penetrate the microphone, corrode its components, and block the sound path, protection is needed. Acoustic vents are used: they are transmissive for sound while being impermeable to water or hydrophobic, and thus fulfil a crucial function for outdoor microphones. Then, microphones need to transmit their output voltage to a recorder via electrical wires. When microphones are interchangeable, they use an audio connector as interface, which needs to be weatherproof too. A minimal microphone assembly only requires soldering of microphone elements and cables, as well as sealing of the other microphone parts using glue if used outdoors.

Basic microphone properties can be augmented with attachments. Windscreens, usually made of synthetic foam or fur, reduce unwanted wind noise which comes from friction of air against the microphone. They also reduce potentially damaging water pressure from rain drops. Furthermore, parabolic reflectors or horns can be used to gather sound over a larger area before concentrating it to the microphone element, but the gained amplification is traded off against higher directivity: the sound pickup pattern becomes narrower.

Sonitor microphone components

Microphone element. We chose to use microelectromechanical (hereafter MEMS) microphones due to their high performance at small sizes, the potential of that newer technology to mature and offer higher performance than conventional microphone capsules, and their lower part-to-part variation and sensitivity to temperature variations (Lewis *et al*. 2013). Different elements exist that can fulfil different requirements by prioritizing low-noise recording, a wide frequency response, or weatherproofing. We are using microphone elements from different manufacturers. We used a tried-and-tested element from Knowles (SPU0410LR5H-QB), which was used by the company Biotope.fr inside the now discontinued BIO-SMX-US microphone as a substitute for SMX-US microphones by Wildlife acoustics. We also used it inside our own housings since 2017 for recording birds and bats. We tested Invensense's ICS-40720 element, which features low-noise recording (specified signal-to-noise ratio of 70 dB) and also Vesper's VM1000, which is a piezo-electric element that is waterproof and resistant to various environmental stresses.

Printed circuit board (PCB). Microphone elements can be directly soldered to cables, but this requires great care and dexterity for a precise soldering result that does not exceed the temperature tolerance of the element. Moreover, a precise alignment of the microphone within the housing and with the acoustic vent is needed for compatibility with external attachments and for enabling consistent part-to-part quality. It is thus preferable to reflow-solder MEMS elements to printed circuit boards, which can be made in electronic laboratories or workshops equipped with reflow ovens. This is readily available as a paid service and is a burgeoning business satisfying the needs of electronic equipment manufacturers and electronics hobbyists in need of prototypes. Cables can then be more easily soldered to PCBs without damaging the microphone element. The microphone and conductive tracks can be attached on the bottom side of the PCB, which guarantees a result that is flush with the housing. PCBs can be ordered in any size and shape with a variety of support materials.

Housing. We chose to integrate the microphone elements into simple metal tubes, which can be made out of stainless steel or lighter aluminium. These metals offer high resistance to weather and mechanical shocks, are cheap and readily available, and easy to glue. They can be painted to reduce their visibility in natural environments. Due to their hardness, metals can also be lathed with high precision to ensure stable results within tight tolerances so that any attachment can easily fit the housing.

Wires and connector. We chose standard 30 AWG stranded wires for more flexibility compared to solid wires. On one end, the cables are connected to the PCB, which is connected to the microphone element. On the other end, the wires are connected to Mini-Con-X series waterproof connectors without the grommet, which is needed to release the tension when the connector is attached to flexible cables. This connection form is commonly used in most autonomous sound recorders. Mini-Con-X connectors can withstand some abuse and are ingress-protection rated at IP67 (dust tight and protected against water up to 1 m deep).

Acoustic vent. We use Gore acoustic vents to protect the element against solid and liquid ingress. Different products in varying sizes and protection levels against water are available. GAW112 vents can be used, they appear identical to the ones used in SMX-US, SMX-U1, and SMX-II microphones from Wildlife acoustics. They need to be coupled with windscreens, as GAW112 vents let water pass after immersion or drop projection. We also tested GAW325 vents, which are IP67 rated. Freshwater ingress per se only temporarily blocks microphone elements that are not waterproof from vibrating, but will not short-circuit the microphones due to the low conductivity of water. However, water leads to corrosion, which will destroy microphones and conductive tracks, given enough time. The GAW3XX series also have a support material, which can be made of woven or non-woven PET material. The PET (woven) support elements are better suited as they absorb water less.

Microphone assessment

All assessments of the microphones' technical qualities were performed with SM2Bat+ recorders (Wildlife acoustics), which allow to record two channels up to a maximum sampling frequency of 192 kHz. We used a battery-powered one-driver Anker SoundCore loudspeaker for emitting audible pure test tones at 1 and 10 kHz (generated using Audacity 2.2.2) and an ultrasonic calibrator (Wildlife Acoustics) that emits chirps at 40 kHz. Test sounds were emitted to the front of the microphones and when needed also to the side at a 90° angle. We measured the amplitude of test tones in recordings with a sampling frequency of 96 kHz in Audacity by exporting the frequency spectra with a Hanning window size of 1024 and choosing the frequency window that included our tone's base frequency.

Weatherproofing vs. sound attenuation. The only point that is permeable to sound is the acoustic vent, and its permeability to water ingress is given by its specifications. The sound attenuation at 1 kHz is usually also indicated in the product specifications given by the manufacturer in decibels (dB), as this is the frequency most relevant for recording human speech. However, terrestrial wildlife sounds span frequencies from 20 Hz to 200 kHz, so we measured the transmission at three representative frequencies: 1 kHz (birds and amphibians), 10 kHz (insects), and 40 kHz (bats) to quantify the acoustic vents' trade-off between sound transmission and ingress protection.

We compared sound attenuation of 2 GAW113 and 2 GAW325 vents with an open setting without vent, outdoors (Figure 1). We recorded the US calibrator and loudspeaker tones at 3 m from the microphones, to the front and to the side at a 90° angle to the side. Four Knowles microphones were used, first open, then with the vent holders, and then two of them were covered with the GAW112 vent and the other two with the GAW325 vent.

Windproofing vs. drying after rain. We used Knowles elements; one was protected by a GAW112 vent and a windscreen (Wildlife Acoustics), one had a 6 mm long horn attached, and one had a GAW325 vent outdoors. All three configurations represented similar levels of water ingress protection, but we used the Knowles microphone with the 6 mm horn instead of the Vesper microphone (for which it was designed) to equalize the microphone model. We emitted test sounds with the loudspeaker and the calibrator at approximately 4 m. We placed a 62 W fan at approximately 30 cm from the microphones, to the front and to the side (90 degrees) to simulate wind. We recorded the test sounds to check how prone to noise the vent-only and horn-only microphones are in comparison to the microphone with the

Figure 1. Setup used for testing microphone attachments outdoors. Foam strips reduced ultrasound echoes and the microphones were approximately 1 m above the ground and parallel to each other.

windscreen. Then, we drenched all microphones in distilled water to simulate heavy rain. We continued recording test sounds immediately after, as well as 1, 3, 18, and 66 hours after the simulated rain to check how long sound transmission was attenuated by the different wet attachments. We measured the sound level of the 1, 10, and 40 kHz tones recorded by each microphone relative to the sound level recorded after 66 hours of drying.

Cable length vs. signal loss. The latest microphones of Wildlife Acoustics usually advertise built-in amplifiers to strengthen the relatively low voltage signals of the microphones so that they do not degrade over long cable distances. High frequencies are more prone to signal degradation because the capacitance of the cable causes more attenuation at high frequencies. We tested whether the output signals of the Knowles microphones were affected by long cables, which are sometimes needed for installing microphones far apart or in different locations than the recorders themselves. We attached two Knowles microphones to the recorder, one via a 5 m cable and the other one via a 52.5 m long cable. They were close to each other and pointing in the same direction. We recorded test sounds emitted with the loudspeaker and the ultrasound calibrator at 6 m from the recorder. We recorded the same test sounds after switching the cables to check whether the results were driven by the microphone itself. We measured 20 ultrasound chirps for each microphone with each configuration.

Directivity vs. amplification. We built different horns for amplifying the acoustic input signal before it is transduced by the microphone (Figure 2). Doing this results in an increased signal-to-noise ratio and ultimately greater detection ranges. However, acoustic horns are generally directive: At high frequencies, horns will mainly respond to sounds within their opening angle, where direct sound can reach the throat of the horn. Outside the opening angle, low-frequency sounds reach the throat of the horn by diffraction.

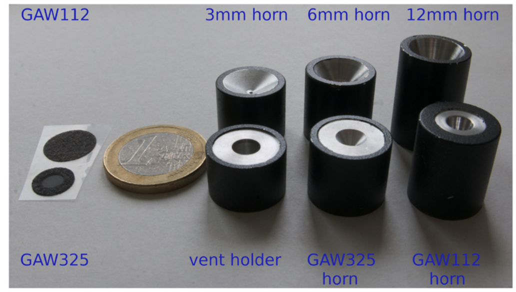

Figure 2. The different acoustic vents and horns tested, as well as the vent holder. 1 EUR coin for scale.

The reasoning behind using horns is that in stereo deployments, there is a redundancy of recorded data: omnidirectional microphones pointing in opposite directions are recording much of the same data twice. To make better use of them, one can use acoustic horns that amplify the sound from the front and decrease sound from the back or the sides. Ultrasound, which propagates less far, benefits especially from horns, because even very small horns can achieve considerable amplification. For ultrasound, horn dimensions can also be held as small as the existing microphone housings. Also, microphones usually suffer from a drop in the frequency response and/or signal-to-noise ratio in the ultrasound range, thus horns help to attain a desirable, more linear frequency response.

We chose horn designs with steadily increasing amplification with frequency starting approximately from 10 kHz and minimal directivity. Conical horns are generally more suitable than exponential horns, which do not amplify sound much above a certain threshold. Horn dimensions were chosen by calculating and simulating the theoretical analogue amplification in-axis and off-axis using numerical methods to choose the most favourable designs. The gain of the horns was calculated using one-dimensional equations for conical horns[9]. Since the one-dimensional calculations could not predict directivity, Boundary Element Method models[10] were set up to model the directivity of the horns. The ultimate gain depended mainly on the ratio of the areas between the mouth and throat of the horn, while the frequency range depended on the length of the horn. A long and narrow horn will also be resonant, which will increase the gain but reduce the fidelity of the recorded sounds.

We investigated whether ultrasonic horns could amplify the signal enough to compensate for the transmission loss due to the acoustic vents. We also tested how much amplification could be gained with different horns placed in front of the Vesper microphones, which do not require vents.

The Knowles and Invensense microphones require the use of the GAW112 or GAW325 vents for ingress protection. The diameter of the vents' active surface (through which sound travels) dictates the maximum mouth diameter and theoretical amplification of the horn. The resulting horns were named after the vent they were designed to hold (GAW112 and GAW325 horns). We compared sound attenuation of three GAW112 and three

GAW325 horns with and without vent to the open microphones. We tested three horns of each type on three different Knowles microphones, by first recording with open microphones, then with the horns attached, and finally with the vents pasted onto them. We recorded the US calibrator and loudspeaker tones at 3 m from the microphones.

For the waterproof Vesper microphone, we were free to test three different horns whose mouth diameter was only limited by the diameter of the housing but tested varying lengths. We also tested 3 other ultrasonic horn types designed for the Vesper element (thus not holding vents) on three different Knowles microphone elements (for consistency with our measurements of the vent-holding horns). We had 3, 6, and 12 mm long horns, with a throat diameter of 0.75 mm and a mouth diameter of 12 mm. We first recorded open microphones, and then successively attached horns of increasing length to each microphone. We recorded the US calibrator and loudspeaker tones at 6 m from the microphones due to the greater amplification of these longer horns.

Cost. We assessed the cost in working time and money at each step of the creation process for 100 microphones. We contrasted the cost for 3 microphone designs presented later. We considered the ordering of individual parts, components assembly, and microphone testing. We estimated labour and prices from our own purchases and working time. For the costs of building the PCBs and metal housings and horns, we asked three different suppliers for quotes and chose the best offer.

Results

Weatherproofing vs. sound attenuation

The GAW112 vent reduces ultrasound transmission from the front only slightly, by almost 2 dB, while sounds from the side are reduced by more than 7 dB, which is partly due to the vent holder itself (Figure S1)[3]. The GAW325 vent reduces ultrasound transmission by almost 15 dB but relatively less for sounds coming from the side (almost 11 dB).

Windproofing vs. drying after rain

The windscreen significantly reduced wind friction noise (Figure 3). The vent-only and 6mm horn configurations were affected by wind friction noise at up to 3 kHz, greatly masking the 1 kHz test tones, although they were still audible and visible in spectrograms. Data for windproofing and weatherproofing are available on OSF[3].

The GAW112 vent with windscreen combination needed much longer to dry than the 6 mm horn (Figure 4). When wet, from one to three hours after drenching, high audible frequencies (10 kHz) were attenuated around 20 dB and ultrasound around 30 dB more than the 6 mm horn. After at most 18 hours, the droplet that could have blocked sound from reaching the microphone acoustic port had evaporated and the microphone recorded sound levels as high as when entirely dry. Low audible frequencies (1 kHz) were not impeded even by water-logged windscreens. The waterproof, hydrophobic GAW325 vent ensured that no water blocked the sound path: sound of all frequencies

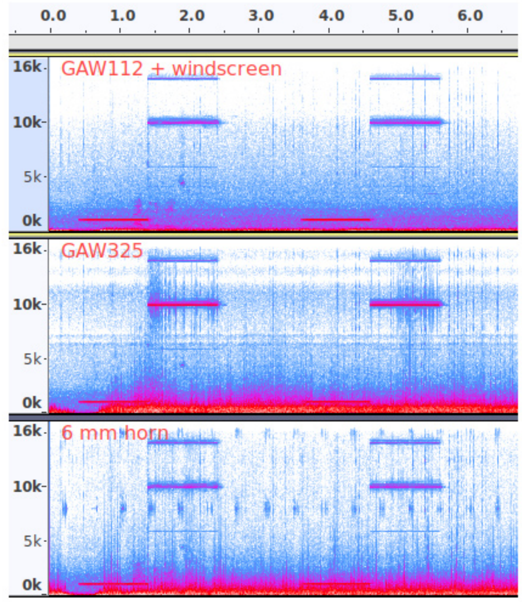

Figure 3. Spectrograms of different microphone designs showing wind noise. Without windscreen, 1 kHz test sounds are masked by wind noise.

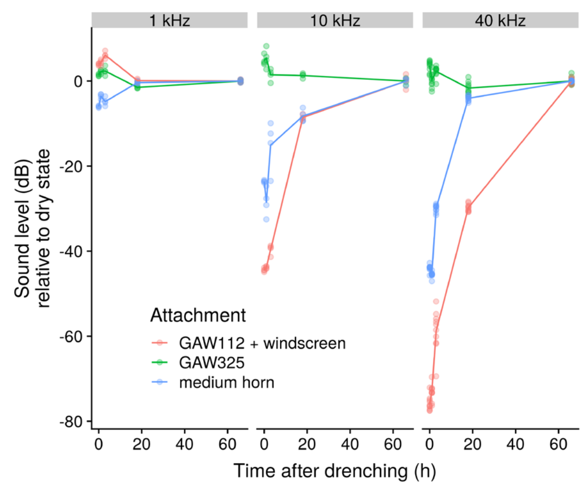

Figure 4. Recorded sound levels with drying time for different microphone configurations at different frequencies.

were recorded at approximately the same level, irrespective of the time after drenching.

Cable length vs. signal loss

We found that the 52.5 m cables decreased the sound level of our 40 kHz test chirps by 1.2 to 1.3 dB compared to 5 m cables. Data for signal loss with increasing cable length are available on OSF[3].

Directivity vs. amplification

The GAW112 and GAW325 horns were capable of mitigating but not completely offsetting the ultrasound transmission loss caused by the acoustic vents (Figure S1)[3]. The longer the ultrasound horns for the Vesper microphone, the higher the achieved transmission, but the losses for sounds coming from the side also increased, as the horns were more directional (Figure 5). Data for directivty/amplification assessment are available on OSF[3].

In accordance with the theoretical predictions, we found no measurable positive or negative impact of the ultrasound horns on audible frequencies. Our open microphones were also directive, with ultrasound levels around 5 dB lower to the side compared to the front.

Cost

We calculated the costs for each of our three recommended microphone designs (Table 1), which are presented in the discussion. The costs ranged from 12 to 33 EUR per unit, with a bulk assembly of 100 units. Required labour was slightly lower for our budget "Bufo" design. Data for material and labor costs are available on OSF[1].

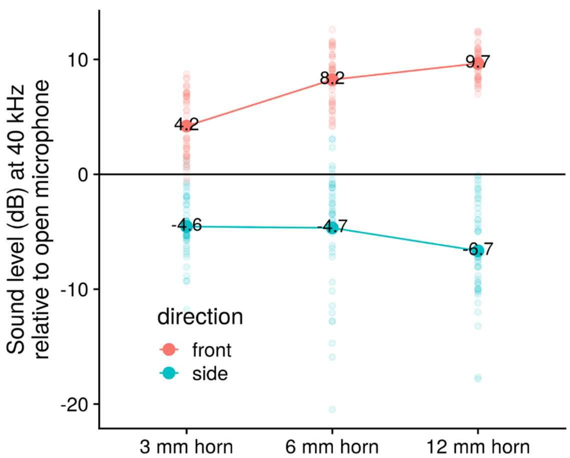

Figure 5. Sound level amplification obtained with different conical horn lengths for different source directions.

Discussion

The best microphone configuration will depend on the organisms of interest, the presence of wind and rain, and the need for directional recording. Many different combinations are possible, all of which have not been tested or built here. We compiled a list of microphone configurations that would be optimal for recording different taxa and named them after representative genera (Figure 6).

Protecting microphones against water and wind

For recording birds, manufacturers like Wildlife Acoustics couple GAW112 vents with windscreens to achieve high protection levels against water ingress and wind noise. However, in habitats or regions with little wind, it becomes worthwhile to use only high-performance vents like the GAW325, thus avoiding sound transmission losses when windscreens are drenched with water after rain.

For recording bats, high degrees of protection come at the expense of ultrasound transmission. The high-performance waterproof Gore vents muffle ultrasound too much, and the GAW325 horn cannot offset that loss. The classical approach with unprotected microphone elements would be to use GAW112 vents with windscreens: ultrasound is only slightly attenuated with the GAW112 vent. Notably, GAW112 horns only offer minimal amplification, so that manufacturing costs are not justified. However, windscreens are not needed for bats because wind noise only reaches frequencies around 3 kHz, which explains why Wildlife Acoustics forewent the decision to include those on their latest SMM-U2 microphone for bats. Moreover, drenched wind screens block ultrasounds much more than audible frequencies. Thus, a sensible approach would be to use waterproof elements like the VM1000, coupled only with a GAW112 vent that prevents droplets to block the acoustic port. Interestingly, since all microphones are able to record sounds underwater and record normally thereafter (see supplementary materials), the Vesper microphone seems to attain waterproofing only because of the tight solder pattern around the acoustic port, which prevents water to get inside the housing.

Table 1. Labor and cost for each step of building the three recommended designs. Complete data are provided in the supplementary information raw data table.

Step	Bufo cost	Bufo labor	Otus cost	Otus labor	Myotis cost	Myotis labor
Buy and adapt connectors	467	5	467	23	467	23
Buy wires, epoxy glue, solder iron	50	105	50	105	50	105
Order complete PCBs	618	20	698	20	618	20
Order metal housings			944	15	2133	15
Solder wires to PCB and connector		200		200		200
Insert and glue microphone		100		100		100
Glue tube to connector				100		100
Glue acoustic vent	67	100	135	100	67	100
Test microphone		100		100		100
Total for 100 units	**1202 EUR**	**10.5 hours**	**2294 EUR**	**13 hours**	**3335 EUR**	**13 hours**

Figure 6. Recommended microphone designs: the minimalist Bufo, the silent Otus, and the allrounder Myotis.

Achieving high sound quality

We recommend using microphones with high signal-to-noise ratios whenever possible[5]. To date, the Invensense element has the highest specified signal-to-noise ratio (70 dB) among our microphones. At a price point of 2.58 EUR, it is roughly four times more expensive than the Knowles element (0.62 EUR), and the waterproof Vesper element (1.58 EUR) is almost three times more expensive. However, all units are so cheap that replacing broken ones would not be an economic consideration, and they represent only a fraction of the price of commercial microphones (at most 1%). According to a preliminary assessment, the Invensense and Vesper elements perform as well as the Knowles element in the audible range, while the Vesper element trails behind for recording ultrasound. However, the Vesper element has the advantage that it does not require a high-performance vent or a windscreen when recording bats, and it can be easily combined with horns.

We would like to stress the benefit of using acoustic horns to amplify sound "for free". The horns we tested considerably improved signal-to-noise ratios, essentially transforming average elements into high-quality microphones. The advantage of such horns has seldom been exploited (but see ultrasonic horn of Wildlife acoustics and Petterson M500 microphone), although the only downside seems to be the loss in directivity.

Surprisingly, we did not find a large signal loss when using long cables. Including pre-amplifiers in microphones (like some manufacturers do) seems unnecessary, which simplifies microphone design.

Recommended designs

The minimalist: Bufo. This microphone is the cheapest, simplest, and, like its namesake, ugliest design. It is easy to assemble, as it only consists of an audio connector, wires, the Vesper microphone on its PCB with a GAW112 vent glued onto it, and epoxy glue. The glue is required to make the microphone waterproof and hold the module in place. Only the Vesper microphone is suitable for this design as it can withstand higher environmental stress due to its piezoelectric design. The downsides of that design are that it is not repairable (due to the epoxy glue, only discardable), and not modular (horns and vent holders cannot be attached). The Bufo is equally suitable for birds and bats.

The silent one: Otus. Like its namesake, this is the most silent microphone with the lowest specified self-noise, enabling recordings of maximum signal-to-noise ratio in the audible range. It consists of an audio connector, a simple metal tube enabling only vents to be attached, and the Invensense element. The recommended configuration for birds would be with a GAW325 vent. In regions and habitats where winds are prominent, a windscreen can optionally be fastened to it with a cable tie.

Note that when using a GAW112 vent with the necessary windscreen, you would essentially get a microphone similar to Wildlife Acoustic's SMM-U1. However, the Otus can also record audible sound and could have higher-quality recordings: The SMM-U1 probably uses the same Knowles FG element as the SMX-U1 that we tested and found to have shorter detection ranges. We only recommend this configuration when single omnidirectional microphones are required and rain is not too frequent as to avoid ultrasound transmission losses due to water-logged windscreens. We next present a microphone that does not require a wind screen, which is more modular than the Otus and better suited for bats.

The allrounder: Myotis. This microphone would be intended mainly for bats. Even though it records the entire sound spectrum, the audible sound interval is recorded slightly less cleanly than with the Knowles or Invensense elements due to the lower specified signal-to-noise ratio. The microphone consists of an audio connector, a metal tube designed for attachments, and a waterproof Vesper microphone with a GAW112 vent glued onto it. The microphone can be used without or with horns to narrow and amplify the pickup area to the desired degree, which is often desirable for bat surveys to focus on flyways. This combination is particularly useful when doing stereo recordings, where the redundancy of recording with two omnidirectional microphones can be reduced while also increasing the detection ranges. This design without a windscreen enables microphones to dry quickly to record sounds soon after rain. Wind friction is restricted to low frequencies and thus not problematic when recording bats, but it is still possible to attach windscreens in areas prone to wind when low-frequency sound recordings are desired.

Future developments

F1000Research allows for article versioning. We welcome prospective co-authors to continue develop our open-source microphone system. Further technological improvements will lead to new products, and there are many development opportunities.

We found significant variations in the amplification attained by different microphone-horn combinations, which are probably caused by variable micro-alignment of the horn with the microphone's acoustic port. Our PCBs were slightly too small for the space they had in the housing but this has been corrected in the PCB design files provided in the supplementary materials.

We need to design a screwable attachment system that allows horns to be easily attached and removed. It should feature rubber rings for waterproofing. We need lighter, attachable audible horns of similar dimensions as the ones used here, which would be usable in the field. We are designing larger ultrasonic horns that are less directive while still offering similar amplification levels.

More acoustic vents should also be tested to find high-performance acoustic vents that do not reduce ultrasound transmission too much. However, they are difficult to source as they can only be purchased in batches of 1000 from the manufacturer Gore, and ultrasound transmission is also not tested by the manufacturer. This also underlines the fact that we could only test ultrasound transmission at 40 kHz, although several bat species vocalise well above 100 kHz. However, no affordable, commercial ultrasound emitters are available to our knowledge.

To allow our microphones to be used on a broader range of recorders, we should also design housings for other acoustic connectors. The signal loss in even longer cables should be tested, and if substantial, small amplifiers should be designed to compensate that loss. Finally, testing the microphones in freshwater systems could reveal new opportunities in that field.

Data availability

Underlying data

Raw data for microphone assessment are available on OSF in folder: Microphone assessment. Data for different cable lengths, cable drying, cost and labor, and transmission are available in the indicated csv files.

DOI: https://doi.org/10.17605/OSF.IO/HEZKW[3].

Extended data

Expanded microphone building instructions are available on OSF in folder: Building instructions.

Table S1. Available open-source devices and commercial products for recording sound in terrestrial habitats. Available in folder: Microphone assessment.

Figure S1. Absolute amplitude of all the different microphone attachments measured at 3 and 6 m from the microphone. Available in folder: Microphone assessment, File: Extended data – Microphone assessment.

DOI: https://doi.org/10.17605/OSF.IO/HEZKW[3].

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Open Peer Review

Current Referee Status: ? ✓ ✓

Version 1

Referee Report 17 January 2019

https://doi.org/10.5256/f1000research.19151.r42345

✓

Catharina Karlsson
Department of Biological Science, National University of Singapore, Singapore, Singapore

This study outlines three open-source hardware solutions to microphones for bioacoustics monitoring. The authors justly acknowledge the lack of transparency from current manufacturers of the technical details of the components, especially the microphone element. Another important note is the decrease in cost in comparison to off-the-shelf products which as the authors note, are not only expensive but difficult and impractical to get repaired. Considering the increasing use of open-source hardware in the bioacoustic field this article is a very nice addition to allow practitioners an easier time of assembling their own equipment.

Even though this is a nice article, it is a bit difficult to follow at times and it doesn't flow that well. The introduction is good, but I recommend the authors to look through the structuring of the methods and the results section.

The justification for only testing MEMS elements is not thorough enough as it is not compared to the other types of elements that are on the market. What are the benefits of using a condenser element for example?

For the sentence below (methods section) I think it is better to just state the representative frequencies rather than giving readers (especially inexperienced ones) the impression that these are representative frequencies for those taxonomic groups (amphibians and birds go above 10kHz depending on species for example). Especially as it is stated in another section that insects can also hear sound up to ultrasonic frequencies.
"1 kHz (birds and amphibians), 10 kHz (insects), and 40 kHz (bats)"

The English need to be proof read up throughout, three examples follow (especially in the methods section, I think it makes it a bit stodgy and difficult to follow).

“This microphone would be intended mainly for bats.” reads better as “This microphone is intended for bat recordings”.

“This microphone is the cheapest, simplest, and, like its namesake, ugliest design.”
Sentences like this one can be cleaned up a bit, *Bufonides* are not ugly (you just have not looked closely enough), and there are better words to use than ugly (i.e. basic design, rough etc).

“It is thus preferable to reflow-solder MEMS elements to printed circuit boards, which can be made in

electronic laboratories or workshops equipped with reflow ovens."
Sentences like this one does not make a lot of sense (after the comma), I had to re-read several times before I understood what you meant as the way the sentence is structured it could refer to the MEMs element or the circuit board (but you mean neither). I would use a full stop instead of using a comma then re-write the second part to something along the lines of "Reflow-soldering can be performed in reflow equipped electronic laboratories or workshops".

The section I was really interested in was to see how the weatherproofing affected the performance of the microphones – however, there is only mention of how it affects the ultrasonic frequencies? It would be nice to see a graph of how the frequencies are affected by different levels of waterproofing (it would even be interesting to see how complete waterproofing, such as a plastic bag compares to vents and no proofing as I've worryingly seen that used at times). In general, the result section feels a bit rushed and not developed enough. It was especially difficult to follow, both in the methods and results section, which element and which vent was used where. Occasionally only the vent is mentioned and no element (remind the reader again).

I think you missed a bit in the discussion, it is worth mentioning that the first time all these things must be sorted out they will take considerable time and I think your estimate of labour is on the low side. It often takes considerable effort to figure out where to source everything the first time – in addition it needs to be highlighted that these cost estimates are for Europe (Germany to be precise, it is in the supplementary information but I do not think it is mentioned in the text), there can be considerable variation depending on where you are based (both lower and higher). The sourcing time is also a labour and it can take considerable time to find suppliers, sort out shipments etc so it should at least get a mention.

I am pleased that someone has managed to find waterproof vents that come in smaller batches than 10,000 pieces. I also acknowledge the quite comprehensive supplementary material that is attached with more in-depth details of assembly – the article itself is really the tip of the iceberg of the amount of work that has gone into this study. I do believe that comprehensive manuals and instructions like these are a necessity to ensure other people use it. All in all, this is a very nice and timely article and I hope we start seeing more of this kind of work that is written for field scientists coming out.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Yes

Competing Interests: No competing interests were disclosed.

Referee Expertise: Acoustic Ecology

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Referee Report 16 January 2019

https://doi.org/10.5256/f1000research.19151.r42344

Holger Klinck
Bioacoustics Research Program, Cornell Lab of Ornithology, Cornell University, Ithaca, NY, USA

This is a very interesting paper which provides very useful information for researchers in the field of terrestrial bioacoustics, especially those involved in remote passive acoustic monitoring efforts.

General comment:
The English in the present manuscript requires improvements. Please carefully proof read and spell check the manuscript to eliminate existing grammatical errors. For example, "*As transducers of mechanical energy into electrical signals*" is not proper English. Another example is "*Commercial microphones are relatively expensive, specialized on particular taxa, and often have opaque technical specifications.*" Specialized on should be replaced with specialized for. Also, technical specifications cannot be opaque. This sentence needs to rephrased. For example: Technical specifications on the microphones are often not publicized. Language issues like these exist throughout the manuscript and need to be addressed.

A few detailed comments:
Which MEMS type is being used in the recommended designs? Sounds like the Bufo is based on the Vesper 1000 MEMS but it is not mentioned which MEMS was used for the Otus and Myotis.

What really should be included in the manuscript are frequency response curves for the various designs indicating the sensitivity across the entire frequency range of interest. For example, the gain of the horns will be frequency dependent and alter the frequency response of the actual MEMS. A single frequency test is informative but doesn't provide enough information. This is especially true for frequencies in the 50-100 kHz range.

The authors emphasize the importance of the microphone's SNR. The MEMS mics used in the designs feature SNRs between 60 and 70 dB. However, most of the recording system listed in Table 1 feature mics with a SNR of 80 dB. The authors should include talk about these differences in the discussion section.

In addition, microphone sensitivity is also an important parameter. How do the selected MEMS mics differ in sensitivity (and compare to the mics listed in Table 1)? Again, a comparative frequency response curve would answer many of these questions.

Most MEMS these days can be wired differentially or single-ended. Differential outputs are typically lower noise and in case of the MEMS and increase the sensitivity. Is this something which could be accommodated in your design? Should this be considered?

Many autonomous systems aim for low power consumption. How do MEMS compare to traditional mic designs in that regard?

BTW, TDK recently released the ICS-40730 MEMS with a SNR of 74dB. To my knowledge this is currently the MEMS with the best SNR.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Yes

Competing Interests: No competing interests were disclosed.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Referee Report 15 January 2019

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Sarab S. Sethi
Department of Life Sciences, Dyson School of Design Engineering, Imperial College London, London, UK

I enjoyed reading this paper, in particular the thorough nature of the methodology to test various configurations and their effect on amplification, directionality and quality of the audio signal recorded by the microphones. Furthermore, the three clear recommended designs will be particularly useful for ecologists to immediately start incorporating this research into their projects. Commercially available microphones rarely appreciate their weaknesses with such honesty, and as such it's difficult to find the correct solution for each situation without specialist knowledge.

I only have a small number of comments as outlined below, but generally I believe this paper is welcome, and should add to the growing appetite for high quality engineering in the field.

General

- The structure of the paper didn't quite flow from the Results to Discussion sections. On page 7, in the text under 'Cost' and in Table 1 mention is made to Bufo, Otis and Myotis whilst full descriptions of each of these configurations is only given a lot later. I'd recommend moving the recommended designs to the end of the Results section of this paper rather than Discussion
- The lowest frequency tested in all your examples is 1kHz, however you also mention that audible range goes as low as 20Hz. Many terrestrial mammals vocalise with fundamental frequencies under 1kHz (e.g. gibbons, elephants). Ideally we could see results starting at 100Hz or so, or if not this limitation should be made clear in the text

Introduction

- "microphone signals are filtered at the source only for commercial reasons, to enable either bird or bat recordings and sell multiple specialised products" – I can believe this, but would like to see a citation

Methods

- You only compare MEMS microphones for well justified reasons. However, I would still like to see this mentioned more clearly in the introduction or even the abstract. Some mention of Electret Condenser Microphone (ECM) drawbacks would be appreciated
- "This connection form is commonly used in most autonomous sound recorders" – which ones?

Results

- "The vent-only and 6mm horn configurations were affected by wind friction noise at up to 3 kHz, greatly masking the 1 kHz test tones" – I expect this will be a lot worse for lower frequencies I suggested testing above?

Discussion

- It is possible to keep windscreens mostly dry – if they are mounted under a sheltered place (e.g. under a solar panel in Sethi et. al.). They will still get wet, but nowhere near the submerged drenching described here. If this is possible, would this change recommendations?
- Table 1: give per unit costs too please
- "We would like to stress the benefit of using acoustic horns to amplify sound "for free"." – but later you appreciate the added directionality. This is very important in mono setups and definitely not a free amplification

Is the rationale for developing the new method (or application) clearly explained?

Yes

Is the description of the method technically sound?

Yes

Are sufficient details provided to allow replication of the method development and its use by others?

Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?

Yes

Competing Interests: No competing interests were disclosed.

Referee Expertise: Autonomous ecosystem monitoring, bioacoustics, time series analysis

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.