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AURITA: an affordable, autonomous recording device for acoustic monitoring of audible and ultrasonic frequencies

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ABSTRACT

Passive acoustic monitoring can be used for many purposes including biodiversity and habitat assessments and studying the ecology of populations, communities and soundscapes. As such, acoustic recording devices are essential data collection tools for bioacousticians and soundscape ecologists. Currently available commercial options are typically expensive and limited to recording either ultrasonic or audible frequencies. Here, we present the AURITA (Audible and Ultrasonic Recording In Tandem) for the autonomous collection of both audible and ultrasonic acoustic data. This self-contained, modular unit combines the Solo, an open-source, Raspberry-Pi-based recorder and a commercially available bat recorder, the Peersonic RPA2, enabling it to capture sounds from 60 Hz to 192 kHz in WAV format. The configuration presented costs ~£350 (excluding memory cards and batteries) to produce and can be maintained and repaired in the field. Two nine-week field tests involving 12 AURITA units were conducted in 2016 and 2017 and confirmed their reliability, resulting in 34,093 h of audible data and 551 h of ultrasonic data; all units were retrieved successfully and intact. The AURITA proved to be reliable in the field and produced high-quality acoustic data, making it ideal for simultaneous monitoring in both audible and ultrasonic frequencies over continuous periods of time.

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Acoustic; ecology; sound; recorder; soundscape; affordable equipment

Introduction

A wide range of animal species use vocalizations for a variety of vital functions; mating calls are important for successful reproduction, echolocation is used for feeding and navigation, alarm calls can help avoid predation and territorial calls can prevent unnecessary conflicts (Farina 2014). Recording and analysis of sounds made by animals is widely used in disciplines such as bioacoustics, which focuses on species communication and behaviour, and ecoacoustics, which investigates sounds at population, community and landscape scales (Sueur and Farina 2015). As a passive technique, sound recording minimizes human interference when conducting population surveys and does not require line-of-sight and so can be used in conditions where visual detection is problematic, e.g. in darkness or dense canopy

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(Kasten et al. 2012). This aspect is particularly useful for surveying bats and owls, whose activities are often limited to night-time and thus, surveys must be performed in darkness.

In addition to biological sounds, the study of soundscape ecology includes sounds produced by abiotic (e.g. wind and rain) and anthropogenic (e.g. traffic and aeroplane noise) sources within the environment (Pijanowski et al. 2011a). Recording soundscapes offers a means of conserving the acoustic character of specific sites as well as monitoring long-term changes due to climate change or habitat disturbance (Pavan 2017). As all of the above-mentioned disciplines depend on the availability of suitable recording tools, development and optimization of sensors used to capture and analyse sounds is itself regarded as an important area of research (Villanueva-Rivera et al. 2011).

A variety of off-the-shelf recorders are currently available, including the Wildlife Acoustics SM4 and SM4BAT (Wildlife Acoustics, Massachusetts, USA), Bioacoustic Audio Recorder (Frontier Labs, Brisbane, Australia), Swift (Cornell Labs, New York, USA) and the Anabat Express (Titley Scientific, Brendale, Australia). However, all of these recorders are designed to monitor either audible or ultrasonic frequencies. At present, the only commercially available units capable of recording both audible and ultrasonic frequencies are the Wildlife Acoustics SM3BAT (Wildlife Acoustics, Massachusetts, USA) and Soundscape Explorer Terrestrial (Lunilletronik, Fivizzano, Italy). The SM3BAT is expensive (ca 1600 USD, excluding microphones) and, when simultaneously recording both sets of frequencies at the same time, is limited to the unit's highest sampling rate (256 kHz) and must use the manufacturer's proprietary format in order to use triggered bat recordings while also recording audible data (King 2015). Although the SM3BAT is still available from Wildlife Acoustics, their latest generation of recorders, the SM4 and SM4BAT, is capable of recording only audible or ultrasonic data, respectively (Wildlife Acoustics 2018), and hence, both units would be required in order to perform simultaneous recording at both frequencies. The ability to record using Wildlife Acoustics' proprietary audio compression format (WAC), previously available with the SM3BAT, has also been discontinued in the latest SM4 and SM4BAT models, possibly due to the 30% decrease in energy efficiency when recording in this format (Wright 2015). Although the Lunilletronik Soundscape Explorer is more reasonably priced (500 Euros) and capable of recording both audible (24 or 48 kHz sampling rates) and ultrasonic (192 kHz sampling) frequencies, it cannot record both frequencies simultaneously, does not support triggered recordings and has a maximum storage capacity of 64 GB (2 × 32 GB SDHC cards) (Lunilletronik 2015).

Although commercially available, autonomous recording devices have been available for some time, for example the Wildlife Acoustics SM1 was first produced in 2007 (Wildlife Acoustics 2017); the high cost of such devices has usually made them inaccessible to less well-funded studies (Joo et al. 2011). Until recently, handheld-type recorders (e.g. Olympus DM-240, Zoom H4) were often used as an alternative for autonomous acoustic monitoring (e.g. Farina and Pieretti 2014; Towsey et al. 2014). However, these are generally limited to using Secure Digital High Capacity (SDHC) storage (32 GB maximum capacity) and/or can only record in stereo, effectively halving potential storage capacity. Recording a complete 24-h period in 44.1 kHz, 16-bit mono WAV format requires 7.09 GB, which means that most handheld recorders could only capture ~4.5 days of continuous data. Compressing audio data is an option but lossy formats (e.g. MP3) can result in artefacts (Towsey et al. 2014) and loss of detail (Villanueva-Rivera et al. 2011), although some of the more recent, and costly, handheld recorders (e.g. Olympus LS-P4, £200) can now record in lossless,

Table 1. Comparison of price, data capacity and power consumption for different recording devices. Note: capacities shown assume 256 GB for SDXC cards, although larger capacities are available. Power usage when active will vary depending on what the device is doing (i.e. idle, recording or writing to disk) and is presented as a range to represent this. Prices shown include the additional cost of a microphone (SMM-U1 for SM3BAT and SM4BAT FS and Clippy EM-172 for Solo) where one is not provided with the basic unit.

Device	Cost (£)	Supplier	Data Storage (GB)	Power usage (mW)	
				Active	Sleep mode
SM3BAT	1899	Wildlife Acoustics	1024 (4 × SDXC)	250–800	0.5
SM4BAT FS	1039	Wildlife Acoustics	512 (2 × SDXC)	155–270	1.8
Anabat Express	834	Titely Scientific	32 (1 × SDHC)	69–113	3.1
RPA2	210	Peersonic	32 (1 × SDHC)	405–605	30
SM4	945	Wildlife Acoustics	512 (2 × SDXC)	135–185	1.8
Solo (Pi A+)	63	N/A	256 (1 × SDXC)	315–450	–
Audiomoth	36	Open Acoustic Devices	32 (1 × SDHC)	17–70	0.08

compressed formats such as FLAC (Free Lossless Audio Codec). Sound recording equipment for musicians and film-makers offers recording mono WAV format to SDXC (e.g. Tascam DR-70D) but is typically larger, more expensive (£200+) and consumes more power. Being primarily designed to record sound within the audible frequency range, such devices are typically unable to handle sampling rates above 96 kHz and thus incapable of monitoring all of the ultrasonic frequencies at which bat vocalizations occur.

Increasing interest in acoustic monitoring in the last couple of years has seen the advent of several alternatives and the adoption of microcontrollers (i.e. Raspberry Pi and Arduino) by a community of developers, who freely make their designs and programmes available for a wide variety of applications, providing an invaluable point of access for those lacking the relevant skills and/or time to develop their own solutions. Recent developments, such as the publication of the Solo article by Whytock and Christie (2017), the Bat Pi 2 (AK Fledermausschutz 2017) and production of the Audiomoth (Hill et al. 2017), further suggest the use of microcontroller technology is also becoming more commonplace within the scientific community. A comparison of the main features for some of the recording devices mentioned above is provided in Table 1.

Here, we present a more affordable alternative to commercial options, which is also capable of simultaneously capturing audible and triggered ultrasonic recordings, the device for Audible and Ultrasonic Recording In TAndem, or AURITA (Figure 1). The unit is self-contained, utilizes a mix of open-source and commercially available recording solutions, and is capable of being mounted off the ground, making it suitable for studies in public locations and reducing the risk of animal damage. It additionally benefits from a modular design, allowing the substitution or replacement of incorrectly configured or faulty components *in situ* with no additional cost other than that of the component itself.

Design considerations

While some ad hoc systems are capable of simultaneously recording both audible and ultrasonic frequencies using a single input channel, e.g. Audiomoth (www.openacousticdevices.info), it was decided to use two separate recorders for the following reasons. First, bat recordings create large files, ~nine times the size of equivalent audible recordings, due to the high



Figure 1. The AURITA (Audible and Ultrasonic Recording In Tandem) internal component layout (author's own).

sampling rates required. The use of triggered recordings, that only record for set periods, normally in the order of seconds, when triggered by activity within the ultrasonic frequency range, can therefore save a considerable amount of disk space. Second, bat activity is also typically measured in 'passes', represented by short, distinct time periods where activity is recorded (Collins 2016). The use of triggered recordings is therefore more compatible with this methodology and additionally reduces processing load by avoiding the need to deal with overly long files. In contrast, audible frequency recordings are typically either continuous or use sampling schemes to record at pre-set time intervals (e.g. one minute every 5, 10 or 20 minutes, 1 h at dawn, etc.). While the above sampling schemes can reduce data storage requirements and power consumption if the device is equipped with a power saving sleep mode, they may potentially lead to the loss of important information if sampling occurs too infrequently (Pieretti et al. 2015). Therefore, separating audible and ultrasonic recordings into two separate data streams facilitates analysis of the results by enabling the most appropriate workflow to be applied in each case.

Audible sound recording

For audible frequency recordings, we chose an ad hoc design known as the Solo (Whytock and Christie 2017), which has the potential to store large amounts of audio data as it supports

both mono- and stereo-WAV recording, if using a matched pair of microphones with a single 3.5-mm stereo plug, and a single, high-capacity SDXC card (up to 256 GB). The Solo is an open source, autonomous, high-definition audio recording device capable of handling sampling frequencies up to 192 kHz (96 kHz Nyquist frequency), which can be powered by any 5 V micro-USB supply (700 mA minimum). With a build price of approximately £50, excluding microphone, batteries and SD card, the Solo is also reasonably cost-effective (Whytock and Christie 2017). By default, the Solo operates in continuous recording mode although more recent builds (post September 2016) can also be configured to use pre-set recording schemes (1 min on/off, 5 min on/off and 9 pm to 6 am night-time mode) as well as accept user-defined, custom-written calendar scripts (Whytock and Christie 2018a).

For this project, all Solo units were built from a Raspberry Pi A+(Farnell element14, Leeds, UK), Cirrus Logic audio card (Cirrus Logic, Texas, USA) and PiFace clock module, used to time-stamp recordings (OpenLX SP Ltd, London, UK). Since this project began, the Cirrus Logic audio card (CLAC) has been discontinued from sale and the most recent Solo build now utilizes the Sound Blaster PLAY! 3 external sound card (Creative Technology Ltd, Singapore) instead of the CLAC (Whytock and Christie 2018b). However, this does highlight that reliance on mass-produced consumer electronic components can sometimes be problematic when such components go out of production or are in short supply and alternatives must be found and/or adapted for purpose.

We chose the EM172 omni-directional, electret condenser microphone capsule (Primo Microphones Inc., Texas, USA) as the external microphone due to its high sensitivity and low-noise performance (-28 ± 3 dB sensitivity (ref: 1 kHz, 0 dB = 1 V/Pa), max. input = 122 dB, SNR 80 dB), low cost (<£30) and small size; these specifications are very similar to the microphone supplied with the Wildlife Acoustic SM4 (Wildlife Acoustics 2016). Microphone capsules were ordered fitted with a 30-cm cable and 3.5-mm jack (FEL Communications Ltd, Sandown, UK).

Ultrasonic sound recording

Although some ad hoc alternatives, for example the Bat Pi 2 (AK Fledermausschutz 2017) and the Solo (Whytock and Christie 2017), are also capable of recording bats, configurations for these units suggest using Dodotronic Ultramic192, 200 or 250 K external ultrasonic USB microphones, which cost upwards of 200 Euros each (Dodotronic, Castel Gandolfo, Italy). This added expense, along with the cost of the recording device itself, makes such solutions less cost-effective in comparison to some commercial options. The basic Bat Pi 2, for example, costs approximately 528 Euros (~£460), excluding power banks, to build (AK Fledermausschutz 2016). Additionally, the option to use triggered recordings for bats is not currently available for most ad hoc recordings systems and the Bat Pi 2 is, to the best of our knowledge, the only device that currently supports triggered recordings for bats (AK Fledermausschutz 2017). Although detection algorithms have been developed for the Audiomoth, these have only been implemented for the New Forest cicada (*Cicadetta montana*) and gunshots (Hill et al. 2017). For these reasons, we chose the Peersonic RPA2 Bat Recorder (Peersonic Ltd, Windsor, UK), which is capable of triggered recordings. At £216 for the basic board, microphone and clock module, this is more cost-effective than other commercially available passive bat recorders, which can cost over £1000 and is comparable

in price to ad hoc systems when the additional cost of an ultrasonic microphone is taken into consideration.

The RPA2 can be powered externally through its 5 V micro-USB connection and supports SDHC cards (up to 32 GB), although storage is also subject to a limitation of 3000 individual recordings. It is triggered automatically, capturing sounds as WAV files at sampling rates of 384 kHz (192 kHz Nyquist frequency), for a pre-set, maximum duration of between five seconds and four minutes. The RPA2 is also equipped with a sleep mode to preserve battery life and data capacity during times with no bat activity (i.e. daytime). Furthermore, the RPA2 can be powered by three AA-cell batteries for use as a portable, manually triggered bat detector capable of either heterodyne or frequency division audio output and a display screen that shows the peak frequency of any detected sounds. This dual-ability offers added value to anyone potentially interested in performing both static and walked transect surveys. RPA2 units are supplied with an in-built ultrasonic MEMS microphone (ST Microelectronics, Geneva, Switzerland), which is fitted perpendicular to the main circuit board. To mount it at the front of the case, we removed the microphone from its 10 2.54-mm pin sockets and inserted 20-cm male/female jumper cables between the MEMS module and the system board.

Power consumption and supply

Average power consumption for the Solo build described in this paper (i.e. Raspberry Pi A+) is 71 mA (0.35 W) (Whytock and Christie 2017). Alternative builds replace the Pi A+ with the Pi B+ or Pi-Zero, which consume 200 mA (1 W) and 82 mA (0.41 W), respectively; however, it may be possible to reduce demand for the Pi B+ by switching off unnecessary components such as the USB hub and ethernet port (Whytock and Christie 2018c). The Solo does not incorporate an effective power-saving mode and the use of recording schedules does not decrease power consumption, only data storage requirements (Whytock and Christie 2018a). The Peersonic RPA2 uses 120 mA when active and approximately 5% (6 mA) of this amount when in sleep mode (Peersonic 2016).

USB power banks are compact enough to enable equipment to be self-contained while also offering capacities exceeding 20,000 mAh (3.7 V). The largest capacity available for under £30 at the time of design was the Swees 26,800 mAh (Shenzhen Ruijin Trading Ltd, Kent, UK – no longer available) and two of these were used to power AURITA units, one each for the RPA2 and Solo.

Many USB power banks have an inbuilt energy-saving feature that switches the battery off when power usage falls below a certain limit for a certain amount of time. Essentially, this would happen whenever the RPA2 went into sleep mode, thus rendering the unit inoperable. Moreover, keeping the unit on during the day would also waste data capacity by recording when no bats were present. A solution was therefore devised, with the help of Peersonic Ltd, to solder an 82- Ω load resistor to a USB connector. When connected to a spare power output (most USB power banks have at least two), this draws enough power (~0.25 W) to stop the power bank switching itself off while using less energy than it would take to keep the RPA2 awake all day.

Another potential issue associated with the power supply is ultrasonic noise. While equipment self-noise was not evident for audible recordings, we did experience ultrasonic noise issues with some of the USB power banks. The degree of noise experienced, and the



Figure 2. Examples of AURITA deployment configurations: (a) connected to a 12 V car battery in private locations (b) self-contained using USB power banks in public areas (Author's own).

frequencies at which it occurred not only varied between different makes and models of battery, but also between batteries of the same model and even between power ports within the same battery. We therefore recommend that any equipment configuration is tested before deployment by building an initial prototype, especially if it is planned to build several units. An initial assessment can most easily be performed by making test recordings with the unit and examining the spectrogram for any noise, which usually presents itself as a flat, horizontal line. While it may not be possible to find a completely 'silent' battery, this should provide some indication of whether self-noise, either of the battery or any other component, is likely to be an issue.

In non-public areas, an alternative configuration using a 12 to 5 V DC converter with dual USB output and a regular car battery can be deployed. The battery and converter are stored in a waterproof box beneath the tree and connected to the Solo and RPA2 via two 3 m micro-USB cables routed through plastic conduit tubing (Figure 2(a)). Although other authors have used car batteries to power their recorders (e.g. Solo), these configurations have previously necessitated the recording device being sited on the ground. We chose an alternative configuration that enabled the recording unit to be mounted off the ground in order to reduce attenuation due to reflections.

Enclosure

We housed our unit in an IP67-certified (watertight and dust proof) hard case, the MAX004 (350 × 230 × 86 mm) (Plastica Panaro S.r.l., Marano, Italy). AURITA units can either be ground-based, or, alternatively, attached to poles/trees using galvanized steel fixing band, available from most builders merchants for ca. £7 for 10 m. For the latter, four lengths of fixing band were secured to the rear of the AURITA case (one in each corner) using nuts, bolts and washers. Rubber washers were fitted inside and outside the case, underneath metal washers, to prevent water ingress. Once in position, each pair of bands (top and bottom) was then looped around the tree until the two ends met and could be joined together by passing wire, cable ties and a combination padlock (for security) through the fixing holes, similar to putting on a belt (Figure 2(b)). This method is non-destructive, cheap and offered good protection against animal damage and casual theft. Camouflaging sensor equipment can also provide some security against human interference and so cases were spray-painted a mix of grey, green and brown, to help them blend in with surroundings and to reduce heat absorption.

The AURITA is intentionally modular in design and accordingly we mounted the Solo and RPA2 units inside the case using plastic circuit board feet, allowing easy removal and replacement *in situ*. Microphones either had to be mounted externally or provided with some form of opening that allows sound in, while keeping water out. The EM172 was mounted externally using an M16 plastic cable gland, an idea suggested by Nick Roast at FEL Communications Ltd (2016 email from N Roast to RB; unreferenced). The gland holds the 1 cm dia. microphone capsule in position while maintaining a waterproof seal with the case. Although this should prevent water entering the case, the EM172 itself is not considered waterproof (2016 email from N Roast to RB; unreferenced). Previous studies (e.g. Collins and Jones 2009) have successfully used cling-film to weatherproof bat detectors without an apparent reduction in microphone sensitivity.

To assess the effects of cling-film on audible microphone sensitivity, two identical AURITA units were placed at equal distance (2 m), height and angle to a single speaker (Technics SB-DV280). In order to achieve this, one AURITA was slightly offset to the right of the speaker and the other to the left. One unit had the microphone uncovered, the other being mounted behind PVC cling-film. Pure tone sine waves from 1 to 22 kHz, 10 seconds duration in one kHz increments, were copied to a CD (44.1 kHz, 16-bit), which was played back and simultaneously recorded by both units. Although the room where recordings took place was approximately rectangular, surfaces within the room were not homogeneous. Recordings were therefore made on both AURITAs, in both positions (offset left and right from speaker), and then averaged to account for any differences in acoustics due to positioning in the room. Average power spectral densities of the sine waves recorded by each AURITA were obtained using the frequency analysis tool (Hanning window, window length = 2048, dynamic range = 90 dB) in Audacity® 2.1.2 (Audacity Team 2016). For each 10-second sine wave recording, the middle 8 seconds were analysed as the most stable part of the recording. At 18 kHz, some speaker crackle was experienced and a shorter period of six seconds was used to avoid including this in analyses. As analysis bins did not always fall on the precise frequencies being assessed, the interpolation function in XIXtrFun™ (<http://www.xltrfun.com/XIXtrFun/XIXtrFun.htm>) was subsequently applied to obtain readings for the playback frequencies being tested. The test was also repeated, as described above,

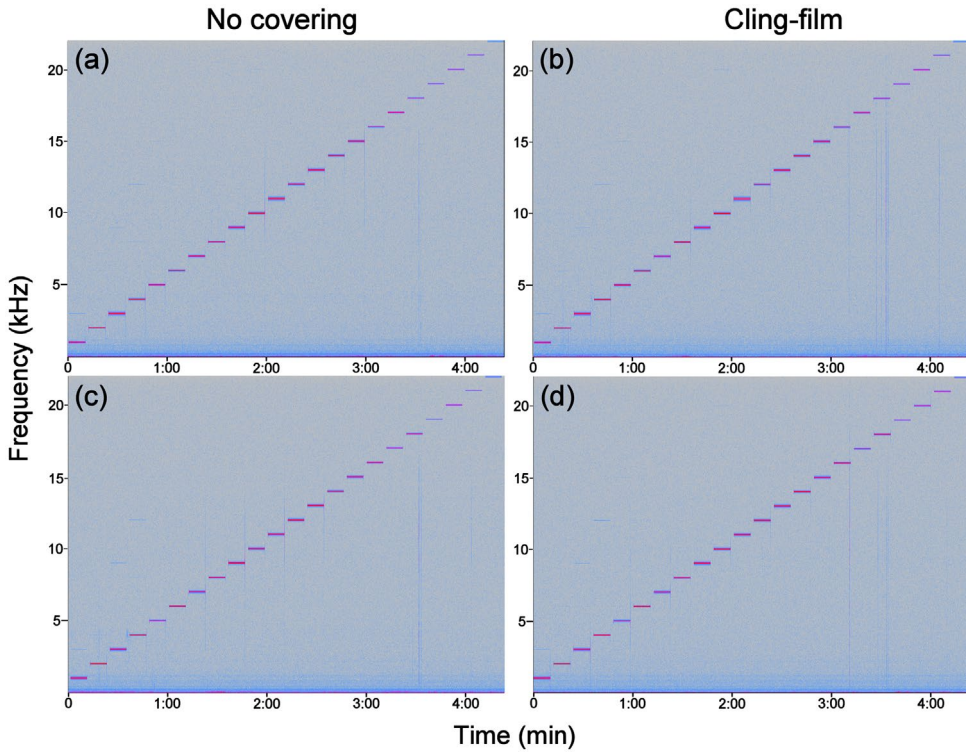


Figure 3. Spectrograms (Hanning window, window length = 2048, dynamic range = 90 dB) and waveforms of pure tones recorded on identical AURITA units to evaluate the use of cling-film as a potential microphone covering: (a) no covering, offset left, (b) cling-film offset left, (c) no covering, offset right, (d) cling-film, offset right.

Note: No post-processing has been performed.

using Saati HD15 acoustic fabric (Saati S.p.A., via Milano, Italy), a potential alternative to cling-film, to analyse its performance. Spectrograms of recordings from both tests are shown in Figures 3 and 4.

Results indicated that where levels recorded through cling-film were lower than using no covering, attenuation was < 4 dB; however, most frequencies appeared to demonstrate some additional gain (Figure 5). The frequency gains observed for cling-film are potentially attributable to the acoustic properties of circular membranes, which act as good sound radiators and have multiple modes of vibration (Open University 2007). The fundamental frequency of a circular membrane, where all parts of the membrane are vibrating in phase, can be calculated using Equation (1) (White and White 2014).

$$f = \frac{0.766}{D} \sqrt{\frac{T}{d}} \quad (1)$$

where f is fundamental frequency, D is membrane diameter (m), T is membrane tension (N m^{-1}) and d is membrane surface density (kg m^{-2}). Although we know the microphone diameter is 10 mm (Primo 2011), it was not possible to either measure surface tension or accurately estimate the surface density of the cling-film used. However, as Equation (1)

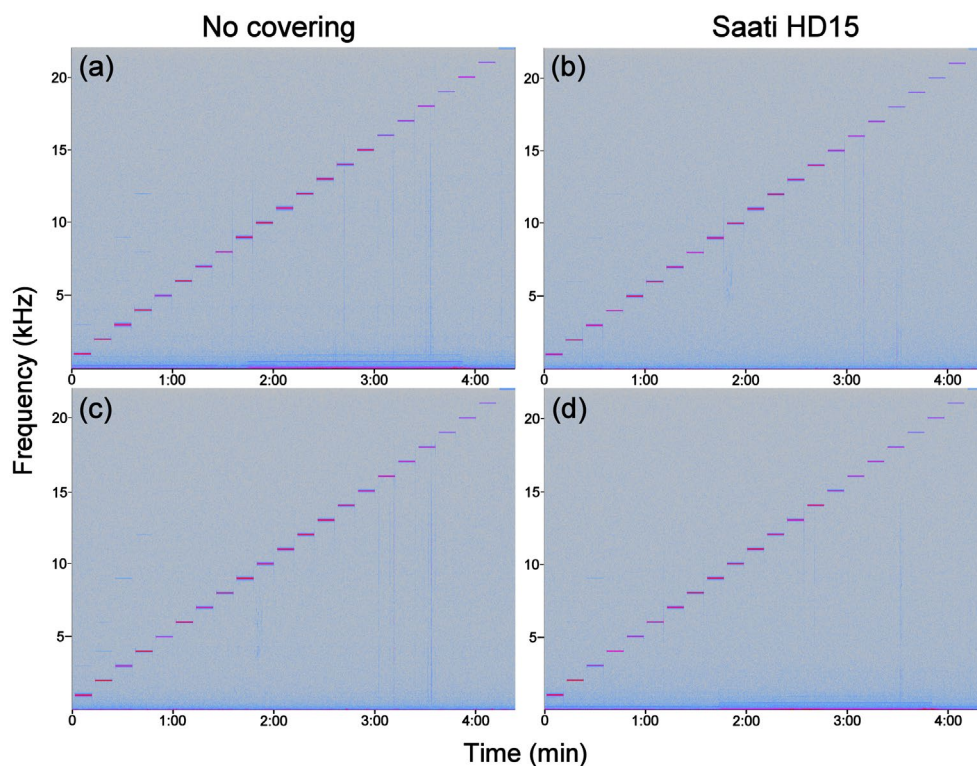


Figure 4. Spectrograms (Hanning window, window length = 2048, dynamic range = 90 dB) and waveforms of pure tones recorded on identical AURITA units to evaluate the use of acoustic fabric as a potential microphone covering: (a) no covering, offset left, (b) Saati HD15 acoustic fabric offset left, (c) no covering, offset right, (d) Saati HD15 acoustic fabric, offset right.

Note: No post-processing has been performed.

illustrates, smaller membranes (D) produce higher fundamental frequencies. As a basic example, a timpani drum of 0.6 m diameter, with a surface tension of 200 N m^{-1} and surface density of 0.26 kg m^{-2} would have a fundamental frequency of 112 Hz (Nave 2017). Adjusting diameter to 0.01 m for our microphone while keeping everything else constant, which is unlikely to be the case but necessary to provide some indication of the expected outcome, produces a fundamental frequency of $\sim 6.7 \text{ kHz}$. This is reasonably close to the lowest frequency peak we observed around 5 kHz, given that thickness and surface tension are likely to be different from a timpani drum. Additionally, a circular membrane does not produce a regular harmonic series ($1f$, $2f$, $3f$, etc.) as it vibrates in a number of different modes ($1f$, $1.59f$, $2.13f$, $2.29f$, $2.91f$, etc.) (White and White 2014). Assuming the fundamental frequency of our cling-film covering is $\sim 5 \text{ kHz}$, the first four harmonics should occur at approximately 8, 10.7, 11.5 and 14.5 kHz, which is also quite similar to the peaks we observed in recordings for cling-film.

For the EM172, cling-film could be held in place over the microphone using the cable gland. To cover the opening for the RPA2 MEMs microphone, in order for the cling-film to remain taut and secure yet be easily replaced if necessary, we devised the method described in Figure 6.

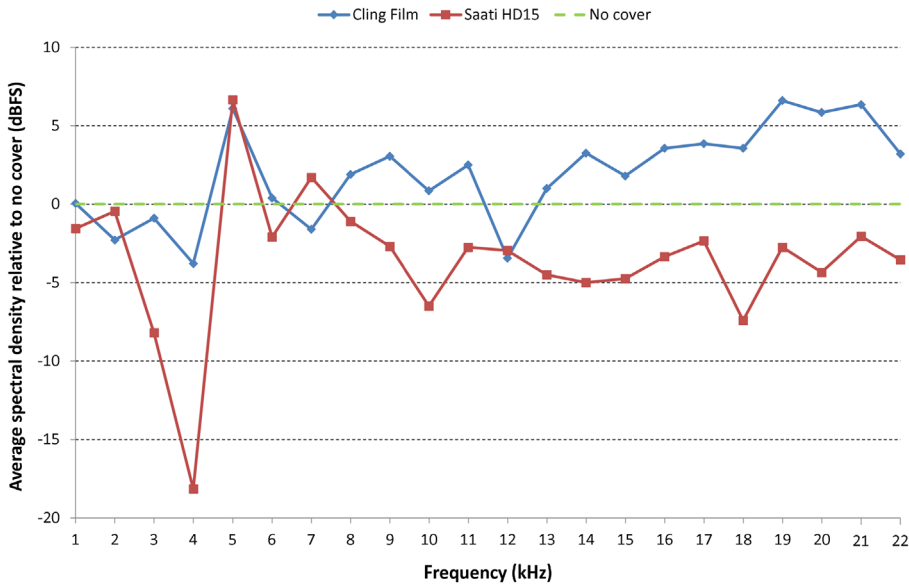


Figure 5. Comparison of average power spectral densities of pure tones recorded on identical AURITA units to evaluate cling-film and Saati HD15 acoustic fabric as potential microphone coverings.

Notes: Performance is shown relative to levels recorded without any covering over the microphone, represented by 0 dBFS.

The finished design was tested in controlled conditions, i.e. without electronic components, under the shower and in the rain, and did not exhibit any leaks. However, as water could potentially enter the case if the cling-film covering the MEMs microphone opening became compromised, the RPA2 and USB power banks were additionally sealed in Ziploc® bags, and a drainage hole, covered with gauze to prevent entry by insects, was made in the bottom of the case as insurance against this eventuality. The total cost of building one AURITA unit, excluding batteries and SD cards, was approximately £350.

Field testing

We deployed 12 AURITA units at different locations in Richmond Park, London from 1 July to 2 September 2016 ($n = 17,078$ h continuous audible and 261 h triggered ultrasonic) and from 2 May to 3 July 2017 ($n = 17,015$ h audible and 290 h ultrasonic). During this time, SD cards and USB power banks were cycled on an approximately weekly basis. All Solo units were configured with the following settings: CLAC_VOL = 31, CLAC_DIG_VOL = 152, DURATION = 30, CLAC_AUDIO_SOURCE = linein, CLAC_SAMPLERATE = 'r44100'. All Peersonic RPA2 units were set to record every night between 20:00 and 05:00, with an auto record threshold of -35 dB and an input gain of -2 dB. Maximum recording duration was initially set to 15 s but later extended to 45 s due to some units prematurely reaching their 3000 file limit. Locations represented mature mixed deciduous woodland (four public, eight private), and the units were attached to 12 trees with circumferences of 1–2.5 m, at heights of between 1.5 and 2.8 m above ground level. Upon completion of recording, all 12 units were successfully recovered in full working order. The longest single continuous period of operation achieved without changing batteries was just under 8 days using USB

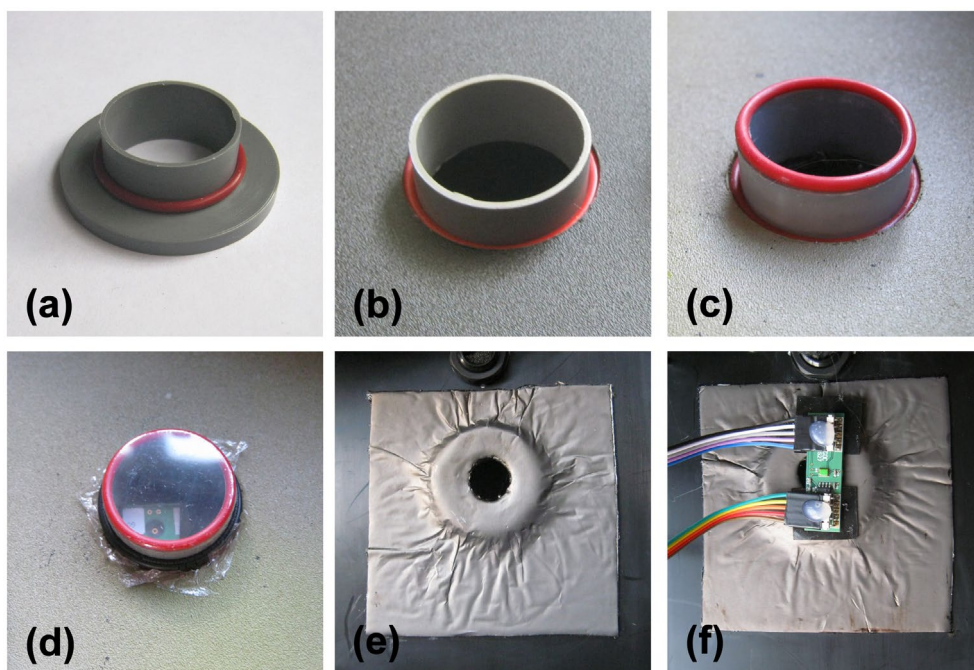


Figure 6. Design to mount cling film over an opening for an ultrasonic microphone: a plastic shoulder washer and rubber O ring (a) were fitted through a hole in the case (b). Another O ring (c) was attached to provide a less abrasive seal and avoid film scarring. Cling-film was then stretched over the opening and held in place using smaller, thinner O rings (d). Inside, water ingress under the shoulder washer was prevented by sealing it with adhesive flash band. A hole, aligned with the centre of the opening, was cut in the band (e) where the ultrasonic MEMS microphone was attached with double-sided foam tape (f) (Author's own).

power banks and 19 days using the car battery configuration (45 Ah 12 V battery). In the latter case, however, the Solo SD cards filled up before the battery ran out, after ~7.8 days recording at 44.1 kHz to a 64 GB card. It could have been possible to further extend their field life either using a larger SD card or a lower sampling rate such as 32 kHz (Nyquist 16 kHz), which should have been sufficient to capture the vocalizations of any birds and anurans (Pijanowski et al. 2011b). Examples of audible and ultrasonic recordings have been provided in the Supplementary Material and their accompanying spectrograms are provided in Figure 7.

Discussion

Recent advances in digital recording and data storage technologies have provided researchers with unprecedented opportunities to perform long-term, unattended, continuous monitoring of the acoustic environment (Farina 2014). While purpose-built recorders typically demonstrate the best performance, their price range can place them out of reach for some researchers and limit their use for large-scale deployments (Joo et al. 2011). Even commercially available devices that support recording in both audible and ultrasonic frequencies are only able to do so subject to limitations on performance, such as being unable to record both frequency ranges simultaneously or requiring the use of higher sampling rates for both

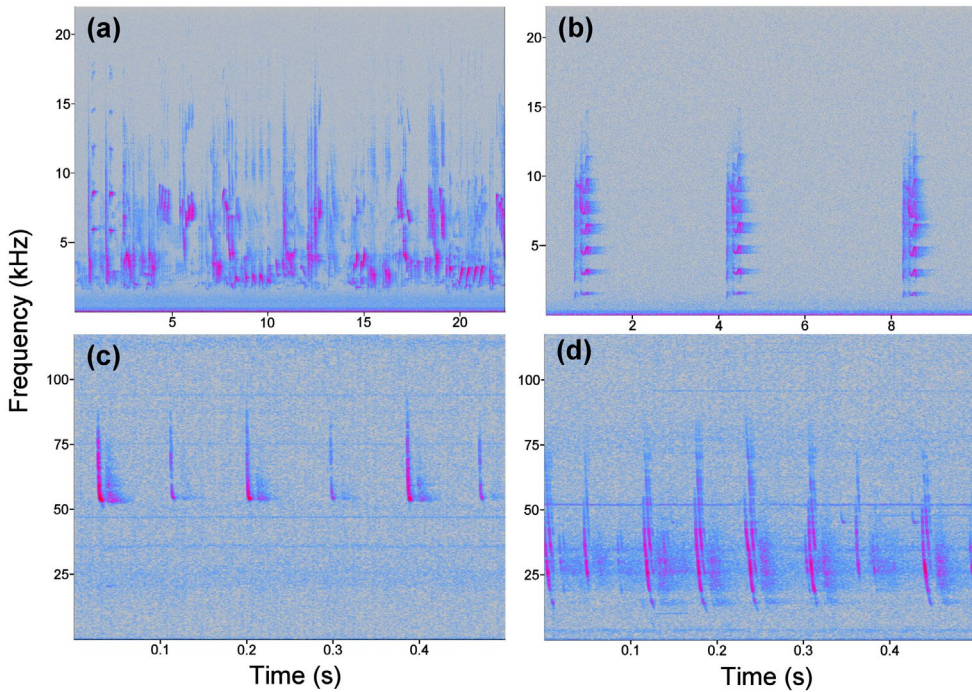


Figure 7. Example spectrograms (Hanning window, window length = 2048, dynamic range = 90 dB) and waveforms of audible and ultrasonic recordings made using the AURITA: (a) dawn chorus (~4:30 am), (b) female tawny owl (*Strix aluco*), (c) soprano pipistrelle (*Pipistrellus pygmaeus*), (d) long-eared bat (*Plecotus auritus*) with common pipistrelle (*Pipistrellus pipistrellus*) in the background. No post-processing has been performed.

formats, thus greatly increasing storage demands. Microprocessor-based solutions developed by the scientific community now offer an alternative, and usually more affordable, route to perform acoustic surveys; however, for bats and Orthoptera, the added expense of an ultrasonic microphone places some of these in the lower price bracket of commercial recorders. Additionally, not all of these options currently support triggered recordings.

We have presented an overview of some of the autonomous recording devices currently available, including both off-the-shelf commercial units and custom designs based on microprocessor boards, and demonstrated how it is possible to combine commercial and ad hoc components to create an autonomous recording device for simultaneous monitoring of both audible and ultrasonic frequencies that are reliable, have a reasonable field life and can capture high-quality acoustic data, at a fraction of the cost of commercially available counterparts. Our intentionally modular AURITA design allowed individual components to be easily removed and replaced without the inconvenience and data loss due to having to remove the unit from the field and send it off for repair. This also allows the user to potentially incorporate specific design features they feel desirable. During the described sampling period, two Solo units (incorrectly configured) and one RPA2 (hardware fault) were replaced with spare components without issue. This feature additionally makes the unit user-serviceable with the option to replace, supplement or upgrade existing components.

As the unit can be attached to trees, it is particularly well-suited to deployment in public spaces, such as parks, and both the unit itself and method of attachment can easily be

secured with padlocks. Although the car battery configuration requires that the power supply is ground-based, the recording unit itself can still be mounted off the ground to avoid attenuation caused by ground reflections. The AURITA has also proven itself capable of withstanding the elements over continuous periods exceeding two months in two successive years and the use of cling-film has provided a watertight seal while enabling sound to be recorded without any significant loss of signal.

In some locations, where bats were particularly active over prolonged periods, the RPA2 would occasionally reach its 3000 file limit after a few nights, before the 32 GB SDHC card had reached capacity. This is probably the RPA2's main restriction when performing long-term surveys and can be somewhat mitigated by extending the maximum file duration for which the RPA2 will record when triggered. Even then, if no sound is detected for five seconds after the previous event detected, the unit will stop recording regardless of the specified maximum threshold. This feature can produce uneven file lengths when using durations longer than the five second minimum and necessitate file splitting by some means, using functions within tuneR (Ligges et al. 2016) for example, if a standard file length is required for processing.

For the Solo units, the main issue encountered was incorrect time stamping due to the loss of date and time settings. This happened on only a couple of occasions and, even then, affected units still recorded normally with the exception that recordings were labelled with an incorrect date and time. Such eventualities can be fairly easily accounted for, either by noting the date and time when each unit is switched on or by speaking it into the microphone once the unit has started recording. Incorrect filenames can then be corrected retrospectively, once the data have been downloaded. Unlike the RPA2, the Solo is not equipped with an in-built configuration screen, as is often the case with microcontroller-based recorders, and can only be reconfigured by attaching it to a computer network or directly connecting a keyboard and monitor via the HDMI port (Whytock and Christie 2018d). As both approaches were impractical under field conditions, units had to be removed, replaced with a correctly configured Solo and then reconfigured elsewhere. Additionally, flashing memory cards with the Solo operating system image and downloading recorded files does require the use of disk imaging software and a Linux file reader, which some users may not initially be familiar with. Detailed, step-by-step instructions, along with locations where appropriate software for these tasks can be freely obtained, are provided on the Solo website (<https://Solo-system.github.io/home.html>).

Arguably, the main factor currently limiting the field life of such equipment is the availability of reliable, affordable and compact, yet high capacity, battery power. Although the car-battery option offers some solution in this regard, its use can potentially limit deployment locations. Nonetheless, the ability to power equipment such as the Solo and Peersonic RPA2 using power over USB is an important feature that offers greater flexibility and choice of options than the more traditional cell-type batteries and future developments in this technology could further extend effective field life.

Authors' contributions

R.B. developed the AURITA configuration and constructed all units used for field testing. R.R. and J.K. assisted with field testing. All authors contributed critically to drafts and gave final approval for publication.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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