Received: 2 November 2023 | Accepted: 25 June 2024

DOI: 10.1111/2041-210X.14390

Methods in Ecology and Evolution
BRITISH ECOLOGICAL SOCIETY

PRACTICAL TOOLS

Spatial ecosystem monitoring with a Multichannel Acoustic Autonomous Recording Unit (MAARU)

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Funding information
Natural Environment Research Council, Grant/Award Number: NE/P012345/1 and NE/S007415/1

Handling Editor: Nicolas Lecomte

Abstract

1. Multi-microphone recording adds spatial information to recorded audio with emerging applications in ecosystem monitoring. Specifically placing sounds in space can improve animal count accuracy, locate illegal activity like logging and poaching, track animals to monitor behaviour and habitat use and allow for 'beamforming' to amplify sounds from target directions for downstream classification. Studies have shown many advantages of spatial acoustics, but uptake remains limited as the equipment is often expensive, complicated, inaccessible or only suitable for short-term deployments.
2. With an emphasis on enhanced uptake and usability, we present a low-cost, open-source, six-channel recorder built entirely from commercially available components which can be integrated into a solar-powered, online system. The MAARU (Multichannel Acoustic Autonomous Recording Unit) works as an independent node in long-term autonomous, passive and/or short-term deployments. Here, we introduce MAARU's hardware and software and present the results of lab and field tests investigating the device's durability and usability.
3. MAARU records multichannel audio with similar costs and power demands to equivalent omnidirectional recorders. MAARU devices have been deployed in the United Kingdom and Brazil, where we have shown MAARUs can accurately localise pure tones up to 6 kHz and bird calls as far as 8 m away (±10° range, 100% and >60% of signals, respectively). Louder calls may have even further detection radii. We also show how beamforming can be used with MAARUs to improve species ID confidence scores.
4. MAARU is an accessible, low-cost option for those looking to explore spatial acoustics accurately and easily with a single device, and without the formidable expenses and processing complications associated with establishing arrays.

Ultimately, the added directional element of the multichannel recording provided by MAARU allows for enhanced recording of sonic environments, further enabling a potential step change in the uptake of spatial acoustics in the wider field.

KEYWORDS
acoustics, ALS, autonomous monitoring, environmental monitoring, PAM, spatial acoustics

1 | INTRODUCTION

Passive acoustic monitoring (PAM) uses autonomous recording units (ARUs) to study the wealth of information stored in an ecosystem's soundscape. PAM is cheaper and more scalable to large-scale, high-resolution wildlife surveys than human field data collectors, and results in archivable raw records that can be revisited and re-analysed as research questions and technologies develop. Spatial information can be added to recorded sound by triangulating its position/orientation of origin based on time delays between sounds reaching two or more microphones. Applications of spatialised acoustics include assessing the positions, movements, territories and number of sound emitters, as well as permitting signal subsetting (e.g. beamforming) for enhanced analysis downstream (Blumstein et al., 2011; Rhinehart et al., 2020).

Spatial acoustic recording requires multiple precisely time-synced microphones. These microphones can either be broadly separated in an array for hyperbolic localisation across a landscape or clustered together closely on a node for direction of arrival (DOA) determination relative to the node (Rhinehart et al., 2020). At present, the most common acoustic localisation systems (ALS) use hyperbolic localisation, with microphones usually placed tens or hundreds of metres apart. Reflecting increased interest in ALS, two key producers of bioacoustics equipment (wildlife acoustics and open acoustic devices) have released GPS time-sync modules for their device, so that they can be used in distributed monitoring arrays. However, ALS arrays can become expensive as they require a minimum of three recorders *per site* (costing over £300 for AudioMoths +GPS and over £2700 for Wildlife Acoustics SM4TS). Localisation accuracy in ALS arrays quickly falls off outside of the array, often meaning many more recorders are generally required in practice (Rhinehart et al., 2020, Supporting Information). Additionally, automated time-precise signal detection is not yet widely used, so localisation in hyperbolic arrays still heavily relies on time-consuming manual annotation (Rhinehart et al., 2020, Supporting Information).

Alternately, individual multi-microphone nodes can be used as ALS. These nodes usually contain three to eight individual microphones and vary in size and structure depending on target species (Chen et al., 2006). Importantly, existing algorithms such as MUSIC (Multiple SIgnal Classification, Schmidt, 1979) facilitate the estimation of a sound's DOA relative to a multichannel node automatically. The MUSIC algorithm creates a vector of MUSIC power at each time point for each possible DOA. MUSIC power can be imagined as a likelihood (based on cross-correlation) of the recorded sounds in each frequency band, coming from each possible DOA angle, at each time point. This process can also be worked backwards on individual nodes to amplify and separate sounds from just desired directions (beamforming), theoretically improving SNR in diffuse noise conditions (Nakadai et al., 2010). These individual ALS nodes can then be used as a lightweight system for spatialising sounds for spatial analysis and sound source separation.

In either case, the uptake spatial ecoacoustics remains limited as these devices are often non- or semi-autonomous, require specialist/discontinued equipment, lack clear instructions, are complex to establish, complex to analyse or are formidably expensive (Table 1, and Supplementary S1). Recognising these limitations, we have designed a Multichannel Acoustic Autonomous Recording Unit (MAARU). MAARU is an open-source, easy to set up spatial acoustic recorder, built entirely from off-the-shelf components, with simple install instructions and pipelines into automated analysis. MAARU provides an accessible platform for those hoping to explore ALS and begin asking new questions with this potentially game-changing technology.

2 | DESCRIPTION

MAARU extends an existing omnidirectional Raspberry-Pi-based ARU (Sethi et al., 2018). We have modified this platform to incorporate multichannel recording for spatial ecoacoustics by altering: (1) the core recorder hardware, (2) on-board software and (3) device weatherproofing.

2.1 | Core recorder hardware

MAARU centres on a Raspberry Pi 3B or 4B, a multichannel microphone array (Circular 6-Microphone Seeed Studio ReSpeaker array), a (renewable) power system and internet connectivity via a 3G/4G/LTE USB dongle (Figure 1). However, MAARU devices are also suitable for non-autonomous deployment with manual battery replacement and data download. The core MAARU set-up (Raspberry Pi and microphone array) weighs <1 kg and measures 15 × 15 × 13 cm with enclosure. The autonomous set-up weighs ~15 kg, with the largest component, the solar panel, measuring 84 × 58 × 15 cm (Supplementary S3).

The ReSpeaker array uses six small (3.76 × 2.95 × 1.1 mm), omnidirectional MEMS microphones, fixed in a circular array on a PCB,

TABLE 1 A summary of some recent acoustic localisation systems.

Setup	Node dimensions	Node cost £	Multi-node-sync	Data collect	Power mW	Power	OTS	If not OTS, open-source hardware	DIY instructions available	Automated analysis tested	Reference
MAARU	2D 6 Mics	202/ 470	No	Manual/ Internet	5000	Solar (battery possible)	Yes	Na	Yes	Yes—HARKBird	This
VoxNet, an update on Acoustic ENSBox. (discontinued)	3D 4 Mics	NR	Yes	Internet	7000	Battery 8–20h	No	No	No	Yes—custom	Allen et al. (2008)
CARACAL	2D 8 Mics	100	Yes	Manual	375	Battery 24h	No	Yes	Semi-enclosure instructions available	Manual	Wijers et al. (2021) + unpublished data
TAMAGO Rpi	2D 8 Mics	600 (estimate)	No	Manual	4000–5000 (Rpi)	Battery	Yes	Na	No	Yes—HARKBird	Suzuki et al. (2017, 2023)
Animal call PAM system	3D 4 Mics	126	NR	Manual	NR	Battery 3h active, 48–60h with sleep	Semi- 3D printing required	Na	No, and some circuitry required	Yes—custom	Yen et al. (2022)
BATLoc	Omi and 2D 1Mic and 10 Mics	NR	Yes	Internet (cable)	NR	Mains	Yes	Na	No	Yes	Verreycken et al. (2021)
SongBeam	1D (line) 4 Mics	80	No	Manual	NR	Battery 6days+	Yes	Yes	Yes	No localisation tested	Zandberg and Lachlan (2023)
Hermans et al LiDAR and bats in 3D	3D 8 Mics	NR	Not tested but possible	Manual	15,000	Battery 20h	No	No	Na	Yes—TOADSuite	Hermans et al. (2023)
Baggenstoss TASCAM	2D 4 Mics	NR	No	NR	NR	NR	Yes	Na	Yes	Yes	Baggenstoss et al. (2021)
Wildlife Acoustics SM4TS and other models or GPS enabled SM3s	2D 2 Mics	1285	Yes	Manual	Variable	Battery 510h+	Yes	Na	Na		Examples given in supplementary of: Rhinehart et al. (2020)
AudioMoth +GPS	Omni – 1 Mic	110	Yes	Manual	Variable	Battery 190h+	Yes	Na	Na	No localisation papers yet	Company website
BAR LT/ BAR LT V2	1D 2 Mics	480 Bar LT/ 260 BAR LT V2	Yes	Manual	Variable	Battery 100–600h Solar possible	Yes	Na	Yes	No localisation papers yet	Company website, unpublished data
WASN Bruggermann	Omni – 1 Mic	NR	Yes	Internet	NR	Battery 60+ h (solar possible)	Yes	Na	No	No localisation tested	Bruggemann et al. (2021)
DIY Hyperbolic recorder	Omni – 1 Mic	NR	Yes	Manual	NR	Solar	Yes	Na	No	Manual	e.g. Crunchant et al. (2022)
RPI: Bird 2D	Stereo – 2 Mics	NR	Yes	Internet	NR	Solar	NR	NR	No	No localisation papers yet	Company website
ESP32 Korvo	2D – 3 Mics	34 (without powering, housing, or SD card)	NR	NR	NR	NR	Yes	Na	NR	No bioacoustics papers yet	Product GitHub

Note: This shows just passive systems which are field-resistant and not dependent on an in-person human observer. OTS (Off the Shelf) refers to equipment that can be easily purchased online and is not dependent on custom electronics such as custom PCBs. 'Semi' OTS equipment refers to components that are enquiry only. For DIY set-ups, this also includes whether recording code is available online at time of writing. Full explanation and further details in supplementary.

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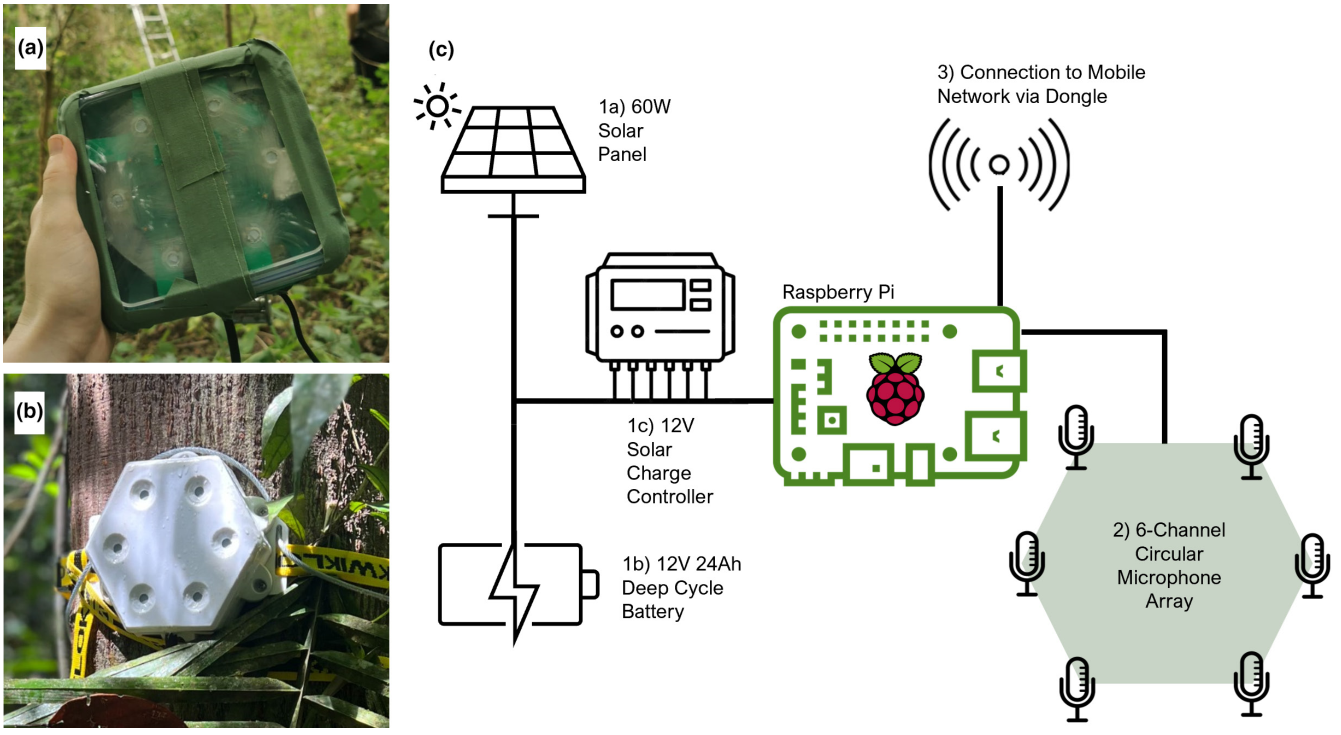

FIGURE 1 The Multichannel Acoustic Autonomous Recording Unit recorder showing the basic enclosure (a), 3D-printed enclosure (b), and a set-up schematic (c).

which attaches to the Raspberry Pi via a Seeed Studio Multichannel soundcard HAT (Hardware Attached on Top). All microphones are managed by the same internal clock, maintaining the consistent synchronisation required for spatial acoustics. Spatialisation dimensions are limited by the dimensions of the recording array. We use a six-microphone 2D circular array. More complex 3D arrays could provide spatialisation in 3D but can be much more expensive or require more complex rigs as components cannot just be affixed to a flat PCB. On the other hand, simpler (1D linear) arrays do not allow for more than forward/backward type spatial beamforming/spatialisation. The size and number of microphones used in the array was used to optimise for low cost and bearing estimation accuracy.

We found that MAARU uses 5W during simultaneous recording and upload, no different to an analogous single microphone recorder (Supplementary S4). A 5W device requires a minimum of 120Wh per day. MAARU's powering needs can be tailored to their environments (mains power, wind, non-recharging battery deployment). Powering equipment should generate more than the minimum allowance as given specifications are based on 100% efficiency which is not representative of real-world deployments. In battery-only deployments, users may opt to disable internet transfer to increase longevity.

One MAARU recorder generates 192kB (16kHz, 16-bit, 6-channel) of data per second, reducing to approximately 96kB after FLAC compression. For data upload to keep up with recording volume, the minimum required upload speed is therefore 0.768Mbps, for deployments using continuous recording. Like the powering system, internet connectivity can be tailored to the need and availability of connection. Data from MAARU devices can be manually downloaded or autonomously uploaded. For our autonomous deployments, we used a 3G/4G/LTE dongle. However, other connection types, such as Ethernet, and Wi-Fi are possible.

2.2 | Device software

Like Sethi et al. (2018), the MAARU software records, optionally compresses and transmits acoustic data on a user-defined schedule while receiving updates and sending log information daily. For MAARU, we developed this code base by adding a multichannel sound card, rolling back package versions for compatibility, freezing the Linux kernel version, adding a kill switch and switching to lossless compression.

The microphones are set to record 16-bit at 16kHz to WAV files, and while lossy compression can be usable for audible range omnidirectional recording (Heath et al., 2021), DOA estimation performs a much finer scale comparison between signals, so we instead use lossless FLAC compression here.

Full details of software amendments, the open-source code and step-by-step set-up instructions are available at https://beckyheath.github.io/MAARU/.

2.3 | Weatherproofing

To weatherproof MAARU, we trialled two enclosure types: a modified 450mL plastic container and a custom 3D-printed enclosure (Figure 1a,b). In both cases, the microphone holes are covered by

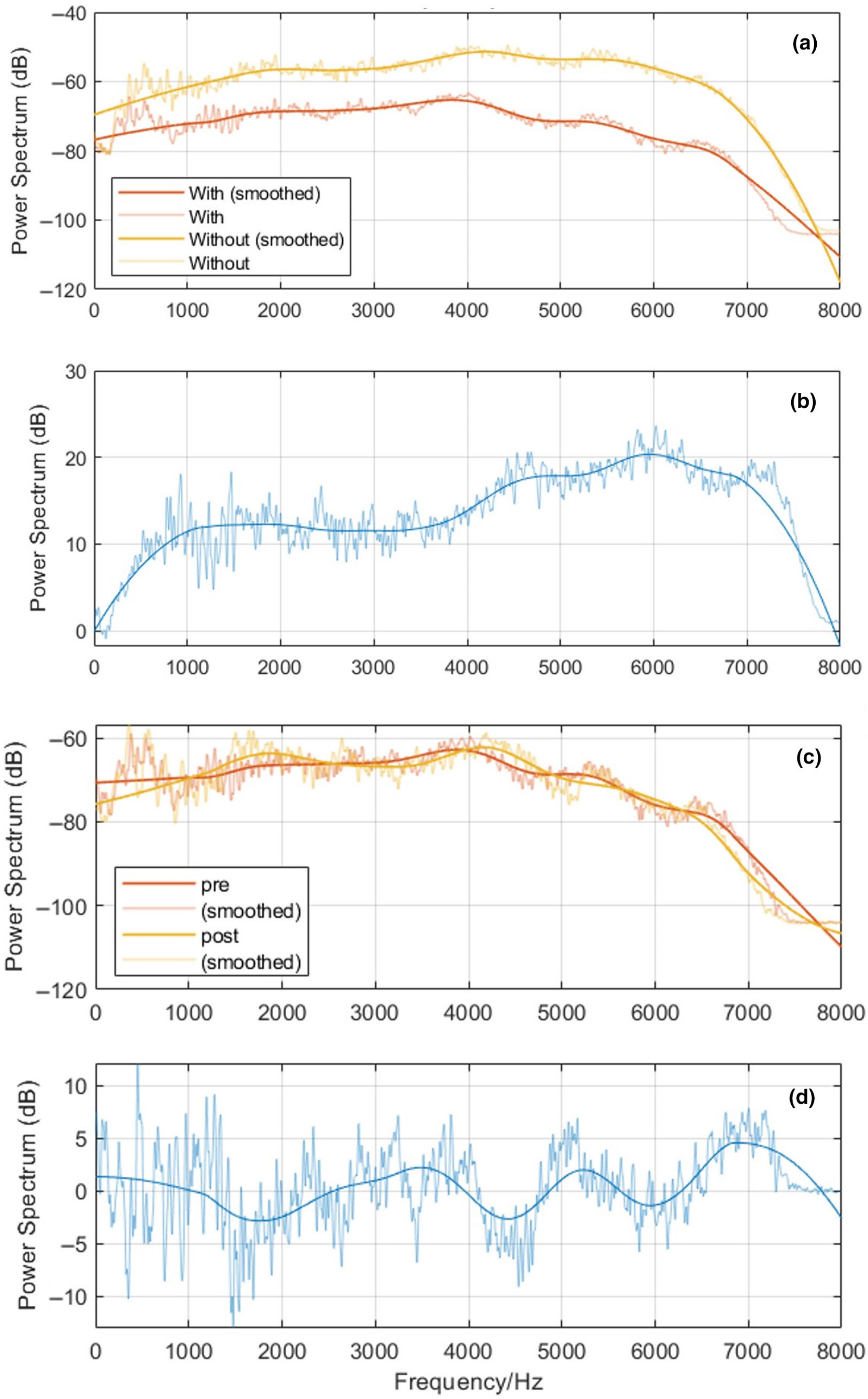

FIGURE 2 (a) Power spectra of sinus-logarithmic sweep signals (sweeps) recorded from devices without weatherproofing (orange) and with (yellow) and the difference (b). (c) Sweeps recorded from devices pre- and post-6-month deployment in the field and the difference (d).

ePTFE Acoustic Vents, which block water droplets with minimal acoustic impedance (Supplementary S3b). Powering components are deployed in dry bags, attached nearby recording equipment.

2.3.1 | Impact on sound quality

We used the MATLAB digital signal processing (DSP) toolbox (MATLAB, 2010) to compare recordings of a fixed-position 50–20,000 Hz sinus-logarithmic sweep for multiple devices, with and without weatherproofing. Weatherproofing caused an average loss in the acoustic signal amplitude of <20 dB (Figure 2a,b).

2.3.2 | Durability

We have evaluated MAARU devices in four field trials/experiments (Table 2). All devices, and both weatherproofing types remained

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TABLE 2 All the field deployments and experiments completed on MAARU recorders.

Trial	Num. Recorders	Location	Duration	Type of deployment	Technical aim	Ecological application
Suburban pre-trial	4	London/Kent, UK	2 months	Fully Autonomous charging and upload	Test core functionality and basic weatherproofing	NA
Temperate forest field trials	4	London/Kent, UK	6 months	Fully Autonomous charging and upload	Test long-term durability and basic weatherproofing	Abundance measuring and space usage (Heath et al., 2023)
Temperate forest field experiments	2	Ascot, UK	2 × weeklong deployments	Non-Autonomous	Field test 3D-printed weatherproofing, and distance testing in realistic noise environments	Beamforming for more sensitive classification
Rainforest field experiments.	4	Manicoré, Brazilian Amazon	Single day deployments, week and 1 month	Non-Autonomous	Test 3D-printed weatherproofing, explore beamforming	Beamforming for more sensitive classification

Abbreviation: MAARU, Multichannel Acoustic Autonomous Recording Unit.

watertight throughout deployments. Our longest was a 6-month deployment in Ancient Semi-Natural Woodland (ASNW) and Plantation on Ancient Woodland Site (PAWS) in the United Kingdom.

In autonomous deployments, data were retrieved successfully from all recorders in almost real time. All recorders uploaded 24 h data continuously in open-air pre-trials. However, partial panel coverage in the 6-month trials led to data loss in autumn and winter as daily sunlight could not compensate for power usage. We also temporarily lost two recorders due to rats chewing cables, and a partial panel fall, but we have adjusted our set-up instructions to mitigate these risks in future. 1700+ hours (550+ GB) of six-channel audio were retrieved from the Temperate Forest field trials alone. All four devices are in working condition and currently being used in other experiments.

Post 6-month deployment, the devices were again tested with a 50–20,000 Hz sinus-logarithmic sweep finding a ±5 dB SPL difference in frequency response (Figure 2c,d).

3 | PROOF OF CONCEPT

3.1 | Direction of arrival estimation

Using a 2D array such as MAARU, DOA is represented by planar azimuth between −180° and +180°, as illustrated in Figure 3a. The accuracy of MAARU's DOA estimation was tested in playback experiments, whereby test tones (pink noise, Eurasian Wren song (Karel, 2020) or single frequency tones) were played at 15-s intervals at five azimuths (−180°, −90°, −45°, 0° and +90°) around a central MAARU device (Figure 3a). For DOA analysis, we used HARKBird (Suzuki et al., 2017). HARKBird adapts the HARK (Honda Research Institute Japan Audition for Robots with Kyoto University) software for robot audition (Nakadai et al., 2017), which performs DOA estimation. HARK operates based on a transfer function and generates a MUSIC (MUltiple SIgnal Classification, Schmidt, 1979) power spectra for each time point.

In our configuration, for each time point, HARKBird calculates the MUSIC power every 5° (i.e. 72 possible azimuths) then, based on the given power thresholds, determines when a signal is present and its direction (Figure 3b,c). We then experimentally optimised MUSIC power threshold settings for each specific test (Supplementary S5) to account for irregularities in amplitude.

We tested 256 signals in total and determined whether a signal had been 'detected', 'aliased/non-primary' or 'missed' by inspecting the MUSIC matrix (Figure 3b,c). Spatial aliasing occurs when the inter-sensor distance is larger than the wavelength of the signal to localise, meaning that higher frequency (shorter wavelength) signals might not be localised correctly. Following Chen et al. (2006), the minimum theoretical frequency that can be accurately rendered by MAARU (inter-microphone distance of 4.63 cm), derived below, is 3725 Hz. Beyond this, limitations of the specific environmental conditions and HARKBird's confidence scoring should be found experimentally.

$$\text{Frequency} = \frac{\text{speed of sound}}{2 \times \text{inter} - \text{mic distance}},$$

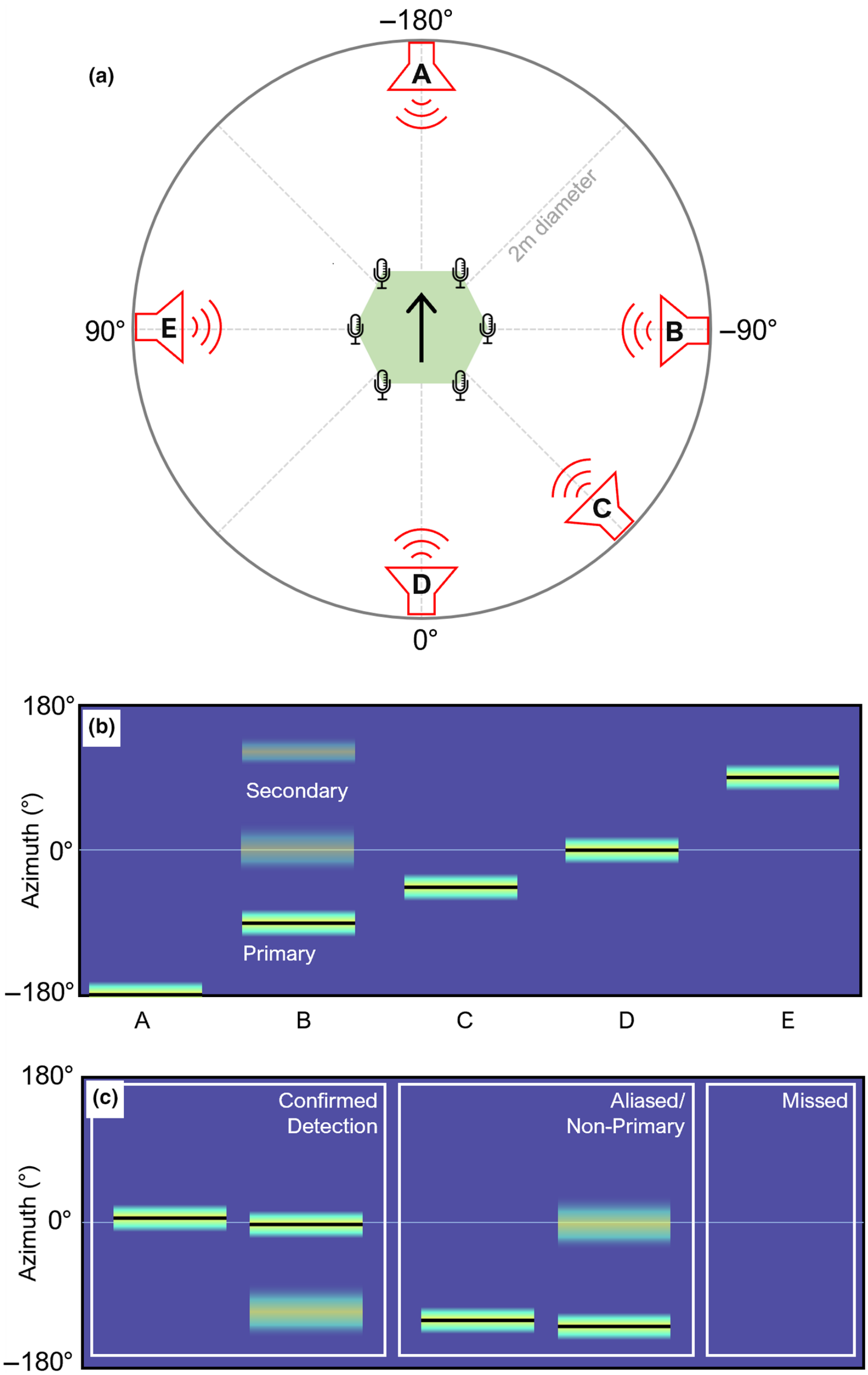

FIGURE 3 Direction of arrival estimation test's basic set-up and example outputs. (a) An overhead schematic. (b) An example direction likelihood matrix where all signals are localised correctly. For each time point, the lightness of pixels gives the MUSIC score (likelihood) that a sound is coming from a given azimuth. The black line indicates the angles at which HARKBird determines there is a signal. Here, signals A–E are localised to the correct azimuth in order. Multiple positions can have high music scores and not count as a detection. (c) The labels used to classify detections where the true azimuth is 0°.

$$\text{Frequency} = \frac{343.2}{2 \times 0.0463} = 3725\,\text{Hz}.$$

In practice, animal sounds are mostly wideband, containing multiple frequency components (Chen et al., 2006). Provided the recordings are appropriately down-sampled ahead of analysis, the lower frequency components can be used for spatialisation purposes. If higher frequency recording is required, arrays with a reduced inter-microphone distance should be used.

The DOA estimation accuracy of MAARU was compared in four experiments (Table 3). Tests were conducted on weatherproofed (WP-Y) and un-weatherproofed (WP-N) devices at 1 m unless otherwise stated. For all tests, we determined the azimuth error in degrees, and proportion of signals with confirmed detections (Figure 4).

Across all tests, all *confirmed* detections were accurately localised to within ±10°, with the median error mostly being 0°, and not increasing to more than 5° (Figure 5). Recall remained at 100% for all signals except at 8 m, 6 kHz and 7 kHz (66.7%–70%, 60% and 0%, respectively). The first test in which no signals were detected accurately was the 7 kHz single frequency test (Figure 4h).

ALS accuracy is very variable depending on environmental conditions (Matsubayashi et al., 2022); however, an accuracy of ±10°

TABLE 3 The direction of arrival estimation accuracy tests completed on MAARU as per protocol in Figure 4.

Experiment	Groups	Origin	Test location	Pre/post 6-month deployment
Test signal	Pink noise Eurasian Wren	Generated in audacity Xeno-Canto	Lab	Pre
Weatherproofing	Weatherproofed (WP-Y) Un-weatherproofed (WP-N)	Na	Lab	Pre
Distance	1, 2, 4 and 8 m	Na	Field—temperate forest	Post
Frequency	100, 400, 500, 1000, 2000, 4000, 6000 and 7000 Hz	Generated in audacity	Lab	Post

Abbreviation: MAARU, Multichannel Acoustic Autonomous Recording Unit.

is of similar values reported by other studies (±10° to 60° (Yen et al., 2022), 1.8° to 8.4° for MUSIC (Tolkova & Klinck, 2022)).

3.2 | Beamforming for more accurate machine learning classification

Beamforming is the manipulation of time delays between recorded signals to amplify sounds that come from target directions. We tested how well beamforming could enhance ecoacoustic analysis by investigating the effect of ODAS' (Open embedded Audition System (Grondin et al., 2022)) delay-and-sum beamformer on the classification accuracy of a trained neural network.

BirdNET is a deep neural network that has been trained on 230,000+ labelled recordings (Kahl et al., 2021). It returns bird species predictions from audio recordings with associated confidence values between 0 and 1. BirdNET is widely used within the bioacoustics community and has been applied to over 140 million audio recordings (BirdNET, 2023).

3.2.1 | Improvement in confidence levels of field recordings

We assessed 55.1 h of acoustic data from Manicoré (Brazilian Amazon) and 79 h of data from Ascot (UK) (both 16-bit, 16 kHz). Beamformed signals were extracted for four directions relative to the recorder ([Azimuth, Elevation] = [0°, +45°], [0°, −45°], [+45°, 0°], [−45°, 0°]).

We used species that had been detected over 30 times in both monophonic and beamformed recordings ($n = 14$) for confidence analysis. Mean confidence using beamforming was higher than that of monophonic recordings (Figure 5, 0.83, SD = 0.15; 0.71, SD = 0.19). The median confidence for beamforming was also higher than monophonic recordings (0.872–0.718, respectively). Significance was confirmed with a Wilcoxon signed rank test ($W = 8457060.0$, $z = 44.64$, $p < 0.001$). While not tested here, simply stacking the six channels may also yield increased BirdNET confidence with more simple processing.

4 | DISCUSSION

We designed MAARU to create a simple, accessible, ALS system that addresses the current limitations to uptake of ALS in long-term environmental monitoring (Table 4).

MAARU recorders are best suited to long-term deployments, desiring real-time analysis, in areas with good network connectivity; however, they can be used in short-term deployments too. MAARU recorders are most suitable to researchers keen on DIY approaches for the detection of lower frequency, close-medium range wildlife, or those just looking for a simple approach to starting with spatial acoustics. MAARU recorders have a maximum sample rate of 48 kHz, but due to the array size, we found DOA estimation to be limited to <6 kHz (theoretical <4 kHz). A combination approach whereby 48 kHz audio is recorded for general presence/absence data is possible with low-frequency indicator species perhaps selected for specific spatial analysis. Researchers looking to investigate whole landscapes, higher frequency species or want to stick with 'plug-and-play' type equipment may be better suited to building distributed arrays with other devices such as GPS-enabled AudioMoths or BART LTs. While users looking for just targeted direction beamforming may be better suited to using something like a SongBeam.

Spatial acoustics is at the forefront of environmental monitoring technology and the creation of accessible, low-cost devices and spatialisation algorithms are vital to their progression. Specifically, spatial acoustic technologies must work towards ALS 'checking all boxes' in some combination of the existing technologies and streamlined analysis methods to reach more ubiquitous uptake.

For MAARU-like recorders specifically, this could include the incorporation of GPS modules for inter-node synchronisation, sensor PCBs in 2D or 3D with smaller inter-mic distances for more accurate spatialisation of higher frequency signals, low power optimisation and the addition of a duty-cycle mechanism to reduce power costs, addition of other sensors (e.g. cameras, temperature and humidity sensors) and analysis via other perhaps more robust ALS methods such as DOA-based sound source separation via Azigrams (Tolkova & Klinck, 2022).

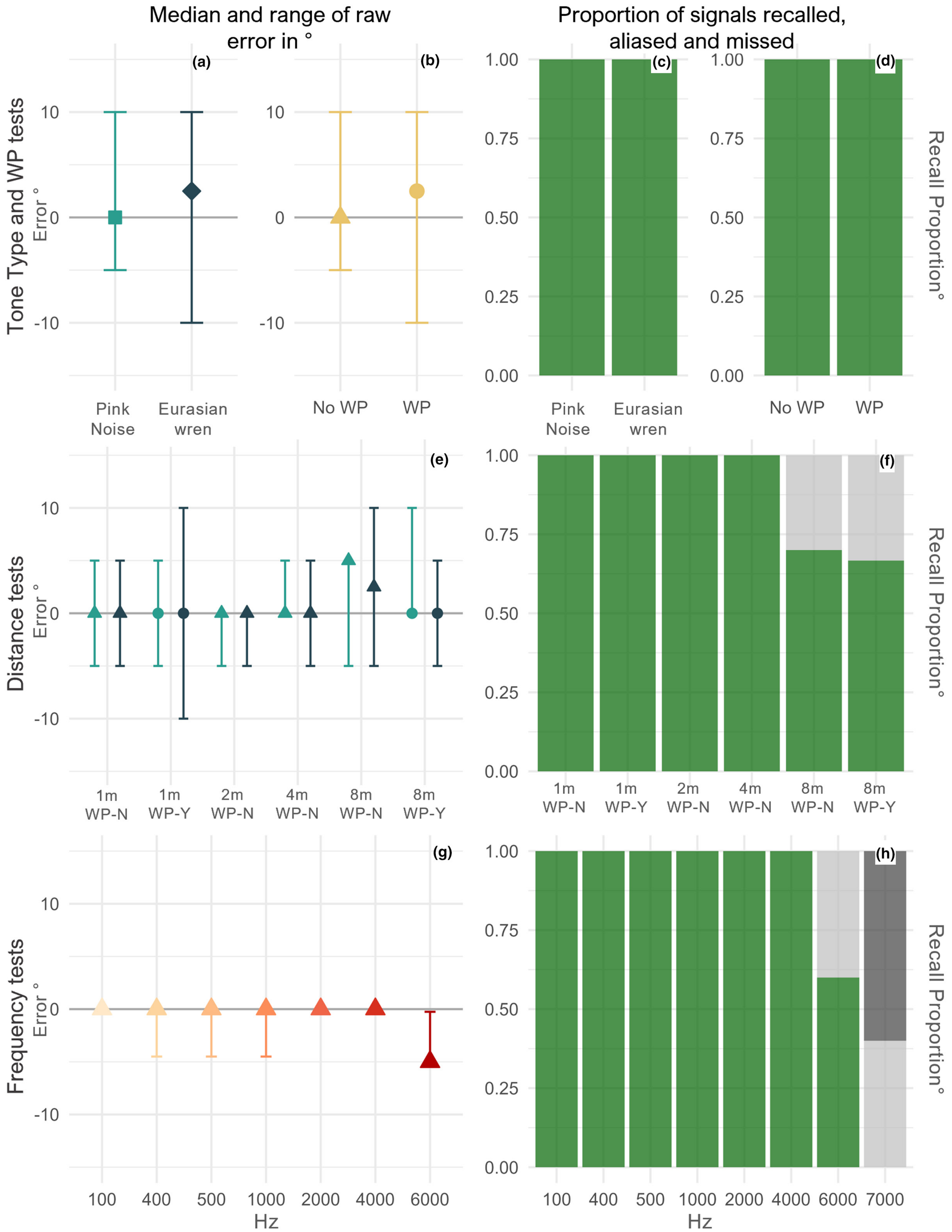

FIGURE 4 The outputs of all direction of arrival estimation tests, as described in Figure 3. The left column shows the median and range of raw errors (differences between the true and predicted azimuths). The right column shows recall/detection rates (green: detected, grey: non-primary and black: missed). The first row shows the results from lab tests at 1 m, the second row shows the results from field distance tests in realistic noise environments and the third row shows pure tone lab tests at 1 m.

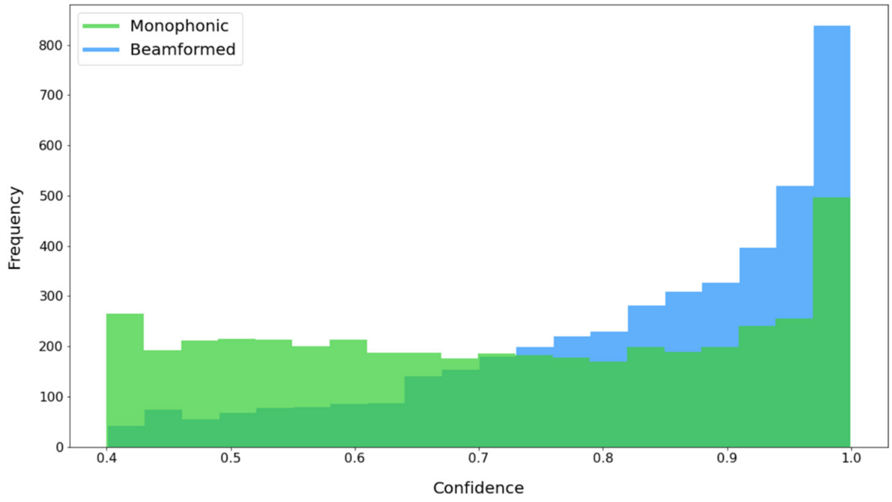

FIGURE 5 A histogram of confidence distributions across all detections for both monophonic and beamformed recordings. Beamformed recordings result in higher BirdNET confidence scores than monophonic recordings.

TABLE 4 The key aims and the degree to which they have been achieved with the MAARU recorder.

Aim	Outcome
Low cost	MAARU combines autonomous PAM with usable multichannel recording for £202, <£10 more than its omnidirectional predecessor Powering is an additional cost that can be tailored to the field area (e.g. +£270 for UK winter deployment)
Accessible	All components could be sourced online at the time of writing MAARU can be built with a power drill and screwdriver
Accurate	All signals could be localised to a high degree of precision (±10°)[a]
Durable	All devices remained watertight throughout deployments in temperate and tropical ecosystems. The premature failure of the two devices has been addressed
Customisable	MAARU is a modular recording unit which can be altered to suit powering and local network capabilities
Useful for ecologists	We have shown successful ports to ODAS, HARKBird and BirdNET Audio from MAARUs can be used to accurately localise signals[a] Beamformed MAARU audio increases BirdNET classification confidence
Low maintenance	Autonomous MAARU recorders can be left in the field indefinitely Non-autonomous MAARU devices have the same set-up and maintenance burden as popular omnidirectional devices

Abbreviation: MAARU, Multichannel Acoustic Autonomous Recording Unit.
[a]With signal components within loudness and frequency restrictions.

5 | CONCLUSIONS

For spatial acoustics to gain traction in ecosystem monitoring, equipment must be widely available, field-ready, inexpensive and low maintenance (Rhinehart et al., 2020). Here, we present a device that fulfils some of these conditions while also being suitable for indefinite autonomous deployment, with capacity for analysis in almost real time. Multichannel acoustic recording can describe patterns that single-channel acoustic ARUs alone cannot, such as tracking the movement, interaction and relation to the habitat of individuals, all while being optimised for sound-source separation. Spatial acoustic systems like MAARU and others mentioned in this paper may revolutionise the way ecosystems are recorded. With spatial ecoacoustics able to provide a more nuanced understanding of individual responses to environmental stressors and facilitate better strategies for protecting and restoring at-risk organisms and environments.

AUTHOR CONTRIBUTIONS

Becky E. Heath led the development of MAARU, with Robert M. Ewers, Lorenzo Picinali, C. David L. Orme and Sarab S. Sethi in supervisory/advisory capacity. MAARU is based on the work of Sarab S. Sethi, Becky E. Heath adjusted the scripts for use with multichannel acoustics and James Skinner and Neel P. Le Penru provided additional developments regarding housing and bug fixes later stages. Device accuracy testing was carried out by Becky E. Heath and Neel P. Le Penru, and classifier accuracy testing was carried out by James Skinner. Data curation, analysis and visualisation were led by Becky E. Heath. Reiji Suzuki provided advice and bug fixes through the port to HARKBird. Manuscript writing was led by Becky E. Heath with valuable contributions from all other authors.

ACKNOWLEDGEMENTS

We would like to extend thanks to Silwood Park, The Woodland Trust (Peter Coles), Bexley Council (Mark Taylor, Patrick English, and

Len Pegler-Vincent) and the Ama Group (Robin Daniels, Leonardo Barrionuevo, Eduardo Barrionuevo, Fernando Barrionuevo and Suelen Marostica) for their support in permitting MAARU field deployments, and IAmLumberJack Ltd. (Jack Bath, Mark Griffiths, Oscar Housego, Aiden Prall) who provided practical support in tree tops during deployments in the United Kingdom. We would also like to extend additional thanks to authors/creators of other ALS systems for providing up to date information about the technical aspects of their systems for Table 1: Matthew Wijers, Andrew Markham, Benjamin Yen, Erik Verreycken, Claire Hermans, Michael Maggs, Leonhard Brüggeman and Anne-Sophie Crunchant. This work was funded through the National Environment Research Council (NERC)'s 'Quantitative Methods in Ecology and Evolution' Centre for Doctoral Training (grant number: NE/P012345/1), NERC's 'Science for a Changing Planet' Doctoral Training Program (grant number: NE/S007415/1), and supported further by Becky E. Heath's College Research Association at King's College Cambridge.

CONFLICT OF INTEREST STATEMENT

None.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/2041-210X.14390.

DATA AVAILABILITY STATEMENT

Website codebase and set-up instructions are available via Zenodo at https://doi.org/10.5281/zenodo.12761111 (BeckyHeath, 2024a). Raspberry Pi software for MAARU available via Zenodo at https://doi.org/10.5281/zenodo.12761142 (BeckyHeath and JamesSkinna, 2024). Scripts use to analyse data for this paper available via Zenodo at https://doi.org/10.5281/zenodo.12761136 (BeckyHeath, 2024b). As acoustic data were recorded in public woodland, it contains sensitive information. In certain cases, acoustic data can be provided, but please contact the authors for more information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1: Supplementary Information.

How to cite this article: Heath, B. E., Suzuki, R., Le Penru, N. P., Skinner, J., Orme, C. D. L., Ewers, R. M., Sethi, S. S., & Picinali, L. (2024). Spatial ecosystem monitoring with a Multichannel Acoustic Autonomous Recording Unit (MAARU). *Methods in Ecology and Evolution*, *15*, 1568–1579. https://doi.org/10.1111/2041-210X.14390