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Methods in Ecology and Evolution

PRACTICAL TOOLS

ChirpArray: A low-cost, easy-to-construct microphone array for long-term ecoacoustic monitoring

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Abstract

1. Advances in passive acoustic monitoring (PAM) have highlighted the importance of recording devices and audio recognition techniques in ecosystem monitoring.
2. This study introduces ChirpArray, a cost-effective and easily assembled microphone array for long-term ecoacoustic monitoring of outdoor ecosystems. The ChirpArray system features a four-channel microphone array that estimates sound source directions, aids in identifying individual animals and provides a detailed behavioural analysis.
3. Unlike previous microphone arrays, ChirpArray is low-cost, low-power and waterproof, making it ideal for extended-field monitoring. It is a fully open source and is constructed from readily available materials, ensuring broad accessibility for applications ranging from local citizen projects to large-scale landscape recordings. This study details the power, storage consumption and localization performance of ChirpArray.
4. Current measurements show that a small solar-power set-up can continuously operate the system. Localization tests using loudspeakers have yielded promising results. ChirpArray is a compact, energy-efficient microphone array designed for long-term outdoor recording, offering considerable advantages in ecoacoustic monitoring. Its exceptionally low power consumption allows for efficient and flexible deployment, making it an ideal solution for extended-field monitoring and large-scale landscape recordings.

KEYWORDS
automated recording unit, ecoacoustics, microphone array

1 | INTRODUCTION

With recent advancements in recording devices and audio recognition techniques, passive acoustic monitoring (PAM) has become an essential tool for ecosystem monitoring (Nieto-Mora et al., 2023; Sugai et al., 2019). Researchers have employed PAM in various ecological applications, including biodiversity assessments (Depraetere et al., 2012; Roe et al., 2021), monitoring the temporal and spatial activity of animals (Farina et al., 2011; Li et al., 2024; Ross et al., 2018) and investigating anthropogenic effects on animal behaviours (Slabbekoorn & den Boer-Visser, 2006).

These studies typically use automated recording units (ARUs), such as the AudioMoth (Hill et al., 2019) and the Wildlife Acoustics Song Meter SM4 (Wildlife Acoustics Inc.), which have scheduled recording functions and can operate long-term outdoor recordings. Most ARUs employ single (monaural) or paired (stereo) omnidirectional microphones. However, an array of simultaneously recorded microphones (usually four or more) can estimate the relative directions of sound sources based on time delays between microphones. Such microphone arrays have been used to identify the locations of individual birds (Sumitani et al., 2021; Suzuki et al., 2017) and mammals (Jensen & Miller, 1999) and to analyse their behaviour and density in detail (Stevenson et al., 2014).

Several existing systems, however, face limitations such as lack of waterproofing (e.g. ReSpeaker USB Mic Array [Seeed Studio Inc.]), dependence on power-intensive hardware such as laptops (e.g. TAMAGO [System in Frontier Inc.], Verreycken et al., 2021) or high costs because of custom fabrication (Jensen & Miller, 1999). Heath et al. (2024) provide an overview of the history of microphone arrays for ecoacoustics, emphasizing the need for affordable and easy-to-construct arrays suitable for long-term outdoor recording. Their work addresses these issues by introducing Multichannel Acoustic Autonomous Recording Unit (MAARU), an open-source and low-cost solution based on the popular Raspberry Pi single-board computer. Although MAARU offers an affordable solution for long-term spatial ecoacoustic monitoring, it has limitations because of its high power consumption, making the system too large to scale for extensive recording projects.

This study, therefore, proposes ChirpArray, a minimal automated recording unit with a four-channel microphone array that can be built using readily available materials. ChirpArray features low power consumption, low cost, and high customizability, making it ideal for long-term, multipoint ecoacoustic monitoring with the advantages of multichannel recordings.

2 | MATERIALS AND METHODS

2.1 | System overview

2.1.1 | Hardware

ChirpArray (Figure 1) utilizes a Sony Spresense microcontroller board as its primary platform. Equipped with an extension board, Spresense offers four-channel analogue microphone inputs, an internal real-time clock (RTC) and a global navigation satellite system (GNSS) module, making it ideal for this project. Table 1 lists the required components and their approximate prices (as of April 2024 in Japan).

The system employs four waterproof electret condenser microphones (CME-1538-100LB, CUI Devices) to capture sound. These microphones require a 2.0 V bias voltage on the input lines. We connected each microphone's input line to the bias pin of the Spresense extension board using 2.2 kΩ resistors (see Figure S1). Detailed hardware assembly instructions are available in the GitHub documentation (https://github.com/0kam/ChirpArray).

The microphones are arranged on the circumference of an 8 cm diameter circle, facing downward to avoid raindrops obstructing them. Although arranging the microphones in a three-dimensional configuration is technically feasible, designing a waterproof housing that avoids sound reflections and maintains localization accuracy presents substantial challenges, which we have not yet addressed.

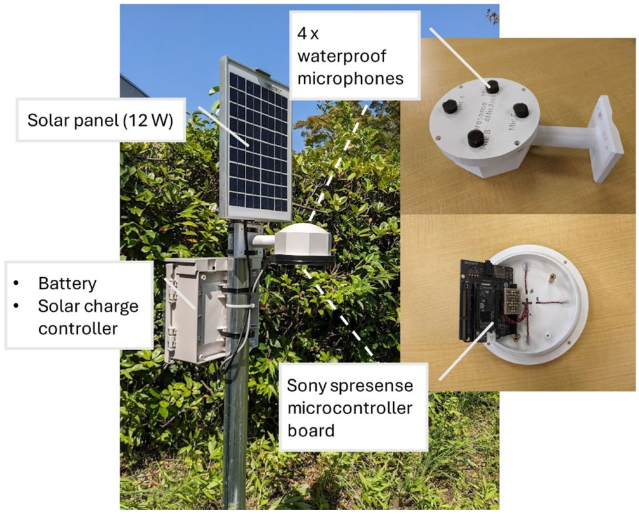

FIGURE 1 Overview of ChirpArray. ChirpArray comprises four waterproof analogue microphones connected to a Sony Spresense microcontroller board.

For the weatherproof casing of ChirpArray, we prepared two options—a 3D-printed case (Figure 2a) and an off-the-shelf outdoor case (e.g. Takachi's BCAP151509G, Figure 2b). Off-the-shelf cases generally offer superior waterproofing performance and are easy to obtain, making them recommended for most users. Using desiccants in these cases can mitigate condensation caused by daily temperature fluctuations.

However, the availability of commercial cases may vary depending on the user's country or region, posing challenges for consistent hardware replication. To address this issue, we designed a housing that can be 3D-printed. Although the 3D-printed case performed well during our field tests, it is still a work in progress. We acknowledge that condensation could occur in high-humidity environments. We plan to refine the design to enhance reliability and leverage the benefits of reproducibility and design flexibility. The 3D model is available on GitHub, allowing users to customize the housing to their needs.

2.1.2 | Software

ChirpArray was developed using the Arduino IDE ecosystem, facilitating easy software installation and recording configuration. For a beginner-friendly guide to getting started with Arduino IDE and Spresense, refer to Sony's official instructions (https://developer.sony.com/spresense/development-guides/arduino_set_up_en.html). The Arduino sketch is available on GitHub (https://github.com/0kam/ChirpArray/blob/main/Arduino/timelapse_recorder/timelapse_recorder.ino).

TABLE 1 Parts list of ChirpArray.

Product name	Product type	Manufacture	Price	Quantity
Spresense main board	Main processing board	Sony	¥6000	1
Spresense extension board	Extension board for microphone inputs	Sony	¥4000	1
CME-1538-100LB	Analog microphone	CUI Devices	¥500	4
2.2 kΩ carbon resister	General resister		Under ¥10	4
Stripboard (36×24 mm)	General stripboard		Under ¥100	1
Pin header (2×8)	General pin header		Under ¥50	1
Micro SDXC card (512 GB)	General microSD card		¥10,000	1

Note: The price column presents the approximate prices of the parts (in Japan, April 2024). The total cost of ChirpArray (excluding power supply) is approximately $130.

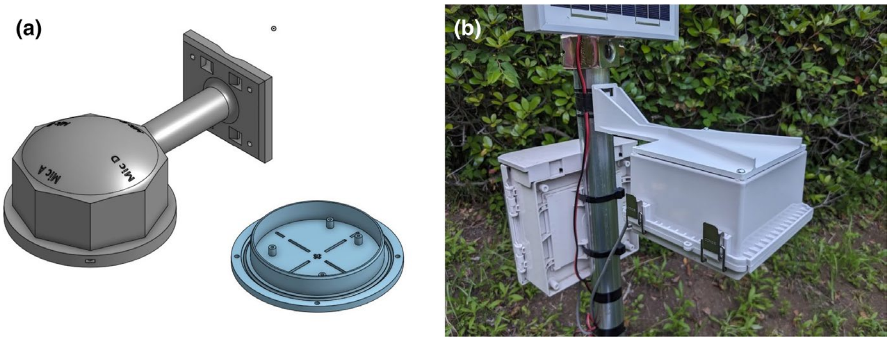

FIGURE 2 Waterproof cases for ChirpArray. (a) The 3D model of the printable case. (b) An example of off-the-shelf cases (Takachi's BCAP151509G).

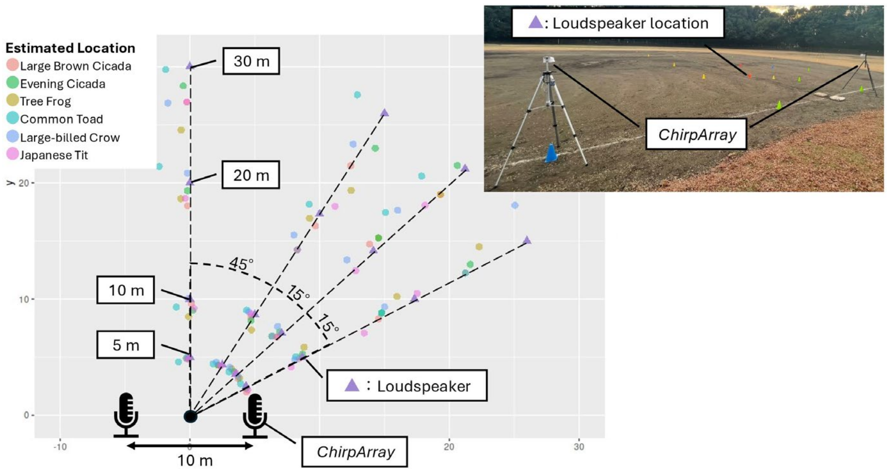

FIGURE 3 Result of the localization experiment. We tested the localization performance of ChirpArray using a loudspeaker. Two ChirpArrays were placed 10 m apart from each other. We played six types of calls including insects, birds and amphibians through a loudspeaker positioned at various locations (indicated as purple triangles). Using the sound sources captured by the two microphones, we estimated the direction of the sound sources and inferred their positions using the multiple signal classification (MUSIC) algorithm (indicated as circles). The colour of the circles corresponds to the type of sound source.

By editing variables in the Arduino sketch, users can set recording schedules, choose audio codecs (WAV or MP3), select sampling rates (16, 48, 192 kHz) and specify the number of recording channels (mono, stereo or four channels). Users can define detailed recording schedules by setting the start and end hours (e.g. 5 AM–7 PM), the start time for recording within each hour (e.g. at 0 or 30 min past the hour) and the duration of each recording session (e.g. 5 min). For accurate scheduling, ChirpArray automatically corrects the RTC time using GNSS signals at start-up. Additionally, for long-term battery operation, ChirpArray enters a deep sleep mode when not recording.

2.2 | Localization performance evaluation

We conducted a sound source localization experiment using a loudspeaker to evaluate the performance of ChirpArray as a microphone array. First, two ChirpArrays were placed 10 m apart and the sound played by the loudspeakers was recorded. The azimuth from each ChirpArray was then estimated to the sound source and combined to perform sound source localization. We conducted experiments by changing the distance and direction from the midpoint of the two ChirpArrays to the loudspeaker (Figure 3) and playing six types of biological sound sources (large brown cicada [*Graptopsaltria nigrofuscata*], evening cicada [*Tanna japonensis*], tree frog [*Hyla japonica*], common toad [*Bufo japonicus formosus*], large-billed crow [*Corvus macrorhynchos japonensis*], and Japanese tit [*Parus minor*]). The sound pressure was set to 70 dB at 1 m from the loudspeaker. Figure S3 shows examples of the recordings as spectrograms.

We applied the multiple signal classification (MUSIC) method (Schmidt, 1986) using the Pyroomacoustics package (Scheibler et al., 2017) to estimate sound source azimuths. Pyroomacoustics is an open-source Python library that enables simulations and analyses of acoustic environments, including sound source localization. The MUSIC method assumes that the number of sound sources is fewer than the number of microphones. In our case, up to three sources can be accommodated, though one or two are preferable in practice. This makes noise suppression crucial for accurate localization. To minimize environmental noise, recordings were split by sound source and processed with band-pass filters tailored to each sound type (Table S1). Although this reduces noise, it may not perform well in highly noisy environments with numerous bird calls or anthropogenic sounds. After filtering, the MUSIC method was applied to estimate the sound source's azimuth by identifying the peak in the MUSIC spectrum.

3 | RESULTS

3.1 | Power and storage consumption

ChirpArray was designed for long-term operation using a small solar power system. The current consumption (Table 2) was measured using a power profiling unit (Power Profiler Kit 2 [Nordic semiconductor]) to properly design the power system. Current consumption measurements were taken thrice for each recording condition, and the average values were presented. Even when continuously recording for 24 h at 48 kHz with four channels, the power consumption per day was approximately 12 Wh. It is possible to record without recharging for approximately 20 days with a battery capacity of 12 V 20 Ah. Because the current consumption in the deep sleep mode is very low (1.50 mA), the battery life will be significantly extended when performing time-lapse operations.

In addition to power, storage capacity is also a factor that limits the recording period. The data size of the sound source is determined by the audio codec, the number of channels, and the sampling rate. Table 2 presents the storage consumption per minute when recording in the WAV format at 16 bits. ChirpArray saves the recorded data on a single microSD card. Therefore, the card replacement frequency is determined by the recording settings and data capacity of the microSD card. For example, if one records in WAV format at a 48 kHz monaural from 4 AM to 7 PM, starting at 0 and 30 min every hour for 10 min each time, the size of the recorded data for 1 day will be approximately 1.85 GB.

To demonstrate the practical application, we designed an operation example using a solar power system (Table 3). In this experiment, ChirpArray was able to perform continuous recordings (16 kHz, 4 ch, WAV) for 24 h in Tsukuba City, Eastern Japan, for 5 months from August to December 2023 (the microSD card (512 GB) was replaced twice). However, in actual research applications, recording at lower frequencies is often more practical. In such cases, users can reduce power consumption, enabling operation solely on batteries or with even smaller solar panels.

3.2 | Localization testing

The results of the sound source localization are presented in Figure 3. The purple triangle indicates the installation position of the loudspeaker, and the circle indicates the estimated position of the sound sources. Although the estimated error of the sound source azimuth from each ChirpArray did not change with the distance (Figure S2), the localization error increased. The average localization errors were 0.42 m for 5 m, 0.67 m for 10 m, 2.10 m for 20 m, and 4.25 m for 30 m. In terms of the types of vocalizations, common toads tended to exhibit relatively large localization errors (Figure S2). This may be because the vocalization of the common

TABLE 2 Current and storage consumption of ChirpArray.

Number of channels	Sampling rate (kHz)	Mean current consumption (mA)	Storage consumption (MB/minute)
1	16	87.5	1.92
1	48	95.2	5.76
1	192	111.0	23.04
4	16	94.3	7.68
4	48	99.3	23.04
Deep sleep	Deep sleep	1.50	Deep sleep

Note: We tested the current consumption using a power profiling unit (Power Profiler Kit 2, Nordic Semiconductor). As the number of channels and sampling rate increase, the current consumption also increases. At the deep sleep state, ChirpArray demonstrated very low power consumption.

TABLE 3 Example of solar-powered application.

Product name	Product type	Manufacture	Price	Quantity
SY-M12W-12	Solar Panel (12 W)	SANYOOO solar	¥2500	1
SA-BA10	Solar charge controller	DENRYO	¥4000	1
WP7.2–12	Battery (12 V, 7.2 Ah)	Kung Long Batteries Industrial	¥3000	1

Note: The price column shows the approximate prices of the parts (in Japan, April 2024). The total cost of the solar power kit is approximately $60.

toad is low in frequency and is easily affected by noise, such as wind.

4 | DISCUSSION

ChirpArray advances ecoacoustic research by providing a low-cost, energy-efficient and customizable microphone array suitable for long-term outdoor deployments. Compared to existing systems such as MAARU, ChirpArray offers several key advantages. Its low power consumption—approximately one-tenth that of MAARU—allows it to operate on a compact solar-powered system, enhancing scalability for large deployments. Additionally, ChirpArray supports any two-wire electret condenser microphones with a 2.0 V reference voltage, giving users greater flexibility to customize their set-ups. This versatility contrasts with MAARU's fixed PCB-mounted microphones and enables future configurations, such as a three-dimensional microphone array to enhance localization capabilities.

While ChirpArray's four-channel recording suffices for single sound source localization, accurately separating and estimating azimuths in environments with multiple sound sources remains challenging. Enhancing ChirpArray's capabilities could involve synchronized recording across multiple units. However, existing synchronization methods, such as using a common audio signal (Hedley et al., 2017) or a pseudo-random signal (Laurijssen et al., 2018), may be unsuitable because of environmental noise or reduced audio recording channels. Exploring alternative synchronization techniques is crucial. Although the current design accommodates up to four analogue microphone channels, the Spresense platform supports up to eight channels when using digital microphones. Implementing digital microphone inputs would require complex modifications that may challenge general users. Investigating straightforward modification methods to enable digital microphone inputs could provide users with greater flexibility in their recording set-ups.

Future enhancements to ChirpArray could include implementing lossless compression techniques, such as X3 compression, to reduce data volume without sacrificing audio quality. This improvement would become particularly beneficial for long-term recordings in remote locations. Additionally, integrating a simple energy detector to trigger recordings based on sound pressure levels in specific frequency bands could enhance efficiency. This approach, similar to that used in devices such as AudioMoth, would allow selective capture of high-frequency calls, such as those from bats, while minimizing the recording of less relevant sounds.

We are also focused on developing a housing design that accommodates a three-dimensional microphone array. This enhancement would improve sound localization capabilities and facilitate advanced ecological monitoring techniques, such as tracking bird species at varying heights. Addressing the challenges of creating waterproof 3D-printed housing remains a priority.

All our development resources are publicly available, encouraging users to customize and suggest modifications to the housing and firmware. This open approach aims to foster a collaborative community that can further enhance ChirpArray's capabilities and adaptability in various ecological monitoring scenarios.

4.1 | Potential applications

Building on the advantages and capabilities of ChirpArray, there are numerous ways this technology can contribute to ecological and evolutionary research. Below, we explore several potential applications where ChirpArray can enhance data collection and analysis in the field.

4.1.1 | Population density estimation

Accurately estimating population density is crucial in spatial acoustics, with wide-ranging applications in wildlife management and conservation. Traditional methods often rely on hyperbolic localization using numerous GPS-synchronized ARUs (Rhinehart et al., 2020). However, deploying several ARUs is expensive and logistically challenging for large-scale studies. Microphone arrays such as ChirpArray can determine the bearing of sound sources directly from the device. This capability allows for precise population density estimates with significantly fewer units when utilizing statistical methods such as spatially explicit capture-recapture (Stevenson et al., 2014).

4.1.2 | Soundscape ecology

Soundscape ecology (Pijanowski et al., 2011) extends landscape ecology by focusing on environmental sounds and the ecological factors influencing them. The spatial distribution of biophony—sounds from biological sources—is a vital research area. Studies have examined relationships between land cover and the frequency and composition of bird songs (Ross et al., 2018), monitored the recovery of soundscapes after disturbances (Ross et al., 2024) and assessed the impacts of anthropogenic noise, such as road noise, on biophony (Slabbekoorn & den Boer-Visser, 2006). Incorporating ChirpArray into these studies can enhance spatial resolution and coverage. This improvement provides more detailed insights into the interactions between organisms, their environment and human activities through soundscape.

4.1.3 | Behavioural ecology

Animals rely on acoustic signals for essential activities such as foraging and reproduction. Quantitative observation of these behaviours is of significant interest in ecology and evolutionary biology. Traditionally, studies of calling behaviour in birds and insects have been conducted through short-term experiments (Endo & Osawa, 2018; Templeton et al., 2005) or brief field observations (Sumitani et al., 2021), including playback experiments. The advent of long-term recording capabilities in microphone arrays opens new possibilities. Researchers can now collect extensive behavioural data in natural settings. This advancement allows for monitoring and analysing animal communication and behaviour over longer timescales and broader areas, leading to more comprehensive insights into behavioural patterns, mating systems and ecological interactions.

5 | CONCLUSIONS

ChirpArray provides a low-cost, energy-efficient and customizable solution for long-term ecoacoustic monitoring. Its ability to capture directional acoustic data enhances research in population density estimation, soundscape ecology and behavioural studies. By reducing equipment costs and simplifying deployment, ChirpArray enables broader spatial coverage and higher data quality in ecological projects. The open-source nature of ChirpArray fosters community collaboration, encouraging further advancements in ecological research tools. Future developments, such as improved synchronization methods and 3D microphone arrays, will expand its applications and effectiveness in studying complex ecological systems.

AUTHOR CONTRIBUTIONS

Both the authors conceived the study. Ryotaro Okamoto designed and developed the hardware and software. Ryotaro Okamoto led the writing of the manuscript. Hiroyuki Oguma led the field testing. Both the authors contributed critically to the drafts and provided their final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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.14474.

DATA AVAILABILITY STATEMENT

All data, 3D models and source codes, including 3Dmodels for the 3D-printed cases, Arduino Sketch, and recording data and scripts for the localization testing, are publicly available via Zenodo. https://zenodo.org/records/14227067 (Okamoto, 2024).

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SUPPORTING INFORMATION

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

Figure S1. How to connect microphones to the Spresense microcontroller.

Figure S2. The relationship between the distance (between the loudspeaker and the midpoint of the two ChirpArrays) and the estimated errors of the azimuth.

Figure S3. Examples of localization test recordings.

Table S1. The frequency bands used in the DoA estimation for each sound sources.

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