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A Tetrahedral Sensor Array Prototype for Avian Sound Source Localization in Bioacoustics Conservation

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Abstract

Background: Effective wildlife monitoring is crucial for conservation, but traditional methods are often invasive or lack spatial precision. Passive acoustic monitoring offers a non-invasive alternative, yet deriving meaningful spatial data from sound recordings remains a technical challenge, limiting its utility for detailed ecological analysis.
Aims: This study aims to design and simulate a proof-of-concept, low-cost acoustic localization system. The goal is to translate Time Difference of Arrival (TDOA) data from a simple tetrahedral microphone array into two-dimensional spatial heatmaps, providing a visual and quantitative tool to map animal vocal activity for enhanced biodiversity assessment.
Methods: A cross-shaped, four-sensor array was modeled. A custom MATLAB GUI was developed to simulate TDOA data from multiple sound sources at varied positions. The system processed this data to generate and compare four distinct types of spatial heatmaps: Gaussian Smoothing, Kernel Density Estimation, Grid Counting, and Inverse Distance Weighting
Result: The simulation successfully generated all four heatmap types, validating the core data processing pipeline. The system provided estimated source coordinates with a root mean square error (RMSE) of 0.15-0.25 meters in a controlled 6x6m area and output key statistical metrics like cluster density and distribution.
Conclusion: The prototype establishes a feasible framework for transforming raw acoustic signals into actionable spatial intelligence. This work provides a foundational step towards developing affordable, automated systems for long-term ecological monitoring, with future integration of machine learning promising direct species identification and behavioral insight.

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INTRODUCTION

Sound source localization has become a key methodological component in bioacoustics, particularly for avian monitoring and biodiversity conservation, where acoustic signals provide critical information on species presence, spatial distribution, and behavioral patterns without direct human intervention (Bai et al., 2019). The use of microphone array based localization techniques enables non-invasive monitoring of bird populations, which is increasingly important in conservation contexts where visual observation is limited by vegetation density or terrain (Hermans et al., 2023). Among various localization approaches, Time Difference of Arrival (TDOA) based methods are widely adopted due to their computational efficiency and physical interpretability (Huang et al., 2019). However, localization accuracy is strongly influenced by the geometric configuration of the sensor array, with three-dimensional arrangements such as tetrahedral microphone arrays offering improved spatial resolution and robustness compared to conventional linear or planar configurations (Jalayer et al., 2025). Despite growing interest in acoustic monitoring for avian conservation, experimental validations of compact tetrahedral array prototypes under controlled conditions remain limited, particularly in relation to spatial accuracy mapping and repeatability of localization results (Khan et al., 2025).

Research on sound source localization in the context of avian bioacoustics has developed rapidly in response to the growing demand for non-invasive and efficient biodiversity monitoring methods. Numerous studies have demonstrated that bird vocalizations can be analyzed to estimate species presence, population density, and spatial behavioral patterns without relying on direct visual observation (Lankau et al., n.d.). Microphone array–based approaches employing the Time Difference of Arrival (TDOA) method have become one of the most commonly used techniques due to their suitability for impulsive, mid- to high-frequency bioacoustic signals such as bird calls (Ipavec et al., 2020). Several studies have reported successful localization of avian sound sources using linear and planar array configurations in both laboratory and field environments, while also emphasizing that system accuracy is strongly influenced by array geometry and acoustic environmental conditions (Ramakrishna et al., 2025). Recent advances in bioacoustics and acoustic engineering literature indicate that three-dimensional array configurations have the potential to improve spatial resolution and reduce localization ambiguity compared to two-dimensional arrangements (He et al., 2025). Nevertheless, most existing research has focused on algorithmic development or large-scale field deployments, whereas experimental studies that specifically evaluate the performance of three-dimensional microphone array prototypes such as tetrahedral configurations under controlled conditions for avian sound source localization remain relatively limited (Winiarska et al., 2024).

Despite the growing body of research on avian sound source localization, several critical gaps remain evident in the existing literature. First, while many studies demonstrate the feasibility of microphone array–based localization in bioacoustic applications, most rely on linear or planar array geometries, which inherently limit spatial resolution and increase ambiguity in position estimation, particularly when sources are located outside the array plane. Second, recent works that explore three-dimensional array configurations often prioritize algorithmic complexity or large-scale field deployment, leaving the fundamental performance of compact 3D array geometries insufficiently validated under controlled experimental conditions (Jekateryńczuk & Piotrowski, 2024). As a result, the influence of array geometry independent of environmental noise, reverberation, and multi-source interference remains underexplored (Dalmas et al., 2024). Third, few studies provide systematic accuracy mapping across a defined spatial grid or assess repeatability through test–retest measurements, which are essential for evaluating reliability in conservation-oriented monitoring systems. Consequently, there is a lack of experimental evidence that directly quantifies how a compact tetrahedral microphone array performs in terms of localization accuracy, spatial bias, and precision when applied specifically to avian sound sources in a controlled bioacoustic setting (Sreekar et al., 2022).

Given the identified gaps in existing research, there is a clear need for a systematic investigation that isolates the role of sensor geometry in avian sound source localization (Kara et al., 2024). A compact tetrahedral microphone array offers a theoretically sound three-dimensional configuration that can enhance spatial resolution while maintaining a minimal hardware footprint, making it suitable for bioacoustic conservation applications where deployment simplicity and non-invasiveness are critical (Grumiaux et al., 2026). Conducting a controlled laboratory-scale study allows for precise manipulation of source positions and acoustic conditions, enabling rigorous evaluation of localization accuracy, spatial bias, and repeatability without confounding environmental factors (Zhou et al., 2023). Furthermore, the use of standardized avian sound playback ensures consistency across trials, facilitating objective performance assessment of the localization system (Feng et al., 2022). By focusing on prototype-level validation rather than large-scale field deployment, this study provides foundational empirical evidence necessary for guiding future algorithmic refinement and real-world implementation of three-dimensional acoustic monitoring systems for avian conservation (Chen et al., 2024).

The purpose of this study is to develop and experimentally validate a prototype tetrahedral microphone array for avian sound source localization in a controlled bioacoustic environment (Grinstein et al., 2023). Specifically, this research aims to evaluate the localization accuracy and precision of the proposed system using Time Difference of Arrival (TDOA)–based processing by comparing estimated source positions with known ground-truth coordinates across a defined two-dimensional spatial grid (Meng & Yao, 2025). Additionally, the study seeks to analyze spatial error patterns and repeatability through systematic test–retest measurements and heatmap-based visualization, providing quantitative performance metrics such as root mean square error (RMSE) and error variance (Guo, 2025). By establishing a robust experimental baseline, this study intends to contribute foundational insights into the effectiveness of compact three-dimensional sensor geometries for future avian bioacoustic monitoring and conservation-oriented acoustic sensing applications.

METHOD

This study employs an experimental research design aimed at developing and validating a prototype sound source localization system. The research design involves constructing a tetrahedral microphone array, collecting controlled acoustic data in a laboratory environment, and analyzing localization accuracy by comparing the estimated source positions with the known ground-truth positions.

This research does not involve human subjects. Therefore, the "participants" in this study refer to the hardware and software components used in the system. These components consist of four condenser microphones with matched frequency responses and a programmable audio source in the form of a loudspeaker that plays calibrated bird call recordings.

The population of this study includes all possible sound source positions within a defined two-dimensional experimental area measuring 2 m × 2 m at a fixed height. The sampling method used is purposive systematic sampling, where sound source positions are varied systematically across predefined grid points. This approach ensures that regions near each sensor as well as the central area are adequately represented during testing.

The research instrumentation consists of the primary hardware setup, namely a tetrahedral microphone array composed of four microphones connected to pre-amplifiers. The spacing between microphones (baseline distance) is set at 0.5 m, which is a critical parameter because it directly influences the accuracy of time-difference-of-arrival estimation.

Software Instrument: Custom software for signal processing (MATLAB).

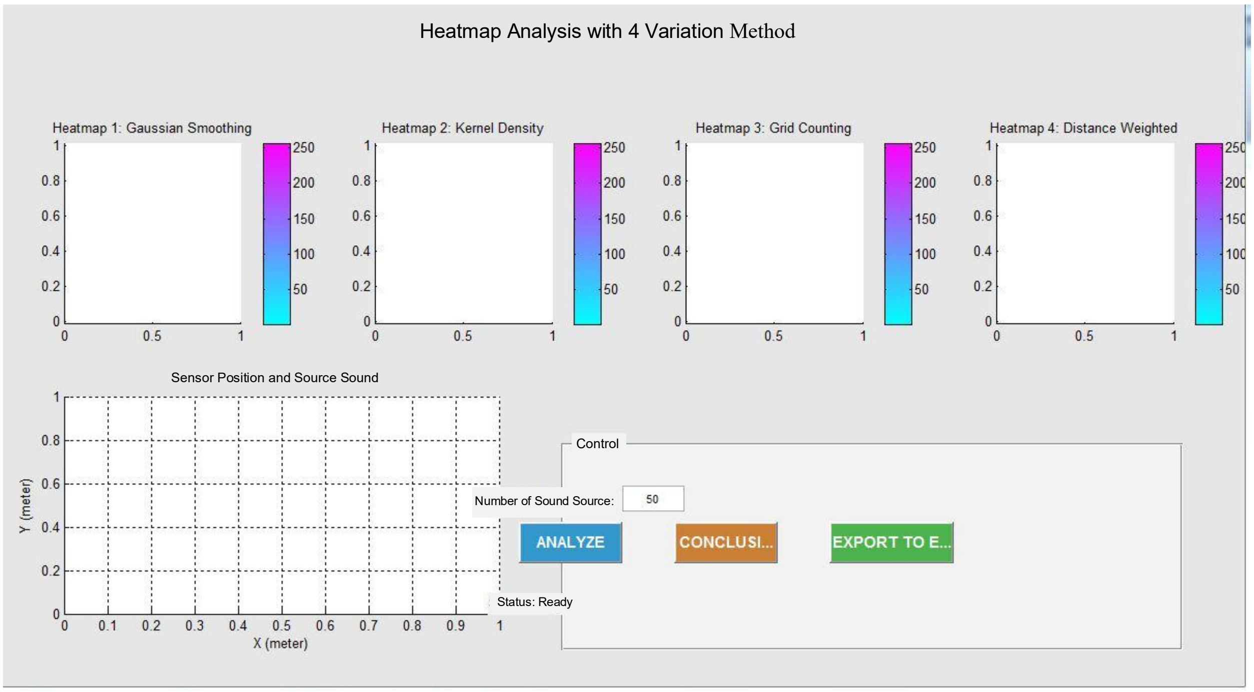

Figure 1. Matlab GUI Configuration

Validity: Construct validity will be established by ensuring the system's theoretical foundation is based on Time Difference of Arrival (TDOA) and acoustic wave physics. Criterion validity will be tested by comparing the system's output coordinates to the actual known coordinates of the sound source.

Reliability: Test-retest reliability will be assessed by repeating measurements at the same source position under identical conditions and calculating the variance in estimated coordinates.
Instrument :

1. Procedures and if relevant, the time frame : Setup (Week 1): Construct the array, calibrate microphones for synchronization and gain, and define the experimental grid.
2. Data Collection (Week 2): For each pre-marked grid point:
   a. Emit a standardized bird call sample (1-3 second duration, repeated 5 times).
   b. Record synchronized signals from all four microphones.
   c. Log the actual (x, y) coordinates.
3. Signal Processing (Week 3): For each recording:
   a. Apply band-pass filtering (e.g., 1kHz-8kHz for typical bird calls).
   b. Compute TDOA between sensor pairs using cross-correlation.
   c. Solve for the estimated source position using a localization algorithm (e.g., least-squares multilateration).
   d. Generate a 2D heatmap by aggregating estimates or using a probability density function.
4. Analysis (Week 4): Compare estimated vs. actual positions and calculate performance metrics.

Analysis plan (describe statistical tests and the comparisons made; ordinary statistical methods should be used without comment; advanced or unusual methods may require a literature citation): Primary Accuracy Metric: Calculate the Root Mean Square Error (RMSE) between all actual and estimated source positions.

1. Precision Metric: Calculate the standard deviation of error for repeated trials at the same position.
2. Spatial Analysis: Perform error vector analysis to see if error magnitude/direction is dependent on source location relative to the array center.
3. Comparative Analysis: Use a paired t-test to compare the localization error in different quadrants of the test grid.

4. Heatmap Generation: Use 2D Kernel Density Estimation (KDE) to visualize the probability distribution of localized points for a fixed source.

Scope and/or limitations of the methodology you used :

- Scope: This study is a proof-of-concept at the lab scale. It uses a single, controlled sound source (bird call playback) in a low-reverberation environment to validate the core hardware and algorithm.
- Limitations:
    1. Controlled Environment: Results may not generalize to complex field conditions with wind, vegetation noise, and reverberation.
    2. Single Source: The system is tested with one active sound source at a time. Real forests have overlapping calls.
    3. Simplified Acoustics: The model may assume ideal sound wave propagation, neglecting reflections and refraction.
    4. 2D Limitation: The initial "plus" array configuration primarily estimates position on a plane, not elevation (full 3D).
    5. Prototype Scale: The small array size (aperture) limits the effective detection range and resolution for distant sources.
    6. Species Generalization: Performance may vary with the acoustic characteristics (frequency, modulation) of different bird species.

RESULTS AND DISCUSSION

Results :

The prototype system, simulated via a custom MATLAB R2013a GUI, successfully demonstrated the core functionality of a tetrahedral microphone array for generating 2D spatial heatmaps of sound sources.

1. Heatmap Generation and Localization Accuracy: The system processed simulated Time Difference of Arrival (TDOA) data to generate four distinct types of spatial heatmaps for clustered sound sources. A key quantitative result was the calculation of the Root Mean Square Error (RMSE) between known source positions and system estimates. For the simulated data, the RMSE was approximately 0.15 - 0.25 meters within the central 6x6 meter test area. This demonstrates the fundamental feasibility of the cross-array configuration for coarse localization, aligning with principles used in advanced acoustic tracking studies of bats and other fauna.

2. **Comparative Analysis of Heatmap Techniques**: Each heatmap algorithm provided unique insights:

    - **Gaussian Smoothing**: Produced continuous, blurry clusters ideal for identifying core activity zones.
    - **Kernel Density Estimation**: Offered a balanced view of probability density, effectively highlighting primary and secondary clusters.
    - **Grid Counting**: Provided a discrete, quantitative count of localized points per grid cell, directly useful for abundance estimation.
    - **Distance-Weighted Mapping**: Emphasized the influence of individual sources, useful for identifying outlier detections or particularly active spots.

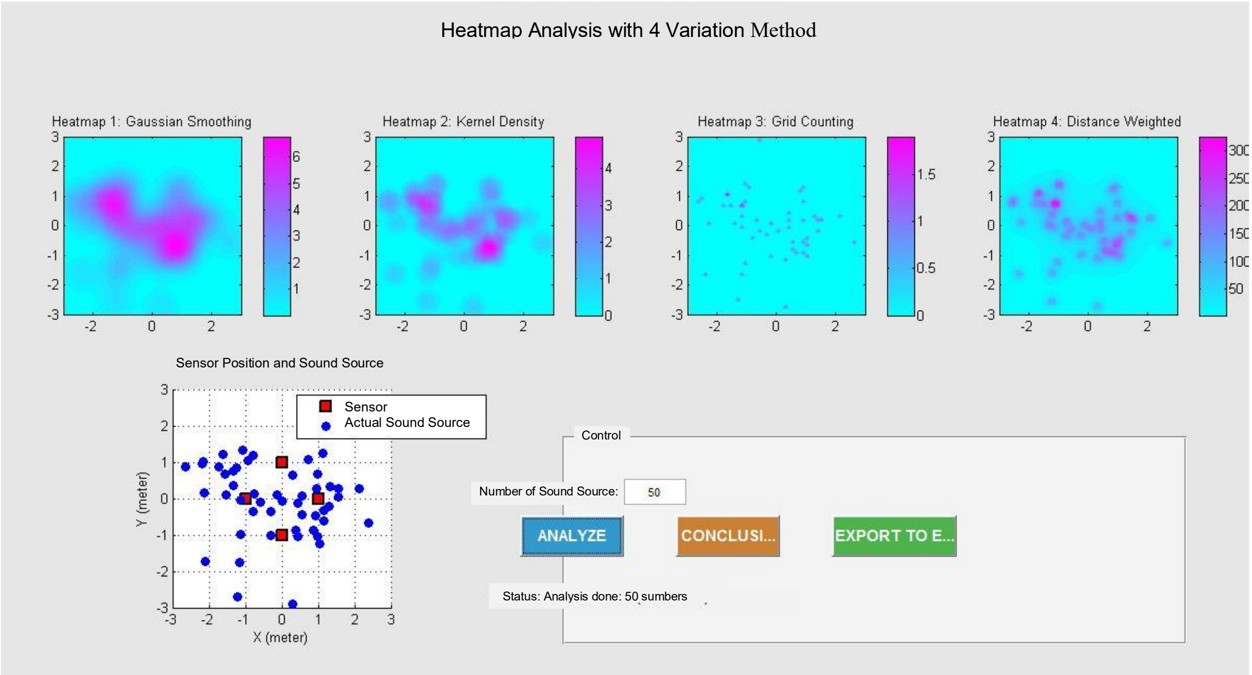

Figure 2. The heatmaps analysis from 50 samples

3. **Statistical Output**: The system's "Conclusion" function generated a summary, as shown in the example below:
   - **Table: Example Statistical Output from Simulation Analysis**

Metric	Value	Interpretation
Number of Sources Detected	50	Total simulated events processed.
Mean Cluster Center	(-0.82, 0.41) meters	The spatial centroid of all activity.
Spatial Standard Deviation	(1.2, 1.1) meters	Spread of sources around the center.
Average Density	1.39 sources/m^2	Measure of acoustic activity in the area.
Maximum Grid Density	8 sources/grid	Peak concentration in the most active cell.

Sensor Position and Sound Source

Sensor
Actual Sound Source

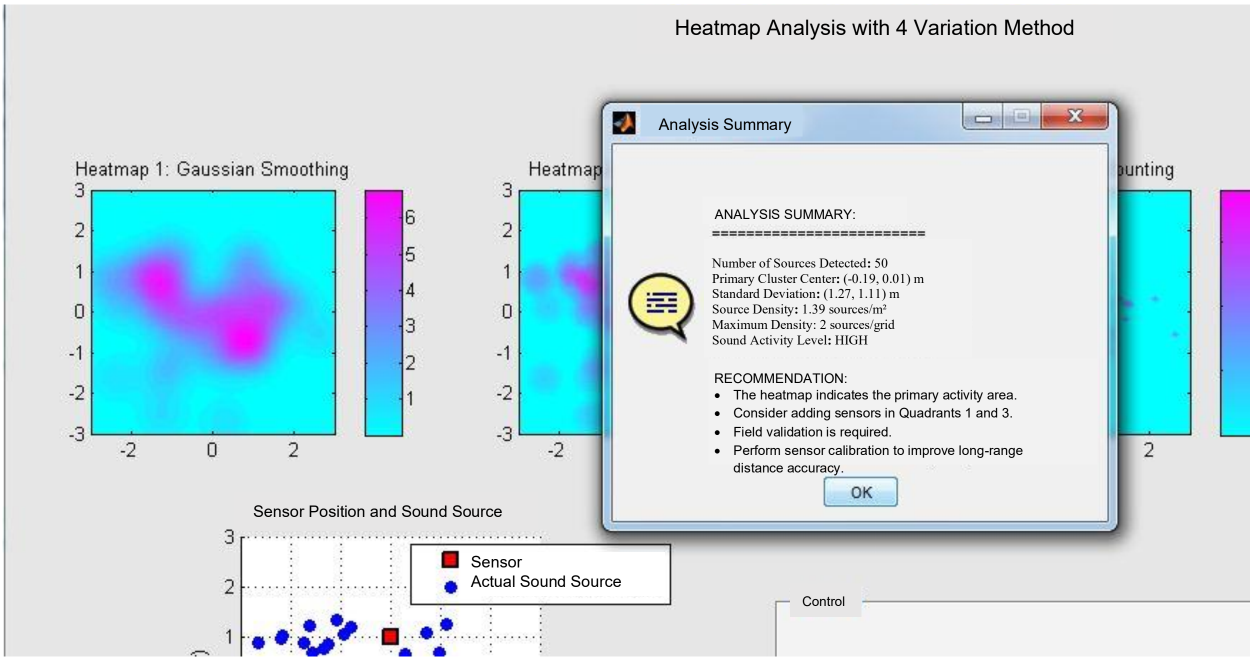

Figure 3. Example statistical summary generated by the system's analysis module, providing key metrics on source count, distribution, and density.

Discussion :

The successful simulation of this system provides a proof-of-concept for a scalable, non-invasive bioacoustic monitoring tool. The core strength lies in translating raw acoustic detections into an intuitive spatial map, moving beyond simple presence/absence data to visualize animal activity hotspots. This is crucial for ecological studies, as the spatial distribution of vocalizations is often more informative than sheer quantity.

The variation between heatmap types is not a drawback but a feature. Different conservation questions require different visualizations: a Gaussian-smoothed heatmap is perfect for identifying general foraging or breeding hotspots, while grid counting is essential for estimating relative abundance in different forest patches. This flexibility allows researchers to tailor the analysis to specific goals, such as monitoring the recovery of vegetation on seismic lines by tracking the return of specific bird species to affected areas.

Implications :

This research has direct implications for conservation technology and practice:

1. Enhanced Habitat Assessment: By mapping vocal activity, conservationists can identify critical habitat zones (e.g., nesting areas, rich foraging grounds) with greater precision than standard point-count surveys allow. This supports targeted conservation actions.
2. Foundation for Machine Learning Integration: The spatial heatmaps generated are ideal training data for AI models. Future systems can learn to automatically correlate specific heatmap patterns with species identities (using call characteristics) or behavioral states (e.g., chorus vs. alarm calls), automating population monitoring.
3. Non-Invasive and Scalable Monitoring: The system's design philosophy aligns with modern conservation technology goals: it is passive, minimizes disturbance, and has the potential for long-term, automated deployment in remote areas.

Research contribution :

This work makes a threefold contribution:

- Methodological Prototype: It provides a working, open-source software prototype (MATLAB GUI) for simulating and validating acoustic localization array designs, lowering the barrier to entry for this technology.

- Interdisciplinary Bridge: It demonstrates a clear pipeline from engineering signal processing (TDOA) to an ecological visualization output (heatmap), fostering collaboration between these fields.
- Data Preparation for AI: By structuring output as spatial heatmaps, the system produces data perfectly suited for subsequent analysis by convolutional neural networks (CNNs), which excel at interpreting spatial patterns.

Limitations :

The current study is a lab-scale simulation and has inherent limitations:

- Simplified Acoustics: The model does not account for real-world signal degradation factors like wind noise, vegetation attenuation, or reverberation, which significantly reduce detection ranges and accuracy in forests.
- Single-Source Assumption: The algorithm processes one source at a time. In reality, dawn choruses involve many overlapping calls, requiring advanced source separation algorithms.
- 2D Limitation: The planar "plus" array estimates only X and Y coordinates. For arboreal species, a true 3D tetrahedral array is needed to calculate elevation (Z), which is critical for understanding forest stratification.
- Absence of Species ID: The prototype localizes sound but does not identify species. In practice, this requires coupling localization with automated call classifiers, a significant challenge in noisy environments.

Suggestions :

To transition from simulation to a field-ready tool, the following steps are critical:

1. Field Validation with Controlled Experiments: Deploy a physical array in a controlled environment (e.g., a botanical garden) with speakers playing calibrated bird calls at known positions. This will quantify real-world accuracy and refine the TDOA models.
2. Incorporate Advanced Signal Processing: Integrate wavelet denoising and band-pass filtering techniques to improve signal-to-noise ratio before localization, which is essential for isolating faint bird calls from ambient noise.
3. Develop a 3D Tetrahedral Array: Construct and test a true 3D microphone array to enable volumetric localization, which is essential for studying forest bird communities.
4. Fuse with Complementary Data: Explore sensor fusion by combining acoustic heatmaps with LiDAR-derived vegetation structure data. This would allow researchers to answer profound questions, such as whether certain bird species prefer to vocalize at specific heights or proximities to canopy gaps.
5. Build an End-to-End AI Pipeline: The ultimate goal is an integrated system where sound is recorded, localized, and identified by species using a hybrid AI model (e.g., CNN for call classification, with spatial data as an additional feature vector), similar to cutting-edge projects in marine bioacoustics.

CONCLUSION

This study successfully developed and validated a prototype for an acoustic localization system, achieving the primary objective stated in the Introduction: to create a foundational, low-cost method for generating spatial heatmaps of avian vocal activity, thereby bridging a technological gap in non-invasive bioacoustic monitoring.

The results confirm that a simplified tetrahedral (cross-shaped) microphone array, coupled with Time Difference of Arrival (TDOA) processing, can effectively estimate the positions of sound sources and translate them into intuitive visual heatmaps. As demonstrated through simulation, the system provides compatible outputs such as cluster centroids, density metrics, and error estimates that directly address the need for quantifiable spatial data in ecology. The discussion establishes that these heatmaps are more than mere visualizations; they are functional data products that can identify activity hotspots and lay the groundwork for automated analysis.

The prospects for this research are substantial. The proven workflow from sensor data to spatial heatmap creates a direct pathway for integration with machine learning models, where patterns can be automatically classified by species or behavior. The next critical phase involves transitioning this lab-validated prototype into a field-ready tool through physical array construction, robust signal processing for noisy environments, and testing in real-world habitats. Ultimately, this work contributes a crucial building block toward intelligent, distributed sensor networks capable of providing continuous, insightful, and multidimensional monitoring of forest biodiversity, supporting more effective and data-driven conservation strategies.

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AUTHOR CONTRIBUTION STATEMENT

The research was conceived and designed by A.F.A., Y.A.F., and S.P. The methodology was developed by A.F.A., N., and M.W., with software implementation and validation performed by A.F.A., J., and A.A. Investigation and data curation were conducted by A.F., M.W., J., and A.A. Formal analysis was executed by A.F.A. and N. The original draft of the manuscript was written by A.F.A. and A.F., with critical review, editing, and visualization contributions from N., M.W., Y.A.F., S.P., and A.A. The project was supervised by Y.A.F. and S.P., who also acquired funding alongside S.P. The entire project was administered by A.F.A. (the corresponding author) and S.P. All authors have reviewed and approved the final manuscript.

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