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Acoustic Modality in Passive Detection Technology

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ABSTRACT

Utilising the acoustic modality for passive detection and localisation of low-flying aircraft and gunshots is vital for border security and situational awareness. This paper presents a comprehensive experimental approach for detecting and estimating the direction of arrival of a single acoustic source using a single vector sensor and two different algorithms: acoustic intensity and velocity covariance. The study includes a thorough comparison of both algorithms for the direction of arrival estimation of a stationary continuous sound source, a hovering drone, and a propeller-driven two-seater manned aircraft flying at low altitudes in various environments. The research findings, which show that both algorithms provide similar estimates for the direction of arrival of the acoustic target in the frequency and time domains, provide a solid foundation for further exploration. Additionally, the results of an array of scalar sensors towards the direction of arrival estimation, using the cross-correlation method at the lab level, are also presented to complement the acoustic vector sensor. A system built around acoustic vectors and scalar sensors can serve as a passive surveillance and target detection system, providing a comprehensive solution for defence and acoustics.

Keywords: Direction of arrival; Acoustic vector sensor; Detection; Localization; cross-correlation

1. INTRODUCTION

During World War I, humans utilised mechanical waves to enhance situational awareness in aerial battlefield settings[1]. However, radar technology advancements displaced mechanical waves in surveillance applications. The emergence of radar-evading low-flying threat platforms such as small fixed-wing manned aircraft, helicopters, and the increasingly prevalent drones of various configurations has contributed to the resurgence of the acoustic. The acoustic signal propagation characteristics of helicopters, propeller aircraft, and Unmanned Aerial Vehicles (UAVs) are significant for two reasons. Firstly, these aircraft can be used for hostile actions on land and sea-based infrastructure because they can fly at low altitudes, making them difficult to detect by air defence radar[2-3]. Secondly, their sound can be used to passively detect and locate them over land[3-7] and sea. Additionally, modern Digital Signal Processing (DSP) hardware and advanced algorithms allow for real-time computations of acoustic measurements[5-6].

Acoustic waves in the air can be captured to extract signal characteristics and gain insights into the source. This passive approach uses acoustic receivers at strategic points to capture sound emissions. It offers a cost-effective solution for applications that include target detection, bearing estimation, localization, classification, and optical sensor cueing. The critical components in acoustics are pressure, particle velocity, and density. Notably, while particle velocity is familiar in acoustics, implementing true particle velocity sensors is a recent development. The Microflown sensor, a key technological advancement, has made it possible to measure the true particle velocity. Particle velocity is a vector quantity and is a crucial aspect of a sound wave, combined with pressure, which is a scalar quantity. Due to the additional information it provides, the Microflown sensor has become popular in noise source detection and localisation in the automotive industry[8]. In recent years, research has significantly increased, focusing on using acoustic methods to detect and locate low-flying aircraft in defence and civil sectors[9-11].

H-E de Bree[4], *et al.* experimentally showed that the spaced pressure probe concept could find a single source's bearing, elevation, and range with advanced processing. The spaced Acoustic Vector Sensor (AVS) concept can find the bearing, elevation, and range of a single source with simple processing and the bearing, elevation, and range of two sources with advanced processing. H-E de Bree[4], *et al.* presented that a single Acoustic Vector Sensor (AVS) can easily give a bearing estimate of a gunshot using the intensity method and that the upper limit to find the location of uncorrelated sources is (4n-2) where n is the number of AVS's. Sutin[12], *et al.* used a cluster of microphones and geophones known as an Acousto Seismic Air Detection (ASAD) system for the detection, bearing estimation, and classification of low-flying targets. Mezei, *et al.* employed two approaches - the audio fingerprints technique and correlation analysis methods - for sound detection of drones[13]. Harvey[14], *et al.* experimentally demonstrated a non-cooperative aircraft collision avoidance system using an

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acoustic sensing system comprising a pair of microphones fixed onboard drones. Blanchard*, et al.* exploited the intrinsic harmonic structure of the sound emitted by the UAV using a pitch detection algorithm and selective bandpass filtering for localization and tracking of multi-rotor UAVs using an array of microphones[15]. Fang*, et al.* proposed and demonstrated the detection of slow-moving UAVs by implementing a biologically inspired vision approach to acoustic detection methods[16]. Grumiaux*, et al.* used neural network-based sound source localization of single and multiple targets in indoor environments[17]. Zhang[18]*, et al.* explored the benefits of combining acoustic characteristics of different aircraft with Automatic Dependent Surveillance-Broadcast (ADS-B) for detecting single and multi-engine aircraft within a range of 5 km to 7.5 km.

The study of the positioning of Acoustic Vector Sensors (AVS) and microphone arrays about Earth's magnetic field is critical in accurately estimating the Direction Of Arrival (DOA) and tracking air targets. Comparing time domain and frequency domain intensity-based algorithms, as well as intensity-based and velocity covariance-based algorithms in the frequency domain using AVS for various air targets in different environments, has yet to be thoroughly explored. A simple and effective method is developed to ensure the precise alignment of AVS with the Earth's magnetic field, leading to consistent and reliable DOA estimation, particularly in identifying the azimuth angle of UAVs/drones.

Through a series of experiments, this research successfully demonstrates the precision and versatility of the measurement techniques in capturing detailed acoustic data from flying sources. A single AVS can detect and estimate the azimuth of a radar-evading low-flying threat platform, sniper, and tank in a battlefield scenario. The sensor can function as an array of wirelessly networked systems for border security and situation awareness. Such a network of acoustic systems can be deployed on naval ships, airships, UAVs, and on the ground, as well as on floating buoys, for early detection of low-flying threat platforms over land and sea in unattended multi-sensor network scenarios. These practical applications highlight the significance of the research in enhancing defence and security operations.

The paper is structured as follows: - Section 2.0 introduces the working principle of the AVS sensor, and subsection 2.1 outlines the existing algorithms from the literature for Direction of Arrival (DOA) estimation. Subsection 2.2: Describes the experiment conducted in the hemi-anechoic room to assess the AVS performance using existing DOA estimation algorithms from the literature in both the frequency and time domains. Section 3.0: Presents acoustic propagation measurements for DOA estimation in the context of a drone and low-flying propeller-driven manned aircraft. - Subsection 3.1: Explores the threshold setting of a flying target. - Subsection 3.2: Briefly discusses the results of an array of acoustic scalar sensors. - Section 4: Concludes the findings of the study.

2. WORKING PRINCIPLE OF AVS AND DOA ESTIMATION

The Microflown sensor is a Micro-Electromechanical System (MEMS) that utilizes two extremely thin heated platinum wires[4,6,8] to generate its output. This innovative sensor is a successful result of research conducted at the University of Twente in the Netherlands and operates based on the principle of a hot wire anemometer. As air flows over the heated wires, sound waves create a temperature difference in the wires[4,8], generating a voltage difference proportional to the airflow (particle velocity) and directional. This sensor is designed to withstand extreme ambient conditions, including high temperatures, dirt, and moisture. It has no moving parts, does not exhibit resonances, and therefore can be reliable.

An in-air Acoustic Vector Sensor (AVS) comprises three particle velocity sensors denoted as 'u', 'v' and 'w' which are mutually placed orthogonal to each other around a microphone. The commercially available AVS includes an outer protective metallic shell similar in size to a half-inch microphone and a separate signal conditioner and power supply module. Compared to the standard version, as presented in the paper, an ultra-small AVS with a small signal conditioner that is compact and lightweight signal conditioner was utilized for DOA estimation. This article provides valuable insights into the application of passive acoustic sensor technology for estimating an acoustic source's Direction Of Arrival (DOA), explicitly focusing on the azimuth angle. It delves into the limitations of small amplitude acoustic waves, known as linear acoustics, in the audible range of 20-20 kHz.

2.1 Algorithm for DOA Estimation

This study implemented two algorithms developed by Nehorai and Paldi[19] to estimate the DOA of a single acoustic source using measurements from a single vector sensor. The first algorithm, acoustic intensity-based measurement, utilizes 4-D acoustic pressure and particle-velocity output. In contrast, the second algorithm, velocity covariance-based measurement, uses only the 3-D acoustic particle-velocity output. The performance of both algorithms was rigorously compared for DOA estimation of a static sound source, drone, and a propeller-driven two-seater manned aircraft in different environments. An alternative to using a vector sensor was discovered by exploring an array of scalar acoustic sensors for DOA estimation at the laboratory level.

The assumptions made for the free-space measurements are as follows[19-20]: (1) Acoustic waves travel in a homogeneous, quiescent, and isotropic fluid; (2) Acoustic waves are considered as plane waves at the sensor, (3) Acoustic perturbations are small fractions of their static values, (4) The spectrum signal is considered to be band-limited. This paper describes two different algorithms, one in subsection 2.1.1 and another in subsection 2.1.2, for estimating the DOA of a single acoustic source using a single vector sensor in free space.

2.1.1 4-D Acoustic Intensity-Based Algorithm

Pressure fluctuation, p and particle velocity, u, the two main parameters of a sound wave, are functions of distance, r, and time, t

$$p = p(r,t) = A \times \cos\omega(t - r / c) \tag{1}$$

$$u = p / (\rho c) \tag{2}$$

where, ρ is the density of air and c is the speed of sound in air.

Instantaneous acoustic intensity, $I(t)$[21] at a distance, r, from the sound source is a function of the instantaneous sound pressure, the area normal to the flow, the distance, and time.

$$I(t) = p(t)dAdr / dtdA \quad (3)$$

The equation of instantaneous intensity in the direction of r can be expressed as follows:

$$I(t) = p(t)u(t) \quad (4)$$

Out of the two components of the instantaneous particle velocity, $u(t)$, the active component, which is in phase with the sound pressure, gives a time-averaged product with the pressure, $p(t)$ called the acoustic intensity, I in the same direction as the particle velocity.

$$I = \frac{1}{T}\int_0^T p(t)u(t)dt \quad (5)$$

Based on the definition of intensity and using AVS output signals, the sound intensity in the x, y and z directions can be determined as I_x, I_y and I_z and. The azimuth angle, ϕ of an acoustic source is determined as:

$$\phi = \tan^{-1}(I_y / I_x) \quad (6)$$

And the elevation angle, θ is determined as

$$\theta = \sin^{-1}(I_z / I_n) \quad (7)$$

where, $(I_n = I_x^2 + I_y^2 + I_z^2)$

When analysing an impulse signal, time domain analysis can be used to evaluate intensity. However, intensity is assessed in the frequency domain for a continuous signal. It involves using the real part of cross-spectral density between pressure and particle velocity to obtain DOA estimation[19] as given in Eqn. (8); $y_p(t)$ and $y_v(t)$ are, respectively, the measured phasor pressure and phasor velocity vector at the sensor.

$$\hat{S} = \frac{1}{N}\sum_{t=1}^{N} \mathrm{Re}\{y_p(t)y_v(t)\} \quad (8)$$

2.1.2 3-D Acoustic Particle Velocity-Based Algorithm

This algorithm estimates the DOA using the measured acoustic particle velocity in three directions and its covariance matrix structure. It computes the covariance matrix[19], $\hat{R}$, as given in Eqn. (9).

$$\hat{R} = \frac{1}{N}\sum_{t=1}^{N} \mathrm{Re}\{y_v(t)y_v^*(t)\} \quad (9)$$

($y_v^*(t)$ is the conjugate transpose of $y_v(t)$)

The azimuth angle is determined from the leading eigenvector of the matrix above, corresponding to the largest eigenvalue. In the frequency domain, it is necessary to evaluate the real part of the cross-spectral density between particle velocities for DOA estimation.

2.2 DOA Estimation in Hemi-Anechoic Room

A meticulously planned experiment was carried out in a hemi-anechoic room to analyze the capabilities of AVS in accurately determining the direction of arrival (DOA) of a stationary sound source within a 360° area of interest in space. The primary goal was to devise a method for positioning the AVS, particularly aligning vector sensors u, v and w with the Earth's magnetic field to consistently and reliably estimate the DOA of an acoustic source. The secondary objective involved comparing the efficacy of intensity and velocity covariance methods in assessing the DOA of a stationary sound source. The schematic view (Fig. 1) illustrates the strategic positioning of AVS, with the particle velocity sensors (u, v, w) aligned along the Earth's magnetic direction. During the experiment, the quadrant system, delineated by the vertical axis North-South (N-S) and horizontal axis East-West (E-W) of AVS, as depicted in Fig. 1, guided the speaker's placement. Starting from the West (W) and moving in a clockwise direction, the first quadrant is the North- West (N-W) quadrant, and lastly, the fourth quadrant is the South-West (S-W) quadrant. The B&K Pulse software and LanXI system created a 1 kHz sine wave signal, played through a speaker to produce a continuous 1 kHz sound. The distance between the speaker and AVS was maintained during the experiment at 1 m. The AVS was fixed on a tripod 0.9 m above the floor. In this experiment, the sensor remained stationary. At the same time, the sound source (the speaker) was placed in four specifically defined locations in a hemi-anechoic room using a magnetic compass to match the quadrant for the given AVS configuration. These locations were in the first quadrant (N-W: 65°) second quadrant (N-E: 110°), third quadrant (S-E: 270°), and fourth quadrant (S-W: 290°). The sine tone signal generated by the speaker in each quadrant was recorded through the AVS. The four voltage signals of AVS, pressure (p), and three particle velocities (u, v, w) were acquired using the PC-based Prosig Data Acquisition (DAQ) system at a 5 kHz sampling rate for 30 s. The offline analysis of signals in MATLAB effectively estimated the DOA of the speaker in the frequency domain using algorithms from subsections 2.1.1 and 2.1.2, Eqn. (8-9). A detailed comparison of the estimated DOA using both algorithms is visually represented in Fig. 2(a), 2(b), 2(c), and 2(d), showcasing a comprehensive time versus azimuth angle plot for each quadrant measurement and a compass plot that reveals the speaker's DOA using the intensity method Eqn. (6) with a time-domain approach. It is worth noting that the azimuth angles align closely and fall within the same quadrant,

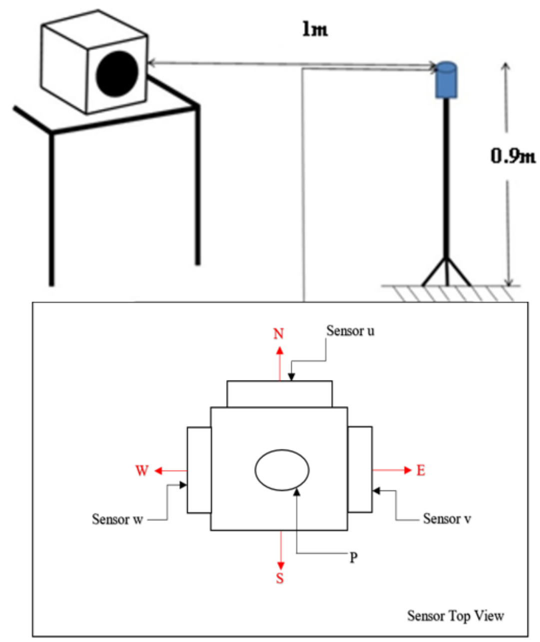
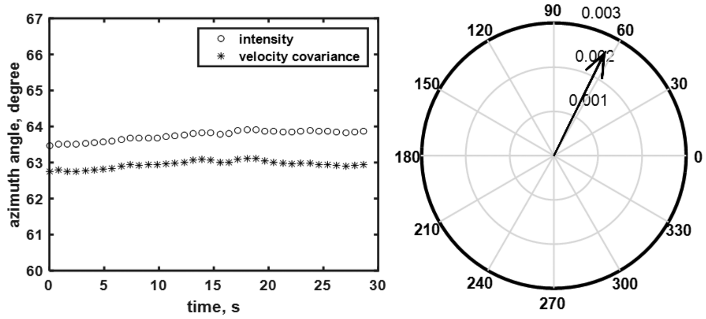


Figure 1. Experimental setup for DOA estimation.



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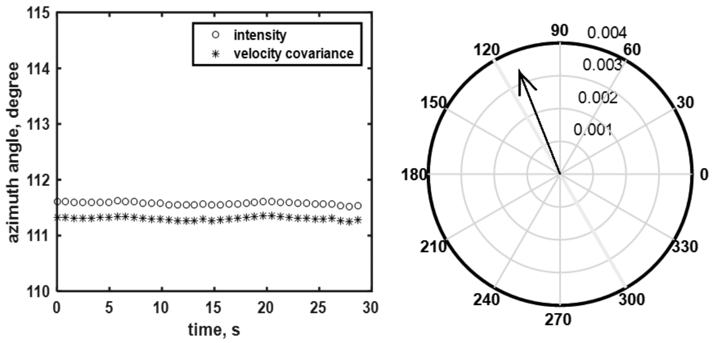

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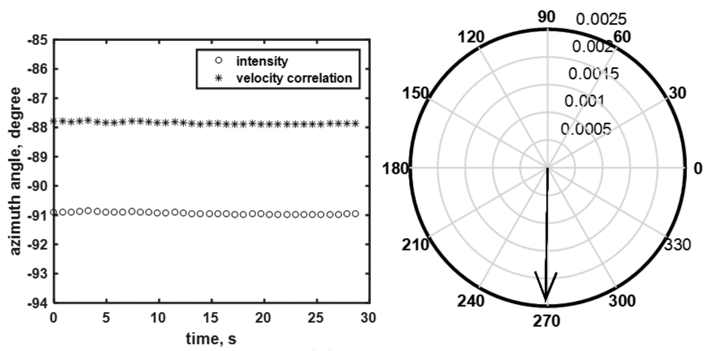

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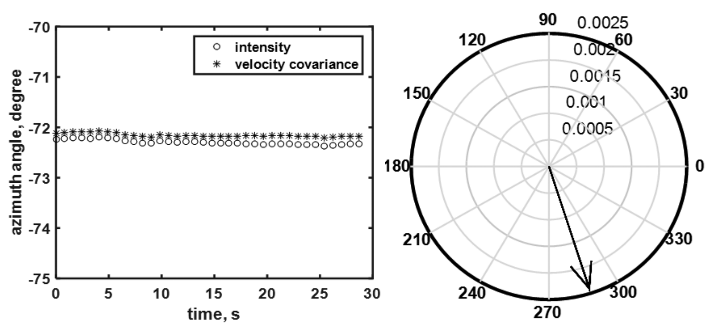


(d)

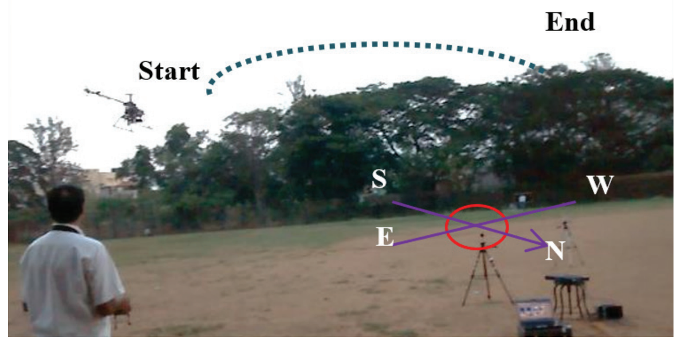
Figure 2. (a) DOA estimation in the first quadrant (N-W); (b) DOA estimation in the second quadrant (N-E); (c) DOA estimation in the third quadrant (S-E); and (d) DOA estimation in the fourth quadrant (S-W)

and validation was verified using a magnetic compass.

This approach efficiently identifies the azimuth angle of the acoustic source within the sensor coordinate quadrant, with the error in the azimuth angle estimation being less than 5 %. Negative values depicted in Fig. 2(c) and Fig. 2(d) must be regarded as 360° + (angle with sign). The time-domain approach offers a faster method for estimating DOA than the frequency-domain approach, with no processing required. It is ideal for analysing impulse signals like a gunshot, especially when dealing with a single frequency and time-invariant signal, as in the lab experiment.

3. DOA ESTIMATION OF FLYING TARGET

The experiments in the previous section confirmed the AVS's ability to estimate the DOA for ground-based acoustic



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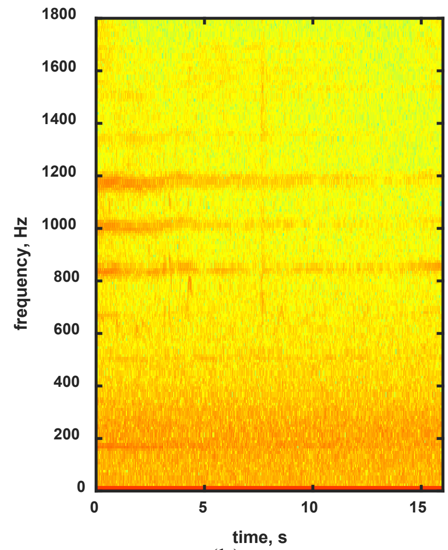

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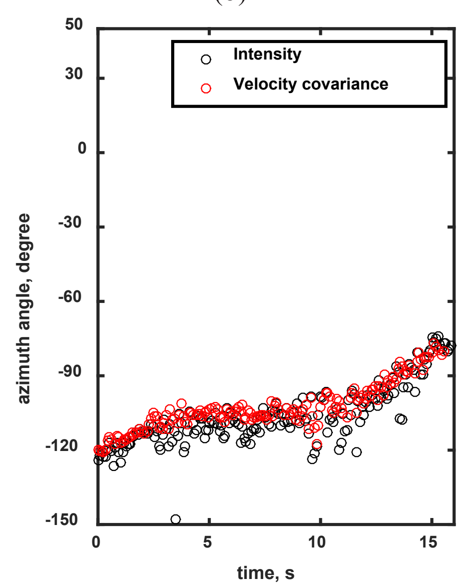


(c)

Figure 3. (a) An AVS with a hovering helicopter; (b) Spectrogram of particle velocity component; and (c) Comparison of DOA estimation method.

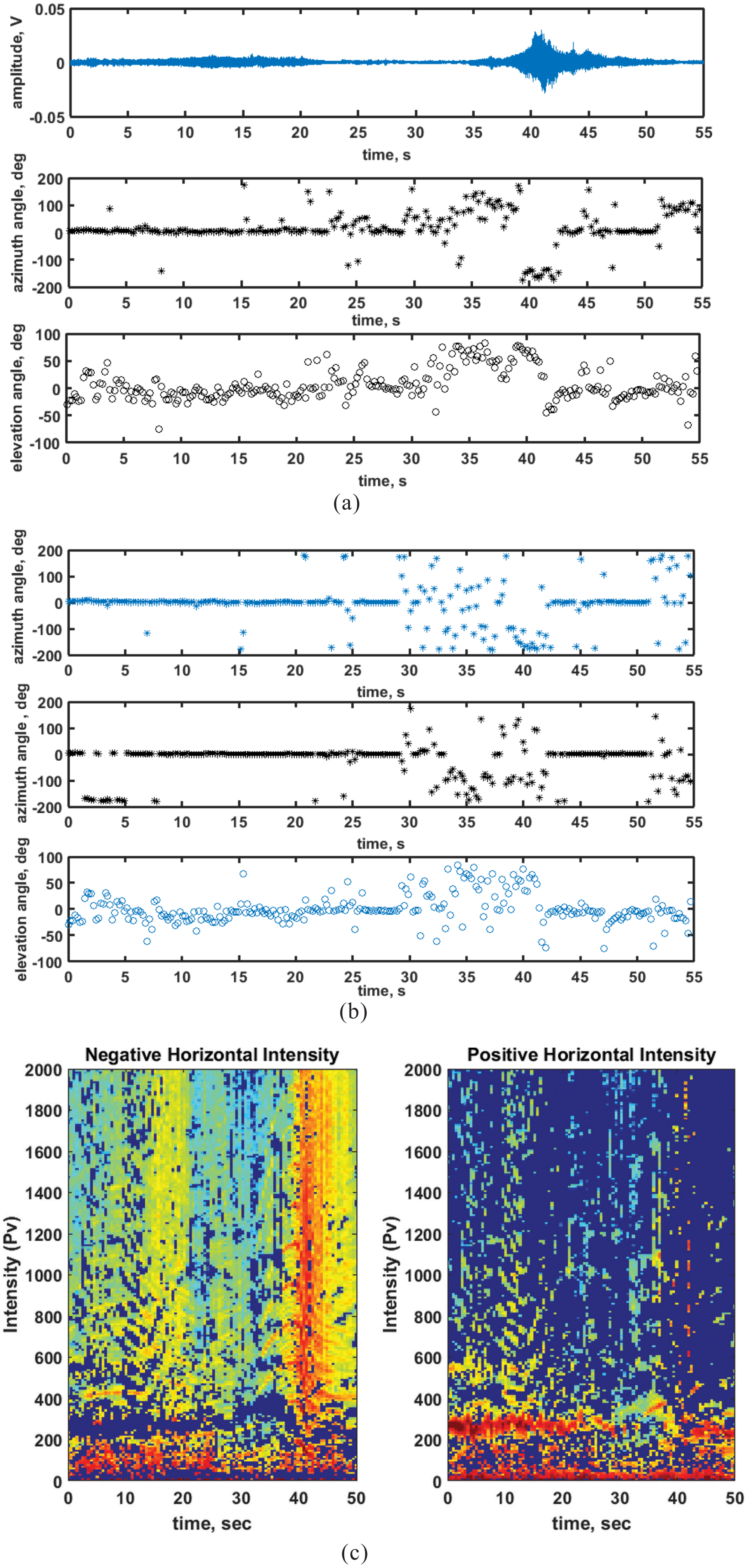
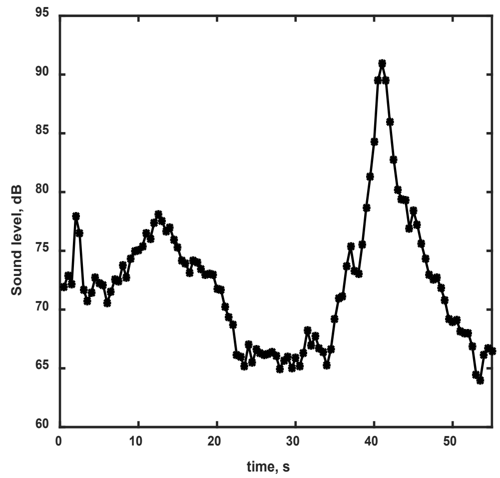


Figure 4. (a) Time domain intensity based azimuth angle and elevation angle; (b) Frequency domain intensity and covariance-based azimuth and elevation angles; and (c) Intensity-based spectrogram.

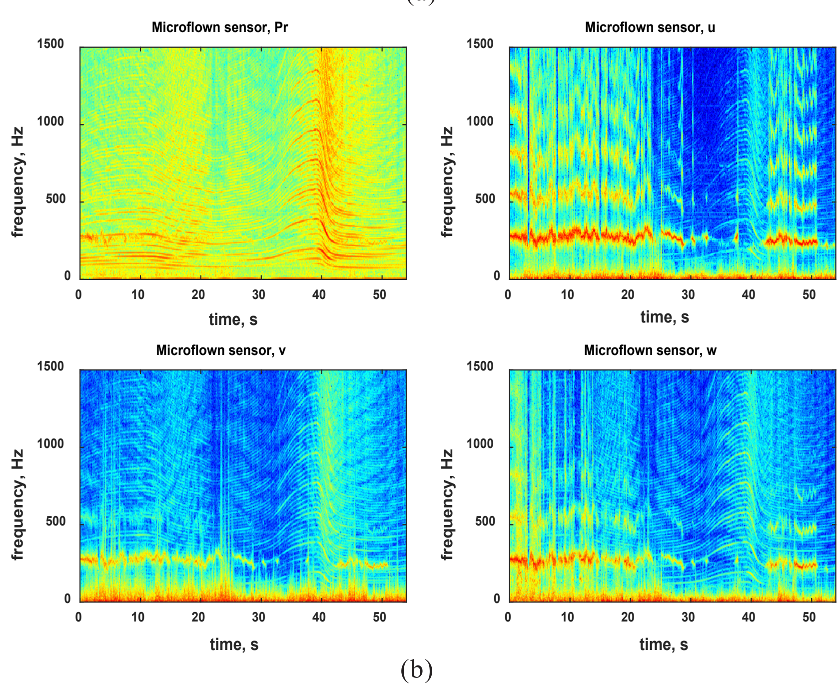
sources. Acoustic propagation measurements of a 10 kg class drone and flight trials of a two-seater propeller aircraft were conducted to advance airborne target DOA estimation further. Acoustic signals from the drone were captured using a Prosig DAQ at a 48 kHz sampling rate with an in-air AVS positioned along Earth's magnetic directions. The drone flew from South-East to South-West, captured in Fig. 3(a). The horizontal particle velocity '*v*' spectrogram in Fig. 3(b) helped identify the drone's propeller blade frequency. Spectral lines within the 1100-1250 Hz frequency range over 0-16 sec were selected for DOA estimation.

Both methods, acoustic intensity and velocity covariance in the frequency domain, show a consistent azimuth angle, as seen in Fig. 3(c). Notably, the drone's movement from the South East (S-E) to the South West (S-W) direction has been verified through the magnetic compass angle and experimental results from the hemi-anechoic room.

It is essential to carefully consider the placement of the AVS and quadrant for accurate DOA estimation, as they differ from the standard coordinate system. In another acoustic measurement, a flight trial was conducted with a two-seater propeller aircraft flying in a circular path over an AVS. The aircraft flew from West to East and back to West at 1000 feet above the ground. The plot of the acoustic pressure, results of the intensity-based azimuth angle, and elevation angle using the time domain approach are depicted in Fig. 4(a). Furthermore, Fig. 4(b) shows the results for intensity-based azimuth angle, velocity covariance-based azimuth angle, and elevation angle using the frequency domain approach. The azimuth angle plot in Fig. 4(a) and Fig. 4(b) shows that the aircraft is approaching the sensor from the West (refer to section 2.2, W: 0° and E: 180°). After taking a turn over the sensor, the aircraft returns to a westward direction. At 40 s, the elevation angle is 90° as the aircraft flies directly above the sensor. The horizontal intensity spectrogram ($I_y = pv$) for the given flight is depicted in Fig. 4(c) with a spectral pattern of negative (left figure) and positive (right figure) intensity of the aircraft signal. The intensity spectrogram directly estimates the time to the closest point of approach, precisely 40 s, with no left-right direction ambiguity[20].



(a)



(b)

Figure 5. (a) Sound pressure level plot.; and (b) Spectrogram plot of microflown pressure, particle velocity signals - u, v, and w.

The occurrence of spectral patterns in the negative horizontal intensity spectrogram indicates approaching aircraft to the sensor from the left side, which in the present experiment is in the West direction. The occurrence of spectral patterns in the positive horizontal intensity spectrogram indicates the aircraft flying away from the sensor to the right side, which in the present experiment is in the East direction. In the negative horizontal intensity spectrogram Fig. 4(c) (left side figure), the spectral patterns are observed before 40 s, indicating that the aircraft approached the sensor from the West. The spectral patterns after 40 s means the aircraft circled back westward. However, in the positive horizontal intensity spectrogram Fig. 4(c) (right side figure), no spectral patterns are observed after 40 s, confirming that the aircraft did not cross over to the East side of the sensor and instead flew back towards the West. The sensor was strategically placed approximately 2.75 m above the ground during the flight trial. The free space model was adopted, eliminating any ground reflections.

3.1 Threshold Setting for Detection of Flying Target

To aid in aircraft detection and avoid false alarms, the plot of Sound Pressure Level (SPL) and time-frequency (spectrogram)[5,22] reveals blade pass frequency and its harmonic patterns[3] typical of any propeller aircraft, indicating the presence of a flying acoustic source. Fig. 5(a) shows a plot of the variation in sound pressure level over time as a propeller aircraft flies over the sensor, with the maximum sound pressure level exceeding 90 dB at 40 s when the aircraft is directly above the sensor, decreasing to 66 dB as the aircraft flies away. In addition, Fig. 5(b) shows the spectrograms of all four acoustic signals. The spectrogram clearly illustrates the spectral pattern of the aircraft up to 55 s. The aircraft can be detected easily up to a distance of 2.75 km from the sensor, considering the speed of the aircraft to be 50 m/s.

Setting the threshold value in Sound Pressure Level (SPL) and analysing the spectral pattern can be an initial step to prevent false alarms and reduce the computational cost of estimating the DOA, leading to reduced power consumption.

An AVS, constructed using DSP hardware and an advanced algorithm equipped with a standalone power supply, can function as an array of wirelessly networked systems for border security and situation awareness. The detection capabilities of an aircraft can be improved through network-based AVS sensors[20]. The communication from this network can be sent to the central server or a patrolling ship to take counteractive action. An acoustic system built around an array of acoustic scalar sensors complements an AVS system toward detection and DOA estimation. Though its footprint is more significant than AVS, it can be economically viable.

3.2 Acoustic Scalar Sensor for DOA Estimation

The microphone is an acoustic sensor that measures only the magnitude of a sound or noise. It has been widely used for research and development in aerospace, automotive, and acoustic engineering[23]. When a pair of microphones is placed at a fixed distance in the same plane, they can determine the direction of a sound source in terms of azimuth angle using a cross-spectrum method[24]. The condenser microphones are precise sensors, and a pair of two microphones can be a more cost-effective solution for single source detection and DOA estimation but may not eliminate an AVS. The experiment involved using a set of four microphones positioned in an equilateral triangle to determine the azimuth angle of an acoustic source[7]. The microphones are spaced approximately 0.18 m apart, with one microphone (mic1) at the center, at a height of 0.33 m, as shown in Fig. 6; mic2 faces East, mic 3 faces North-West, and mic 4 faces South-West. In the counter-clockwise direction from East, the first quadrant is North-East (N-E), and the fourth is South East (S-E).

In the experiment, the speaker was positioned 2 m away from the array in front of two microphones for three separate measurements: between mic2-mic3 in the N-E quadrant, mic3-mic4 in the West, and mic4-mic2 in the S-E quadrant. A standard speaker that produced 1 kHz sine tone was utilized to evaluate the perfor-mance of the acoustic scalar array in estimating the azimuth angle.

Signals from all four microphones were simultaneously acquired for 15 s at a 5 kHz sampling rate using a PC-based Prosig DAQ. Based on the cross-correlation method[7], the analysis is presented in Table 1, showing that the measured azimuth angles are in a similar range with actual values verified by the magnetic compass. The array can estimate the DOA for both continuous and transient signals.

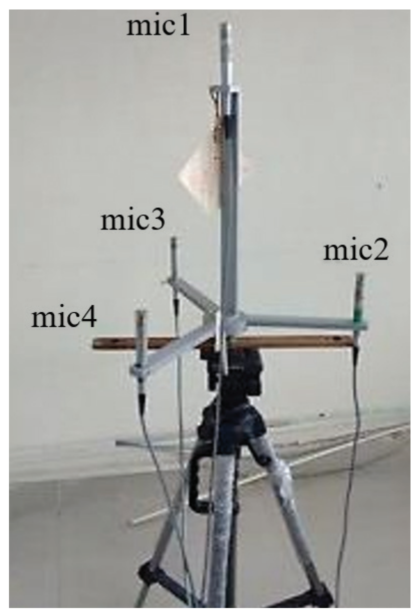


Figure 6. An array of acoustic scalar sensors.

Table 1. Estimated azimuth angle using acoustic scalar sensor array

Position of Source	Measured angle, degrees	Actual angle, degrees
North-East (N-E)	34.21	35
West	149.45	150
South-East (S-E)	-77.63 (282.37)	280

4. CONCLUSION

Experimental studies were conducted using two different algorithms to estimate a single acoustic source's Direction

Of Arrival (DOA). The tests were conducted at the lab level and during aircraft flight trials. It was observed that a single Acoustic Vector Sensor (AVS) can accurately estimate the azimuth angle of both fixed and moving acoustic targets. A system built around it can be a target detection and passive surveillance system. Threshold settings for detecting and analysing the acoustic source's spectral patterns could reduce a standalone system's computational cost and power consumption and prevent false alarms. Additionally, studies on an array of acoustic scalar sensors showed economically viable solutions for passive detection technology to aid in situational awareness. It is recommended that a network of acoustic systems utilizing sensors in the air and underwater can be deployed on naval ships, UAVs, and on the ground, as well as on floating buoys, for early detection of low-flying threat platforms over land and sea in unattended multi-sensor network scenarios.

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