# On-board Acoustic Measurements on Drones: Self-Noise Characterisation and Detection of External Sound Sources

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## Abstract

On-board microphones on drones enable external sound acquisition without the need for ground-based arrays; they can be positioned flexibly and quickly to suit individual requirements and allow for wide-area sound measurements. However, measurement performance is significantly influenced by high self-noise, as well as by flow conditions, microphone arrangement and wind protection. This paper presents a measurement setup featuring a reference acoustic source and several reference microphones on the ground. Various reference signals are used at different measurement distances to validate the measurement capability. Furthermore, the measurement configuration and equipment on the quadcopter are explained, including the mounting of the on-board microphones and the measures taken to protect against flow-induced effects. Finally, the data processing is described, the aim of which is to reduce the influence of self-noise on the acoustic measurement. On this basis, the measurement capability is evaluated across a broad frequency spectrum, taking into account the influence of self-noise. From this analysis, the possibilities and limitations of the applied methodologies are ultimately identified.

**Keywords**: *Drones, Measurements, Acoustics, On-board, UAV*

## 1. Introduction

In recent years, significant progress has been made in the technology, efficiency and versatility of unmanned aerial vehicles (UAVs) and unmanned aerial systems (UAS). In particular, the potential applications of flying drones, which form part of these unmanned systems, have been expanded thanks to improved battery life, more precise navigation systems and advanced sensor technology. These advances have enabled a reduction in drone weight and an extension of flight duration. Based on these optimisations, drones are now used in a wide range of industries, including agriculture, meteorology, film production, parcel delivery and military applications. In these areas of application, imaging sensor technologies are primarily used in drones. However, these are subject to accuracy limitations, for example in poor visibility due to adverse weather conditions, darkness or complex terrain. These limitations of imaging instrumentation necessitate the use of advanced measurement methods. These provide additional data that enhance the accuracy and reliability of flying measurement platforms. A promising measurement method for aerial measurement systems is the detection and processing of sound waves. Studies including [1], [2], [3], [4], as well as recent review papers [5], [6], have shown that acoustic measurements can be used for the detection, identification and localisation of external sound sources.

## 2. State of Art

A recent review paper from 2025 [5] provides a concise overview of the current state of research into sound source localisation (SSL) on UAV platforms, based on 49 systematically selected literature sources. To this end, four research questions are defined: 1. What is the microphone array configuration on the drone? 2. What are the applications developed for SSL? 3. What is the choice of UAV platform used? and 4. Which signal processing solutions were applied? The key conclusion is that, despite significant progress, there remains a substantial need for further research. It has been demonstrated that UAV-based SSL and ambient sound measurements are technically feasible, but Currently, small microphone arrays and classical algorithms dominate, which are rarely executed in real time on the UAV. Significant airflow effects, a lack of realistic datasets and insufficient self-noise suppression significantly limit operational capability. Open questions relate to robust noise suppression, energy-efficient on-board processing, multi-source localisation and machine learning-based approaches. Current work mostly operates under highly simplified conditions and primarily focuses on only a limited subset of the research questions. It therefore allows only very limited conclusions to be drawn about general performance in real-world scenarios. In particular, there is a lack of systematic investigations into the actual measurement capability of the systems. Both measurement

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uncertainties and details regarding repeatability and comparability are inadequately documented. Established reference systems or standardised ground-truth approaches that enable robust validation have so far existed only to a very limited extent and are therefore of limited informative value. To answer these questions, a holistic research approach is required, encompassing not only acoustic measurement technology but also signal processing, energy efficiency and the fluid dynamics of flight boundary conditions. Only in this way can the basis be established for the implementation of a robust flying UAV platform with 'ears'. This is a prerequisite for a flexible acoustic array measurement system involving multiple drones or drone swarms in real time.

## 3. Constraints and Challenges

The advantages of UAVs stem in particular from their high degree of mobility. Drones make it possible to fly quickly into areas that are difficult or dangerous for humans to access, or to scan large areas. Combined with rapid data acquisition and processing, information is captured both in real time and over a specific period. For acoustic measurements, the high flexibility in the instrumentation of various types of microphones and sensors, or the use of microphone arrays, opens up new possibilities for complex measurement and localisation tasks in sound source analysis. Furthermore, the potential for cost savings should be emphasised. Compared to other aircraft, such as conventional helicopters, drones are inexpensive to operate and purchase. Despite this great potential, numerous challenges and research questions remain in real-world applications regarding the practical implementation of sound source detection using drones in free flight. A key cause lies in the significant disparity between fluid dynamic and acoustic pressure scales, as well as the associated length scales. The acoustic signal measured by a microphone on a flying drone is composed of various pressure components (see Fig. 1). Consequently, the measured total pressure fluctuation

$$p'_{Ges} = p'_{Uw} + p'_{Prop} + p'_{Da} + p'_{ext} \quad (1)$$

From the fluid dynamic pressures of the ambient wind $p'_{Uw}$ and the propeller flow $p'_{Prop}$, as well as the acoustic components of the drone acoustics $p'_{Da}$ and the external acoustics $p'_{ext}$. The ambient wind includes the pressure fluctuations of the wind profile and the current flight conditions. For the analysis and localisation of external sound sources, only the external acoustic term is relevant. Due to the mentioned scale disparity and the distance between the drone and the measurement object, this measurement variable ($p'_{ext}$) often has the lowest value and must be filtered out from the other signal components through appropriate signal processing or measurement configuration. This remains a key unresolved challenge to date.

The following criteria are important for use in free-flight conditions:

- Flight state
- Drone noise
- Flight stability
- Robustness in free-flight conditions
- Weather conditions
- Energy efficiency

This gives rise to requirements for:

- Sensor selection
- Sensor position
- Sensor arrangement
- Signal processing
- Data storage

The development of sensors, sensor protection and signal processing are closely linked.

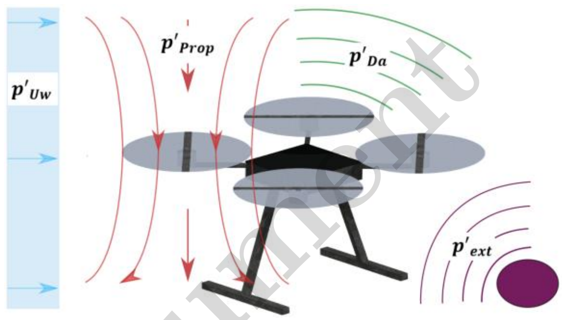


**Figure 1**. Acoustic and fluid dynamic pressure fluctuations around a drone.

## 4. Setup of the Measurement Platform

At the LSTM, a series of modular multicopters was developed, specifically adapted to the requirements of acoustic investigations. An example of the UAV platform used is shown in Fig. 2. The developed UAV platform is equipped with a powerful on-board computer and a data acquisition system, enabling the reading of all telemetry data and the performance parameters of the individual motors. Furthermore, the system allows flexible communication with the ground station via various protocols (2.4 GHz, Wi-Fi, 5G) and can perform fully autonomous flights using RTK-GNSS. The drones have a minimum take-off weight of around 2 kg and, depending on the configuration, can weigh up to 5.5 kg. The maximum flight time is approximately 50 minutes.

**Figure 2**. Modular quadcopter with on-board noise measurement.

## 5. Self-Noise of the Drone

As already described, a particular challenge in on-board acoustic measurements arises not only from the inherent noise of the drone propellers but also from the aerodynamic effects on the microphones. At higher flight speeds, the fluid dynamic pressure fluctuations lead to distortions in the acoustic microphone measurements. To better characterise this problem, flow investigations were carried out in the wind tunnel shown in Fig. 3 using stereo PIV to characterise the local flow velocities during various flight manoeuvres. Fig. 4 shows, as a representative example, the velocity conditions for horizontal flight at 10 m/s. A wide boundary layer with very low velocities can be observed near the drone body. At 100 mm, the velocity rises sharply to over 11 m/s, and near the drone, the flow direction deviates significantly from this. From 100 mm onwards, the flow consistently follows the drone's trajectory. The velocities then gradually decrease with increasing distance. At a distance of 400 mm, the flow stabilises at the ambient velocity of 10 m/s.

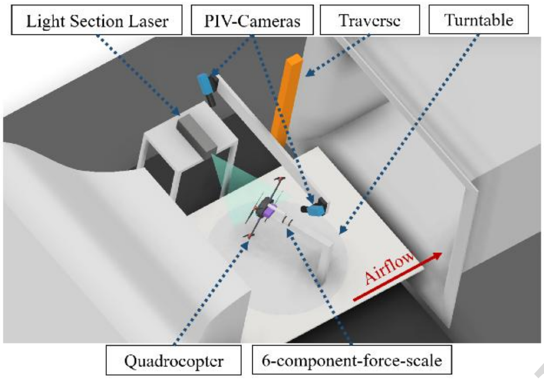


**Figure 3**. Stereo PIV setup in the LSTM wind tunnel.

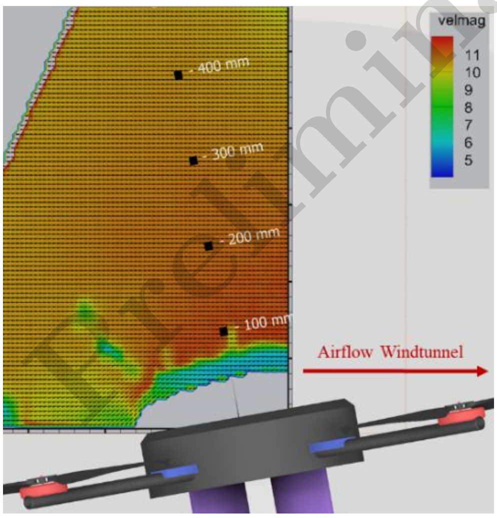


**Figure 4**. Flow characterisation at a horizontal flight speed of 10 m/s.

Based on these results, various wind screens were developed and tested to minimise the impact of aerodynamic flow on the microphones. Extensive measurements of the different variants reveal significant differences in their shielding performance and demonstrate the considerable impact of flow-induced pressure fluctuations on acoustic measurements when wind screen designs are insufficiently effective.

The results of the optimised windscreen variants (Fig. 5) demonstrate that multi-layer windscreen designs, in particular, are highly effective. Multi-layer variants comprising an inner foam or mesh structure, a textile intermediate layer and an outer fur layer proved to be particularly suitable. This configuration enables effective shielding of the microphones against aerodynamic disturbances and thus represents a key factor in the successful execution of acoustic measurements on flying drones. On this basis, further analyses of different variants and material combinations were carried out in order to specifically maximise metrological performance.

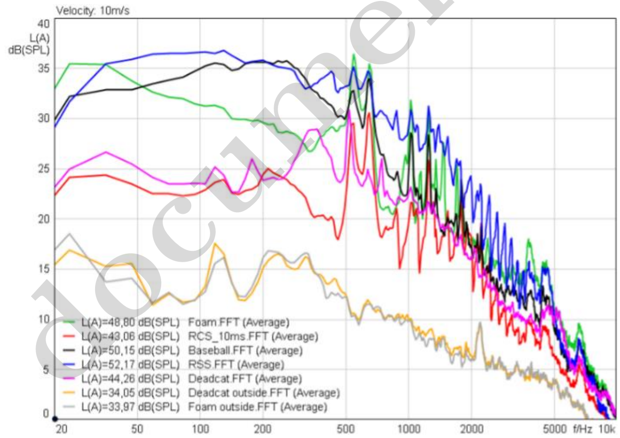


**Figure 5**. Tests in the aeroacoustic wind tunnel of optimised windscreen variants.

The modular UAV platform and the validated measures for reducing aerodynamic disturbances thus provide key tools for successfully carrying out on-board acoustic measurements under real flight conditions [8]. Fig. 7 shows the spectral power density of the inherent acoustic noise of a quadcopter in level flight at 10 m/s. It compares a flight without a payload with a flight carrying a 2 kg payload. A characteristic feature is the pronounced tonal components in the range of the blade rotation frequency and its harmonics. The spectrum shows that both operating conditions behave similarly in their basic structure; however, during flight with a payload, slightly elevated levels occur across wide frequency ranges. At the same time, the acoustic signal is very clearly discernible overall. This illustrates the effectiveness of the optimised wind protection system, as a meaningful spectral analysis is possible even under flight conditions.

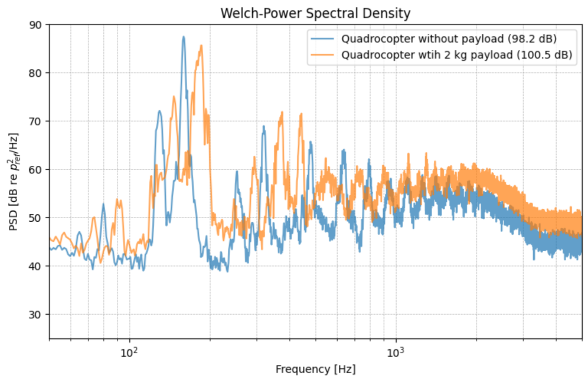


**Figure 6**. On-board acoustic measurement during level flight at 10 m/s for self-noise detection using an optimised windscreen system.

## 5. External Acoustic Measurements

After the characterisation of the drone self-noise, the measurement setup was extended to investigate the detection of external acoustic signals during flight. The aim of these measurements was to evaluate whether a defined external sound source can be detected by the on-board microphone system, although the UAV itself generates strong acoustic and aerodynamic disturbances.
For this purpose, the existing UAV platform was equipped with an extended multi-microphone configuration. In addition to the microphones used for the self-noise investigations, further sensors were integrated into the platform. Two lightweight measurement microphones were mounted above the quadcopter. Below the platform, a spherical microphone array and two directional microphones were installed. This configuration was chosen to compare different microphone types and sensor positions with respect to their suitability for external acoustic measurements during flight.
The acoustic signals were recorded by the on-board computer, which was carried by the UAV during operation. The system allowed remote control and monitoring of the measurement process during flight. This ensured that the acoustic signals and the relevant system data could be recorded synchronously.
A reference loudspeaker was placed on the ground as an external acoustic source. A dodecahedron loudspeaker was used because of its approximately omnidirectional radiation characteristic. Different test signals were emitted, including white noise, pink noise and sinusoidal sweeps. In this way, a defined and reproducible external acoustic signal was generated. Additional reference microphones were placed on the ground to provide a comparison with the UAV-based measurements. The measurement setup with the integrated microphone configuration and the reference loudspeaker is shown in Figure 7.

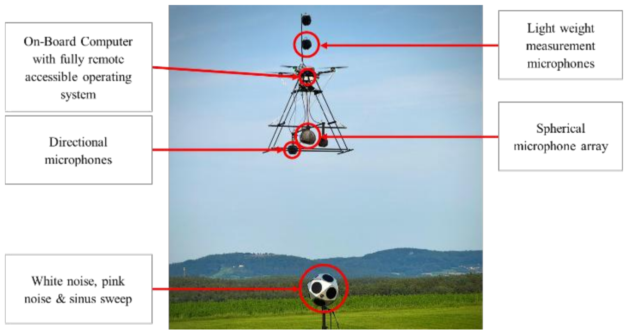


**Figure 7.** Measurement setup with integrated microphone configuration and reference loudspeaker.

The integration of the additional sensors also required changes to the flight configuration. The added structures and microphones changed the mass distribution and the moments of inertia of the UAV. Therefore, the flight controller parameters had to be adapted in order to ensure stable and repeatable flight conditions. This aspect shows that the integration of acoustic sensors on UAVs is not only a measurement task, but also affects the flight mechanical behaviour of the complete system.

Several measurement positions with different distances and angles between the UAV and the reference loudspeaker were investigated. As an exemplary case, the UAV was positioned at a height of 10 m above the reference loudspeaker. In addition, a reference microphone was placed on the ground at a horizontal distance of 10 m from the sound source. Although the two measurement positions are not identical with respect to propagation path and possible ground effects, the use of an approximately omnidirectional loudspeaker allows a first comparison between the on-board measurement and the ground-based reference.

The measurement campaign covered external acoustic signals in a frequency range from approximately 70 Hz to 1300 Hz. In the present paper, the evaluation is shown exemplarily for the low-frequency range between 70 Hz and 200 Hz. This frequency range is of particular interest because atmospheric attenuation is lower than at high frequencies. In addition, the tonal components of the UAV self-noise are less dense in this range than in higher frequency bands. In this context, it should be noted that sound propagation in the atmosphere occurs below a few kHz. According to [7], this frequency range is relevant for sound propagation in the Earth's atmospheric boundary layer. Higher frequencies are also very strongly attenuated by turbulence, the thermal stratification of the wind profile and the ground structure.


**Figure 8.** Spectral evaluation of the UAV-based external acoustic measurement. The upper plot compares the UAV self-noise, the combined signal of external source and UAV noise, and the ground-based reference. The lower plots show the estimated external signal after UAV-noise reduction and additional filtering.



The corresponding spectral evaluation for external acoustic measurements is shown in Figure 8.
First, the self-noise of the UAV is evaluated without the external source. Second, the combined signal of UAV self-noise and external sound is analysed. Third, the external sound contribution is estimated by applying spectral subtraction and further filtering steps.

The results show that the external acoustic signal can be detected by the UAV-based measurement system. A simple spectral subtraction already improves the visibility of the external signal. However, the UAV self-noise cannot be removed completely. Remaining spectral components are still visible, especially close to the blade-passing frequency and its harmonics. These tonal components represent one of the main limitations of the method, because they can mask the external acoustic signal.
The detectability of the external signal was further improved by additional signal processing. In particular, a combination of Wiener filtering and fractional-octave-band filtering reduced remaining disturbances and led to a clearer representation of the external sound component.

This demonstrates that the measurement capability depends not only on the microphone configuration and wind protection, but also strongly on the applied signal processing.
At higher frequencies, the separation of the external sound from the UAV self-noise becomes more difficult. This is mainly caused by the increasing density of tonal and broadband components of the propeller noise. Nevertheless, the measurements show that external acoustic signals can in principle still be detected. For a robust evaluation in higher frequency ranges, however, more advanced signal separation methods are required.
The results also indicate that the developed wind protection and mechanical decoupling concepts are effective for the present measurement configuration. Flow-induced pressure fluctuations did not dominate the measurement signal in the investigated case. In addition, no strong vibration-related disturbances were observed in the evaluated spectra. This confirms that the combination of adapted microphone placement, multi-layer wind protection and mechanical decoupling provides a suitable basis for UAV-based external acoustic measurements.

## 6. Summary

A measurement drone for recording external noise is presented. The acoustic and fluid dynamic boundary conditions are discussed. It becomes apparent that the external noise has the smallest pressure component compared to the pressure fluctuations caused by the propeller and the wind profile. Consequently, special measures are required in terms of sensor technology and sensor design to enable the successful recording of external noise. In addition to sensor technology, these measures encompass sensor positioning on the drone and sensor robustness under free-flight conditions. To this end, extensive investigations were carried out in the wind tunnel and under free-flight conditions. The result is a measurement setup that minimises fluid dynamic pressure fluctuations at the microphones and reduces the drone's inherent noise. The drone's inherent noise was recorded during free flight for this purpose. Optimisations were carried out to reduce these noise components. In addition to the self-noise analysis, first external acoustic measurements were carried out using a defined reference source on the ground. The results show that external acoustic signals can be detected during flight. In the low-frequency range, the external signal can be separated clearly from the UAV noise using spectral subtraction and additional filtering. The measurements also confirm that the developed wind protection and mechanical decoupling concepts are effective under real flight conditions.

Further developments lie in adapted signal processing and in the application of the measurement technology to multiple drones or drone swarms.

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