DEPLOYMENT AND VERIFICATION OF A LARGE MICROPHONE ARRAY FOR UAV FLYBY TESTS

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Abstract

Comprehensive characterization of drone noise emissions during realistic operation remains an ongoing challenge. Microphone arrays offer a promising approach, but they require accurately known sensor positions, which are difficult to realize for large-aperture arrays assembled ad hoc under outdoor conditions. This contribution presents the deployment and a-posteriori verification of a 63-microphone outdoor array with a nominal aperture of approximately 35 m for multicopter flyby measurements. The setup is designed as a compromise between geometric suitability for beamforming and emission mapping, on the one hand, and practical constraints such as transport, rapid installation, and limited personnel, on the other. Geometry verification is performed by comparing RTK-GPS reference positions with a TDOA-based optimization of microphone coordinates from the recorded acoustic data. The resulting reconstruction is sufficiently accurate for assessing deployment quality and for emission mapping. The results also show that the remaining positioning uncertainty can still limit phase-sensitive beamforming, especially at higher frequencies, where small coordinate errors may broaden or shift reconstructed maxima. Nevertheless, it is shown that in this setup, time-domain beamforming with moving focus can be used to align the independently recorded acoustic signals with the drone telemetry data.

1 INTRODUCTION

Small unmanned aerial vehicles (UAVs, drones) are expected to become increasingly relevant in applications such as inspection, logistics, surveillance, and infrastructure monitoring [7]. With broader deployment, their acoustic impact on the public becomes a practical issue, which in turn requires measurement methods that characterize noise emissions under representative operating conditions. Flyby measurements with microphone arrays are attractive in this context because they allow a comprehensive recording of the noise emission characteristics of the vehicle [3].

For such measurements, however, the quality of the results depends strongly on the known array geometry. This is particularly critical and challenging for large outdoor arrays, where sensors are distributed over tens of meters and installed under field conditions rather than in a permanent laboratory setup [1, 5].

The present contribution focuses on the planning, deployment, and verification of a microphone array used in a joint measurement campaign for drone noise mapping conducted by the Technische Universität Berlin Department of Engineering Acoustics (TUB) and the Friedrich-Alexander-Universität Erlangen-Nürnberg Institute of Fluid Mechanics (FAU) [4]. The main objectives are to document considerations for a practical large-array setup, synchronize the independently recorded data streams, and assess how accurately the deployed geometry can be reconstructed after installation.

2 PLANNING AND DEPLOYMENT

The array geometry design is intended for outdoor multicopter flyby measurements in which both source localization and emission mapping are required. This imposes several partly conflicting requirements: broad angular coverage [6], sufficiently large aperture, practical transportability, fast setup by a small team, and reliable knowledge of the final sensor coordinates. A microphone arrangement optimized for source detection purposes may be preferable from a purely beamforming perspective [8], but it is cumbersome to realize in the field. Instead, the chosen geometry and hardware was designed to be easy to transport and set up without specialist equipment.

The final TUB array setup consists of 41 ground-based microphones on acrylic plates and two 25 m fiberglass telescopic masts carrying 11 microphones each (see Fig. 1). A symmetric 8-spoke layout with a diameter of 35 m was selected for the ground microphones, since it provides a good compromise between usefulness and simplicity. Setup aids were prepared in advance, including marked mast positions, predefined spacing information for the ground microphones, and simple construction references for repeated distances. This reduces the risk of gross placement errors and shortens assembly time. In addition, redundant geometric information was intentionally included, for example through known distances between selected microphones, so that the installation could be checked directly on site.

The investigated drone platform was developed at FAU and is a research quadcopter with four rotors, up to 5 kg maximum take-off weight, 15-inch propellers, and typical measurement speeds between 10 and 20 m/s. All flight parameters are freely configurable, enabling autonomous maneuvers with high repeatability. During the campaign, an onboard computer continuously logs the trajectory via RTK-GPS, as well as operating data such as power consumption and individual rotor speeds.

It shall be noted that the independently developed array and drone data acquisition systems do not share a common data stream for synchronization. As will be shown in Section 3, telemetry recordings make it possible to match the acoustic data to the corresponding flight condition.

Table 1 summarizes the main setup information in condensed form.

Figure 1: From upper left: in-progress setup of the array, with the transport vehicle for the measurement hardware and accommodation for three people (TUB). Ground plate with one inverted 1/4" microphone. Measured quadcopter (custom-built, FAU). Aerial view of the finished array setup.

Table 1: Relevant array and drone parameters.

TUB array	
microphone type	1/4" GRAS 40 PK
ground microphones	41
mast microphones	2×11
sampling rate	102.4 kHz
array diameter, height	35 m, 25 m

FAU drone	
rotors	4
blades per rotor	2
propeller diameter	38 cm
rotor axis spacing	49 cm
weight	≈ 3 kg

3 VERIFICATION

The deployed geometry was verified both by external position references and acoustic self-calibration.

3.1 Microphone positions

Ground microphones via RTK-GPS

In the campaign, the drone position and further flight parameters were recorded with high precision using onboard instrumentation and RTK-GPS, while the microphone signals were acquired separately. This creates two practical challenges: the array geometry must be established in a common spatial frame, and the telemetry and acoustic data streams must be synchronized in time.

For a first geometric check and alignment of the array and drone coordinates, the RTK-GPS information is used to obtain absolute coordinates for selected microphones by positioning the sensor at the ground microphone locations. Such measurements provide a useful estimate of placement accuracy and reveal potential large deviations from the intended geometry.

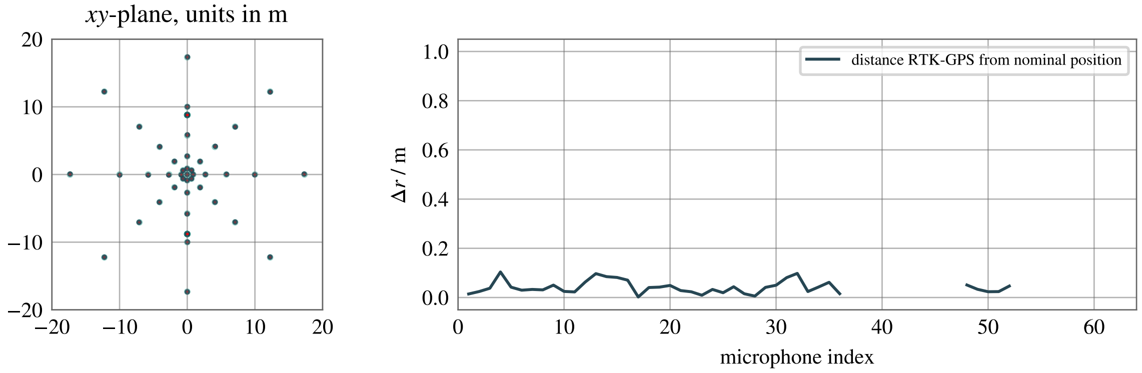

Figure 2: Aligned nominal and RTK-GPS-measured microphone positions in the xy plane (left), and per-channel position errors (right9.

Determining RTK-based positions is only feasible for ground-based microphones, and it does not guarantee that the microphones are connected correctly. Additionally, this verification procedure is time-consuming. As a possible alternative, an acoustic geometry verification based on impulsive sources is investigated in the following.

Clapping for microphone positions

Several approaches for positional self-calibration of ad-hoc arrays can be found in the literature [2, 11–14]. The method used here is based on hand-clap measurements recorded while walking through the array and does not require exact prior knowledge of source or receiver positions, nor of the emission times. Around 200 claps were recorded. For each clap s and microphone channel m, the peak is detected and the corresponding sample is stored as time instant t_{ms}. Roughly 30 detected clap events were discarded because they yielded nonphysical values for the present setup. The remaining events were used to formulate a constrained optimization problem.

Let $\mathbf{x}_m \in \mathbb{R}^3$ denote the unknown microphone positions and $\mathbf{y}_s \in \mathbb{R}^3$ the unknown positions of the impulse source events. For a reference microphone at $\mathbf{x}_0$ (which also does not have to be known), the measured time-difference of arrival (TDOA) values $\tau_{ms} = t_{ms} - t_{0s}$ are modeled by

$$e_{ms} = (\|\mathbf{x}_m - \mathbf{y}_s\|_2 - \|\mathbf{x}_0 - \mathbf{y}_s\|_2) - c_0\, \tau_{ms}, \tag{1}$$

where c_0 is the speed of sound computed from the measured temperature and humidity. The geometry is estimated by minimizing

$$\min_{\{\mathbf{x}_m\},\{\mathbf{y}_s\}} \frac{1}{2} \sum_{(m,s)\in\Omega} e_{ms}^2, \tag{2}$$

over the valid observation set Ω.

Since the problem is invariant under global rigid-body motions, a gauge is fixed by anchoring three microphones: one fully fixed, one with two fixed coordinates, and one with one fixed coordinate. These three microphones can be chosen arbitrarily, but they must not be collinear and should define a plane. The remaining coordinates are optimized with coordinate bounds to keep the solution in a plausible region and to improve convergence.

The optimization is performed in several stages using the trust-region reflective algorithm implemented in `scipy.optimize.least_squares`. A coarse initial fit is followed by outlier rejection based on the residuals. The cleaned data set is then refit with tighter bounds. This staged procedure is useful because the 3D problem can become ill-conditioned when the microphones and sources do not span the volume sufficiently well, for example when most events lie close to a plane. In such cases, the vertical coordinate is only weakly constrained, so successive constrained refinements improve both robustness and numerical stability. The resulting optimized geometry and reconstructed clapping positions are shown in Fig. 3.

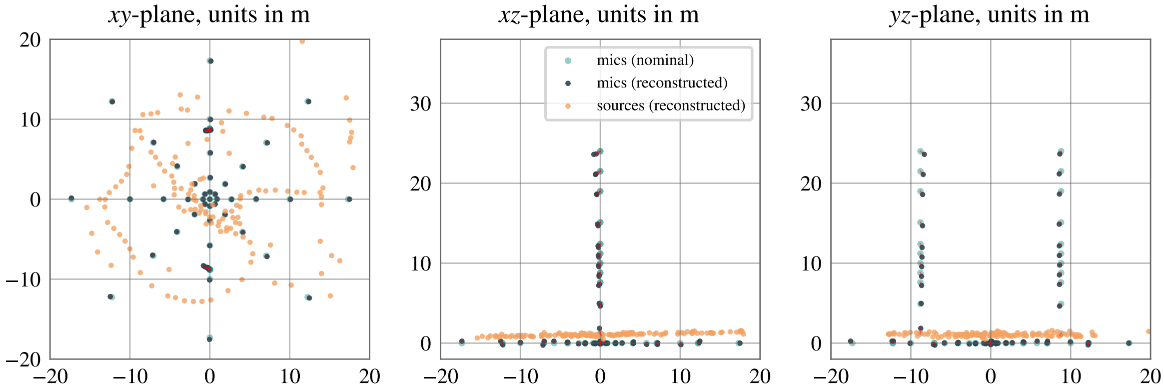

Figure 3: Microphone and clap positions from TDOA-based geometry optimization.

Figure 4 shows the deviations of the reconstructed to the nominal positions. For the ground microphones, the offsets remain moderate, staying below 0.3 m, although they are larger than those obtained with RTK-GPS (see Fig. 2). For the mast microphones, the deviation increases

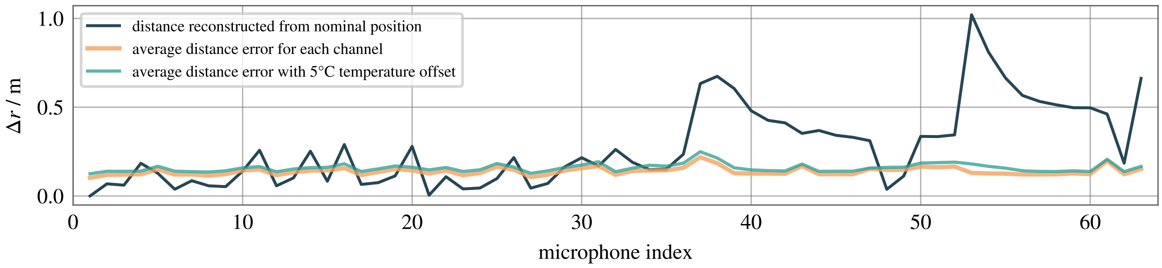

Figure 4: Distances of reconstructed to nominal microphone position (channels 38-48 and 54-64 are mounted on the masts), together with the average relative distance error based on the measured TDOA and reconstructed geometry (a 5 °C temperature offset in the assumed speed of sound would would not significantly affect this metric).

with height. This is plausible, since setting up the mast perfectly perpendicular to the ground array is difficult, and the optimization also becomes less well constrained the farther a microphone lies from the "clapping plane". In practice, the optimization-based reconstruction therefore serves mainly as a verification tool: it confirms that the deployed geometry is plausible, quantifies deviations from nominal positions, and flags suspicious sensors or local setup errors. For emission mapping, this accuracy is generally sufficient because back-propagation and averaging tolerate moderate residual position errors. For high-frequency beamforming, however, the requirements are stricter, since even small coordinate errors introduce phase mismatches that broaden or shift source maxima. The reconstructed geometry is therefore suitable for setup verification and emission reconstruction, but not necessarily ideal for precision beamforming.

3.2 Array & drone data stream time synchronization

Direct telemetry and acoustic alignment

A coarse time alignment can be obtained by comparing rotor-speed information with tonal structures in the acoustic spectrogram (see Fig. 5). It has to be kept in mind, however, that for a precise alignment, the sound travel time from the drone to the microphone channel providing the data for the spectrogram needs to be taken into account and, depending on the performed maneuvers, may change over time.

Moving-focus beamforming for synchronization

A finer adjustment can be achieved via time-domain beamforming with moving focus, using the RTK-GPS track of the drone as trajectory. This is done here with the help of the open-source tool Acoular [9, 10]. To this end, multiple flybys with different speeds and opposite flight directions (see Fig. 6) are evaluated for different time offsets between the acoustic and telemetry recordings in Figure 7. The third-octave band around 250 Hz is used because it is relatively robust against small microphone-position errors and, at higher frequencies, the drone exhibits multiple sources whose relative strength may differ between flight directions.

A time shift of the RTK stream relative to the array data produces a corresponding shift of the beamformed drone position in x-direction between opposing flights. Besides time alignment,

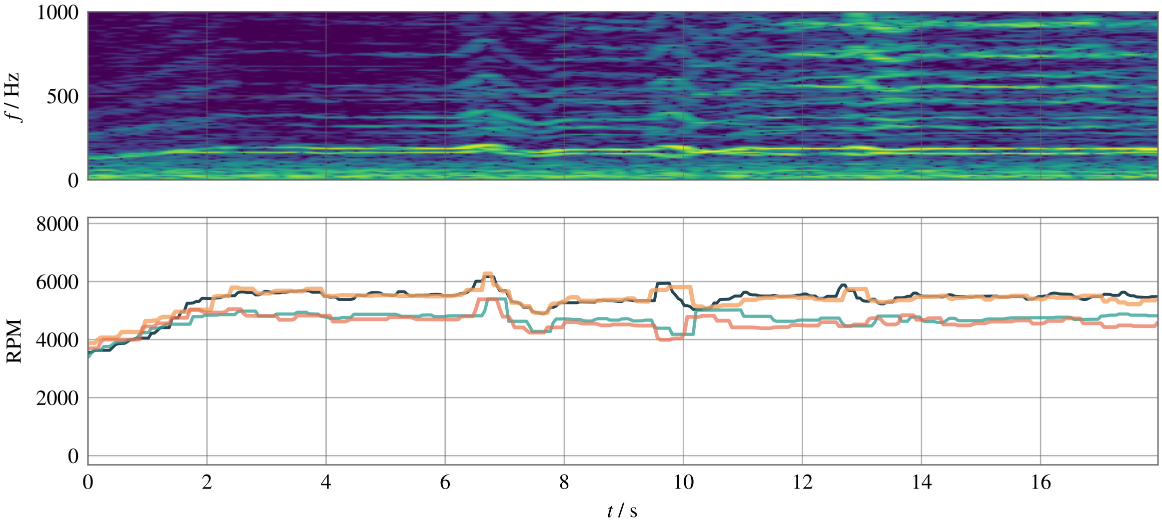

Figure 5: Initial synchronization of the spectrogram with the array-recording and the RPM data of the drone's four rotors: greater maneuver variability makes alignment easier.

this step also allows remaining offsets between the array and drone coordinate systems to be checked and corrected.

4 CONCLUSION

The present work shows that large-scale outdoor microphone arrays for UAV flyby measurements can be deployed in a way that balances acoustic performance with practical field constraints. The chosen setup emphasizes transportability, rapid assembly, and on-site verifiability while still providing the aperture and angular coverage required for emission studies.

Geometry verification was carried out using both RTK-GPS reference measurements and TDOA-based optimization in post-processing. The results indicate that the deployed array can be reconstructed with sufficient accuracy for emission mapping and trajectory-related processing, and that the optimization-based calibration is well suited for assessing deployment quality, including the elevated sensors.

At the same time, the remaining uncertainty remains relevant for phase-sensitive beamforming, especially at higher frequencies, where even small coordinate errors can broaden or shift reconstructed maxima.

The synchronization study further shows that time-domain beamforming with moving focus is a practical way to align the acoustic and RTK-GPS data streams, particularly when evaluated in a robust low-frequency band. Together, geometry verification and time alignment provide a sound basis for reliable flyby measurements and subsequent emission characterization.

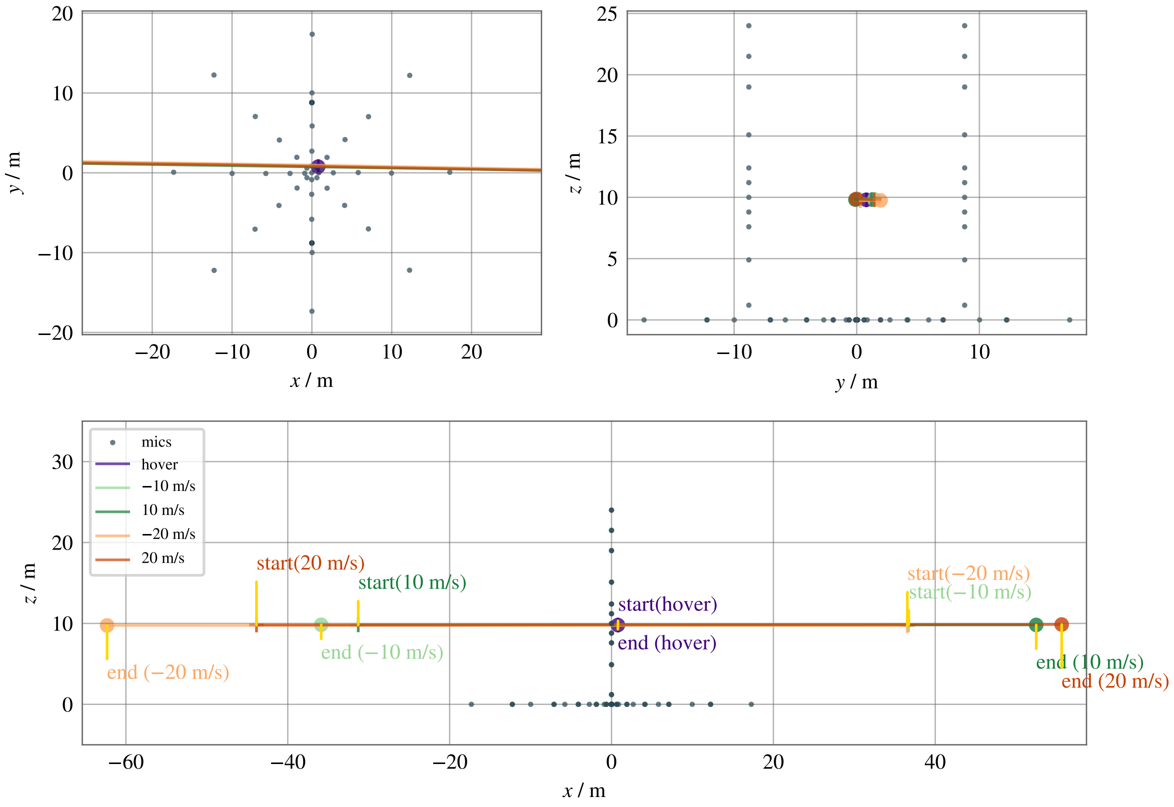

Figure 6: Different views of selected RTK-GPS-logged flight paths.

Acknowledgements

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), project number 422372636. The funding supported the data analysis and manuscript preparation; the data used in this study were collected in prior work. The authors gratefully acknowledge the members of the TU Berlin Department of Engineering Acoustics and the FAU Erlangen-Nürnberg Institute of Fluid Mechanics for their support during the joint measurement campaign.

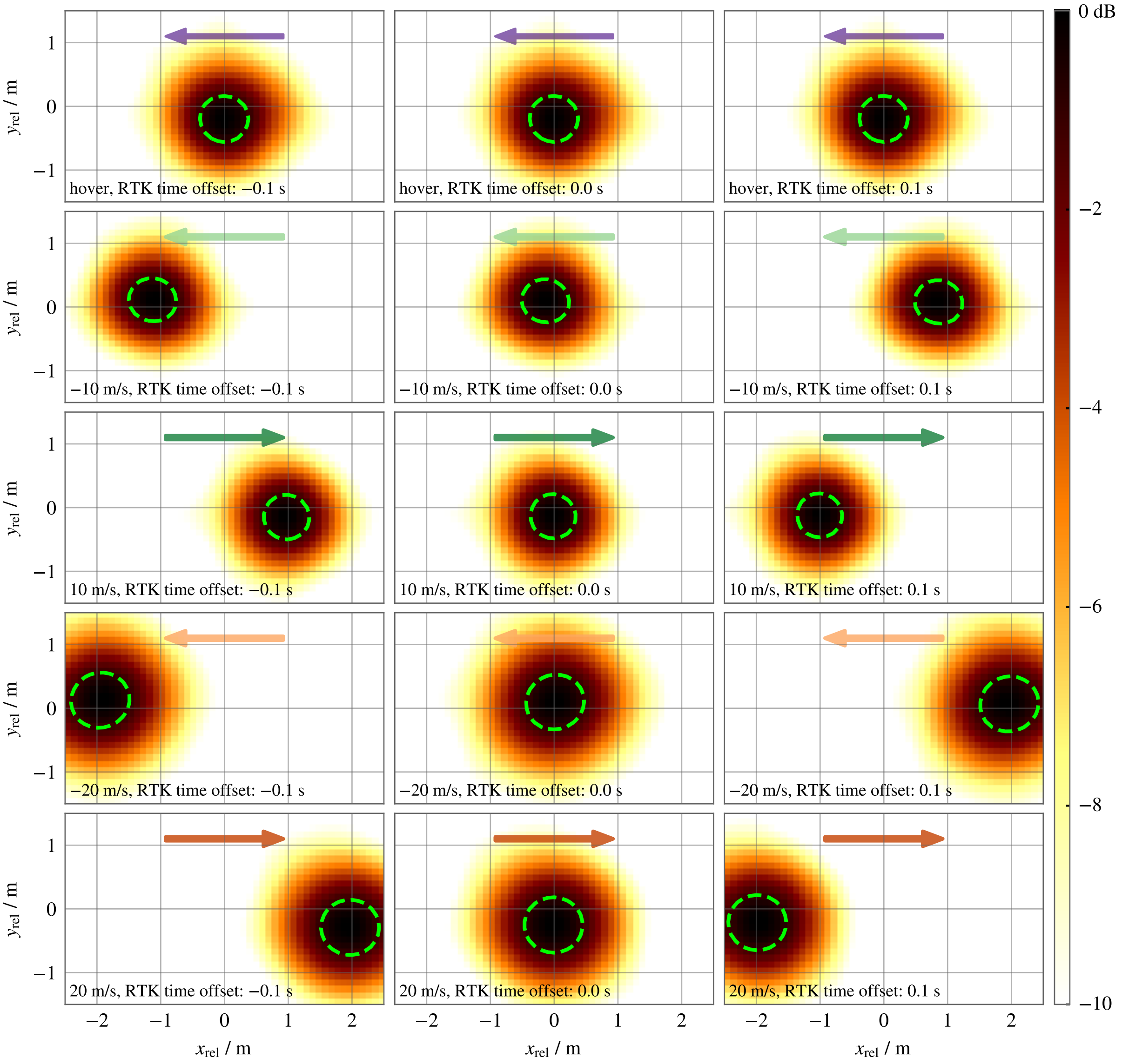

Figure 7: Synchronization of drone RTK-GPS and array time signals via time domain beamforming with moving focus at different flyby speeds, evaluated in the 250 Hz *third-octave band. Dashed green circles mark* 1 dB *below maximum level. Left: sound maps with offset of* -0.1 s*, center: time tracks aligned, right column:* $+0.1$ s *offset.*

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