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Accurate Characterization of Integrated Microphone Arrays for Device-Related Transfer Function Synthesis

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ABSTRACT

This paper presents an improved method for characterizing integrated microphone arrays for Device-Related Transfer Function (DRTF) synthesis. A probe-array extension of the IMPro technique is introduced to measure all device microphones simultaneously, eliminating unknown timing offsets that arise in asynchronous device–probe recordings. A custom four-element probe array and modular test jig were developed to evaluate relative inter-channel propagation delay (RIPD) accuracy across varied microphone-port geometries. Hybrid free-field DRTFs were synthesized by combining IMPro data with Boundary Element Method (BEM) acoustic scattering simulations, demonstrating that the probe-array measurements capture small delay variations essential for precise spatial-audio modeling. The extended IMPro method offers a practical, scalable alternative to anechoic-chamber measurements for modern multi-microphone devices.

1 Introduction

Modern smartphones and consumer audio devices increasingly utilize multiple microphones to enable advanced audio features, including spatial audio capture, beamforming, noise reduction, and robust voice interface functionalities powered by large language models. Accurate knowledge of each microphone's directional response is essential for designing and tuning these algorithms. Traditionally, these responses are obtained through free-field measurements in anechoic chambers. However, conducting these measurements requires access to anechoic laboratory facilities and demands careful mechanical alignment of the device under test. Moreover, both the device fixtures and the automated rotation systems used for measurement re-

peatability can degrade the acoustic integrity of the anechoic chamber.

The growing availability of high-performance numerical simulation tools has enabled hybrid measurement–simulation approaches to complement or even replace traditional free-field testing. Smartphone devices are particularly suitable for numerical acoustic analysis, as their compact and rigid bodies allow accurate modeling of scattering effects using methods such as the Boundary Element Method (BEM).

In our earlier work, we presented the IMPro technique, a method for integrated microphone pressure frequency response measurement using a probe microphone [1], in which the integrated microphone pressure response is measured using a calibrated probe microphone and

subsequently combined with analytical scattering models to synthesize the free-field directional response of a microphone embedded in a spherical device. This approach was later generalized to support arbitrary product geometries by combining IMPro measurements with simulated device-body scattering data derived from numerical acoustic models [2].

A major challenge in extending hybrid approaches to real consumer devices is the unknown time offset between the recordings produced by the measurement system and the device's internal acquisition system. When characterizing devices with multiple microphones, phase alignment across individually measured channels can become a major source of error if microphones have significantly different microphone integration mechanics from each other. This can limit the reliability of response synthesis. To address this, the present work introduces a probe array-based measurement method capable of capturing the responses of all integrated microphones simultaneously using a compact, calibrated array of probe microphones. This approach inherently preserves the relative phase between channels and eliminates the need for post-hoc phase alignment. Because the true microphone-to-microphone response differences in modern devices are often very small, even subtle measurement errors can lead to significant distortions in the synthesized directional responses. Therefore, the experimental setup must achieve exceptionally high sensitivity and stability.

To validate the proposed method, we constructed a four-element custom probe microphone array and evaluated its performance against two high-precision commercial probe microphones used as references. The IMPro measurements with the probe microphone array were combined with BEM simulations of sound scattering for multiple incident angles around the device under test. By merging the measured integrated microphone frequency responses with simulated acoustic fields, we synthesized accurate hybrid free-field directional responses for all microphones within the device.

To investigate the integrated microphone phase response characteristics under realistic microphone port lengths, we designed a measurement jig containing four different sound inlet geometries ranging from 5 mm to 10 mm in length. The jig provides a highly simplified microphone integration whose purpose is to introduce controlled, small delay variations, enabling us to

evaluate the resolution limits of studied probe array measurements.

To further illustrate the impact of small delay errors in integrated microphone characterization, we applied the different test jig IMPro responses to BEM simulation scattering data for a smartphone-like prototype device model and assessed the resulting Direction-of-Arrival (DoA) estimation accuracy using a four-microphone array. This analysis quantifies how phase-related measurement accuracy affects spatial audio processing performance.

The results demonstrate that the use of a probe microphone array and the synchronized IMPro measurement technique, combined with numerical acoustic simulations, provides a robust and efficient alternative to conventional free-field directional measurements. Furthermore, the approach offers significant practical advantages and enables scalable characterization suitable for future multi-microphone consumer products and virtual prototyping workflows.

1.1 Synchronization and observability of relative delays

Relative inter-channel delay between device microphone channels, rather than absolute sound source timing, is the key quantity required by spatial multi-microphone processing algorithms. If the probe and device microphone signals are recorded with a repeatable and synchronized time base, relative delays can be estimated reliably regardless of whether IMPro measurements are performed simultaneously or sequentially, provided that proper time alignment is maintained. In probe array measurements, any constant synchronization offset between probe and device acquisition systems appears as a common delay shared by all channels and therefore does not affect relative delay estimates. Sequential IMPro measurements performed without synchronization support are problematic, as unknown recording-to-recording latency variations can be much larger than the microphone integration delays of interest, obscuring inter-channel delay differences between device microphones.

In the presented experiments, all probe and test jig microphones were connected to a single synchronized acquisition system, enabling reliable delay estimation with both sequential and array measurement configurations. In contrast, smartphone measurements typically

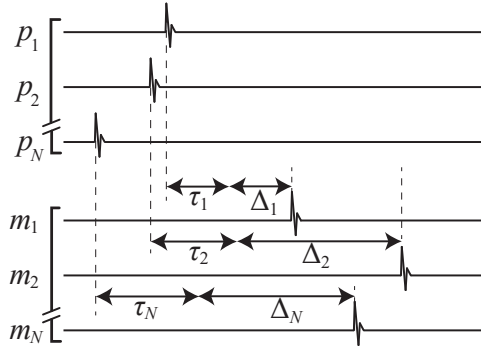


Fig. 1: The measured timing between probe p_i and device microphone m_i contains per-channel integrated microphone delays Δ_i and an acquisition-system synchronization offset τ_i . In synchronized acquisition setup, τ_{sync} is common to all channels $\tau_i = \tau_{\text{sync}}, \forall i \in [1, \dots, N]$ and cancels out in relative device microphone delay estimates (e.g., $\Delta_i - \Delta_1$).

involve independent device and measurement analog-to-digital converters (ADCs), making reliable cross-system synchronization difficult. In such cases, the simultaneous measurement the device microphones using a probe-array offers a robust and practical solution for preserving inter-microphone timing relationships.

2 Experimental description

The objective of the experiment was to evaluate the capability of measuring the relative inter-channel propagation delay (RIPD) of a set of microphone integrations. As previously established, RIPD capture requires at least two probe microphones, synchronous acquisition of the signals from these probe microphones through a common recording system and likewise, synchronous acquisition of the device microphone signals.

Given the increasing integration of multiple microphones (typically three or more) within contemporary commercial smartphone devices, a decision was made to simultaneously evaluate four integrated microphone components. This approach served two purposes: firstly, to assess the capability of determining RIPD, and secondly, to ascertain the practical feasibility of employing four probe microphones concurrently for IMPro measurement. The second objective was critical because of the inherent challenges associated with

achieving accurate and repeatable positioning of a single probe microphone relative to a smartphone device. Consequently, a specialized test jig accommodating four integrated microphones was developed.

Due to experimental constraints, using four commercial probe microphones was not feasible and necessitated the design and fabrication of four copies of a custom probe microphone (Section 2.2). The performance of the custom probe microphone was subsequently validated through parallel data acquisition using a pair of GRAS 40SA commercial probe microphones.

The individual free-field frequency responses of all utilized probe microphones were characterized using methods consistent with prior IMPro publications [1]. The frequency response stability of the custom probe microphones was a primary consideration, and frequent calibration measurements were required. Consequently, a dedicated calibration jig was designed and fabricated to precisely position all four custom probe microphones relative to a 1/4 in. pressure reference microphone.

A four-microphone test jig was specifically developed for the measurement of RIPD. Potential sources of experimental variability, identified as compromising efficacy, included sample variations of the microphone components and probe positioning errors. To mitigate component-related variations, an identical set of mechanical microphone integrations was applied to each microphone capsule sequentially. To minimize measurement errors, the probe-positioning setup was simplified for repeatability and ease of use. Thus a test jig with a removable tube for each microphone was designed (Section 2.1), with each tube differing only in length and the remaining integration design characteristics kept common for all four microphones.

The IMPro responses of the four test jig microphones were measured using both an array of the four custom probe microphones and the pair of commercial probe microphones across two distinct measurement instances. All probe and test jig microphone signals were acquired synchronously via a single recording system. Table 1 details the four removable tube configurations for the test jig. The custom probe array required one recording per setup combination (totaling four), while the commercial probe pair necessitated three sequential recordings per setup. In the latter case, one commercial probe maintained a fixed position at the IMPro reference point of the first test jig microphone, and the second probe was sequentially positioned at the IMPro

Table 1: Test jig tube setup combinations for each microphone channel.

Setup instance	Tube length [mm]			
	Ch. 1	Ch. 2	Ch. 3	Ch. 4
1	5.0	7.0	8.0	10.0
2	7.0	8.0	10.0	5.0
3	8.0	10.0	5.0	7.0
4	10.0	5.0	7.0	8.0

reference point of the second, third, and fourth test jig microphones.

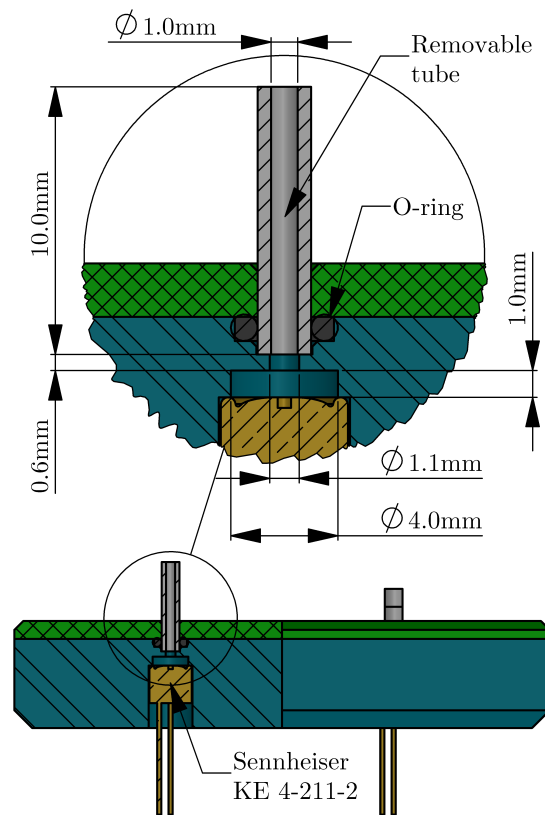
The test jig's removable tubes, ranging from 5 mm to 10 mm in length, were designed to assess RIPD detection capability across sub-sample to multiple-sample delays. A 96 kHz sample rate was chosen to enable sub-sample delay resolution with 1 mm physical tube length variations.

Measurements were conducted in an anechoic chamber. Unlike previous IMPro measurements, spatial averaging with rotations between repeated measurement sweeps was not employed on this occasion. This was justified because RIPD measurement requires only consistent relative responses, not absolute IMPro accuracy.

The positioning of the probe microphones to their respective IMPro reference points was achieved through the use of positioning fixtures [1]. Figure 3 illustrates the measurement setup with the four-microphone custom probe array. Smaller details are shown in Figure 4.

2.1 Test jig design

The test jig contained four identical Sennheiser KE4-211-2 microphones. Plastic parts were fabricated using a stereolithography printer. The key design features are shown in Figure 2. A small 12.6 mm³ volume connects the microphone component sound inlet to a removable aluminium tube with internal diameter of 1.0 mm. Four different lengths of tubes were produced, with lengths 5 mm, 7 mm, 8 mm, and 10 mm. A small o-ring sealed the tube to the test jig assembly. The design allowed the tubes to be easily interchanged between the four microphones, and also aided in the accurate positioning of the probe microphones. Figure 4 shows the test jig and the custom probe microphone array in place during a measurement.

**Fig. 2:** Sectioned side, and detailed views of the 4-microphone test jig.

2.2 Custom probe microphone design

A custom probe microphone was designed and four copies were manufactured¹ based around the Sennheiser KE 4-211-2 microphone capsule [3]. The probe was required to be compatible with existing mechanical positioning systems, and to exhibit a sufficiently broad high-frequency bandwidth to achieve an adequate signal-to-noise ratio at 20 kHz. The acoustic design was first evaluated with lumped parameter model analysis [4, 5] and includes a compensation network [6, 7]. The simulated acoustic input impedance of the probe tip was about $3 \times 10^8 \text{ Ns/m}^5$ at 300 Hz, which is similar to the value of the Brüel & Kjær type 4182 probe microphone at $8 \times 10^8 \text{ Ns/m}^5$.

Plastic parts were manufactured with a stereolithography printer. Other parts were readily sourced from

¹3-D models and construction details are planned to be available at <https://github.com/nokiatech/impro>



Fig. 3: View of the test jig and the custom probe array positioning for IMPro measurements.

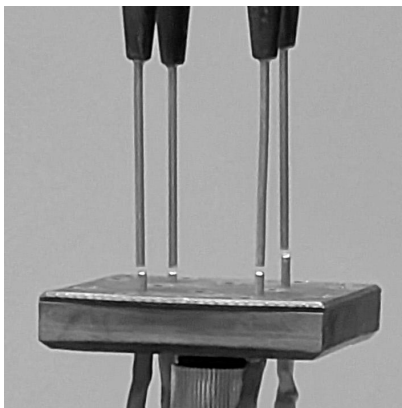


Fig. 4: Detailed view of the test jig and the custom probe array for IMPro measurements, showing the relative positions of the probe microphones, and the alignment of the probe tubes to the test jig tubes.

easily accessible online stores. Figure 5 shows a cross-section of the probe microphone and a detailed cross-section view of the microphone capsule and the connections of the probe and impedance matching tubes. The connecting volume between the microphone membrane, the probe tube, and the impedance matching tube was minimized to improve high-frequency performance reducing resonance magnitudes caused by the probe tube. The measured free-field frequency responses of the custom probe microphones as well as the commercial probes are presented in Figure 6.

3 Results

Figure 7 shows the IMPro magnitude and phase delay responses for each microphone channel of the test jig. Each subplot shows four measured curves, one for each removable-tube length. Because the microphone integration design fixes both the cavity volume and the tube diameter, increasing the tube length is expected to lower the resonance frequency of the primary acoustic system (approximately 3 to 5 kHz) and to increase resonance damping. This behavior arises from the increased acoustic mass and resistance introduced by the longer tube. In addition, the phase delay increases with tube length due to the increased acoustic path.

The phase delay does not increase uniformly across frequencies. In the vicinity of the primary resonance, phase delay values are large and the relative differences between tube lengths are on the order of 10 to 20 μs . Below 1 kHz, the relative phase delay differences are substantially smaller, typically around 1 μs .

The IMPro responses measured on the third microphone channel differ significantly from those of the other three channels in the primary resonance region. These deviations likely arise from mechanical tolerances or 3D-printing inaccuracies in the test jig, which likely caused misalignment between the removable tube and the cavity volume. Such misalignment can partially restrict the tube and thereby alter its acoustic

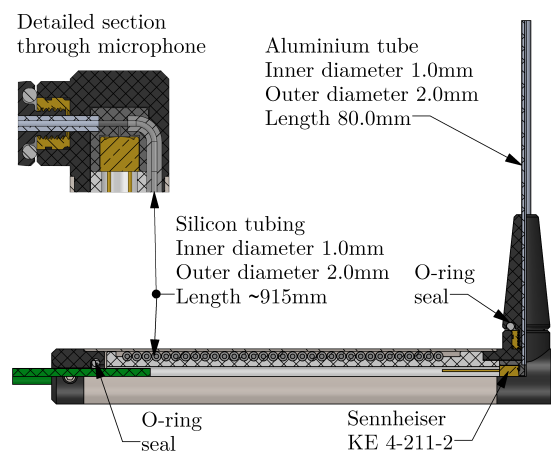


Fig. 5: Cross-sectional view of the custom probe microphone showing details of the microphone capsule and the two connecting $\varnothing 1.0$ mm tubes.

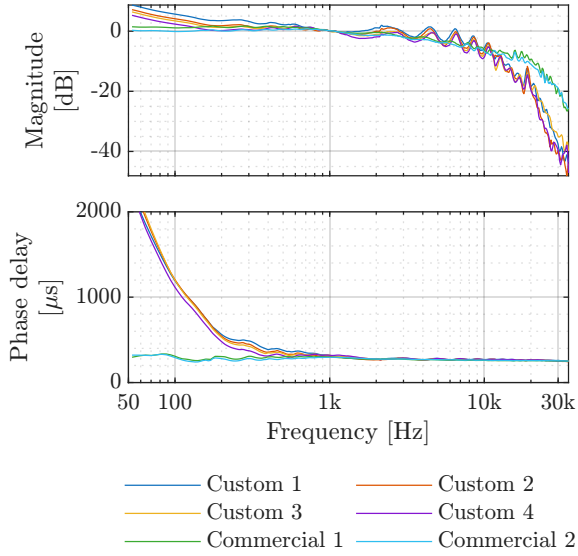


Fig. 6: Magnitude and phase delay calibration frequency responses of the 6 probe microphones.

properties. Data from this microphone channel were therefore rejected and excluded from further analysis.

Figure 8 compares the IMPro magnitude and phase delay responses for the first test jig microphone channel fitted with 5 mm and 10 mm tubes, measured using both a custom probe and a commercial probe microphone. Ideally, the two probes would yield identical responses. While the observed differences are small, some discrepancies are present.

At low frequencies, differences in magnitude response are likely due to small variations in preamplifier gain between measurement sessions, given that variable-gain preamplifiers were utilized. Differences near the resonance frequencies may result from minor inconsistencies in tube replacement between measurements, variations in acoustic loading introduced by the probe microphones.

3.1 Relative inter-channel propagation delay

As shown in Figure 8, RIPD is difficult to identify directly from IMPro phase delay responses of microphone integrations with different tube lengths, as resonance effects dominate the phase behavior. To reduce this influence, the phase delay of the relative response

H_i , defined as the ratio of two IMPro responses with different tube lengths, is analyzed:

$$H_i = \frac{H_{m_A}}{H_{m_B}}, \quad (1)$$

where H_{m_A} and H_{m_B} denote the IMPro responses corresponding to tube lengths A and B , respectively. Table 2 lists the three relative responses analyzed, together with the selected tube lengths and microphone channels.

The expected effect of a difference in tube length is a phase delay shift proportional to the length difference. The ideal delay shift is described by

$$H_d = e^{-ik(l_B - l_A)}, \quad (2)$$

where l_A and l_B are the tube lengths used in forming the relative response, and k is the wavenumber.

The raw IMPro recordings were acquired using a synchronized multichannel system and probe microphone arrays. These data were subsequently reprocessed to emulate four data acquisition strategies: (1) probe array measurement with synchronized acquisition, (2) sequential probe measurement with synchronized acquisition, (3) probe array measurement without synchronized acquisition, and (4) sequential probe measurement without synchronized acquisition. Strategy nos. 1–3 are expected to yield equivalent relative IMPro responses and correctly capture the propagation delay, whereas strategy no. 4 is not.

Figure 9 presents the relative responses H_1 , H_2 , and H_3 for the tube length combinations listed in Table 2, together with the corresponding expected propagation delay responses H_d . Results obtained using the custom probe array are shown in the left column, and those obtained using the commercial probe pair in the right column.

Table 2: The 3 length combinations of the test jig removable tubes and the test jig microphone channel sources for the relative response H_i .

Index H_i	l_A [mm]	Jig Ch.	l_B [mm]	Jig Ch.	$l_A - l_B$ [mm]
1	7.0	2	5.0	1	2.0
2	8.0	2	5.0	3	3.0
3	10.0	1	5.0	2	5.0

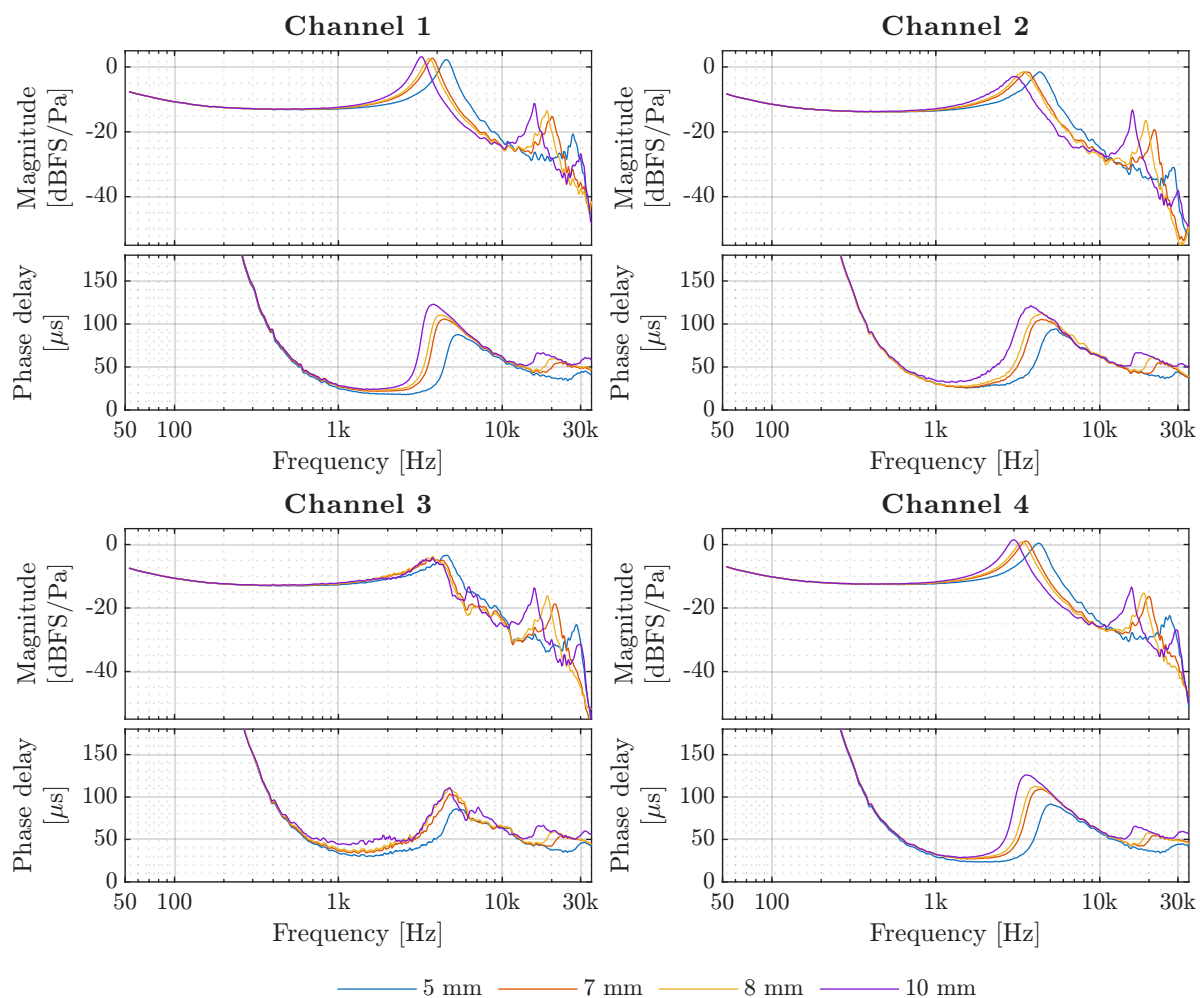


Fig. 7: IMPro responses of the four test device microphones, one channel per subplot. Each subplot shows the IMPro response for each of the 4 different lengths of the removable tubes. The measurements were acquired with the commercial probe microphones.

As anticipated, the sequential asynchronous acquisition strategy fails to reproduce the expected propagation delay. In contrast, the remaining three strategies yield relative phase delay responses that closely match the expected behavior. Among these, H_1 exhibits the best agreement with H_d , while H_2 shows the largest deviation. For the custom probe array, the synchronized array measurements produce identical relative phase responses, as all data were acquired in a single recording with fixed probe positions. In contrast, the commercial probe pair measurements show differences between synchronized and asynchronous strategies, likely due

to small probe position changes between successive recordings when repositioning the second probe microphone.

It should be noted that the tube length combinations used in this study were not ideal, since the selected combinations did not allow isolation of RIPD effects arising solely from changes in tube length within the same microphone integration. Consequently, the measured relative responses include not only the intended tube length effects but also inter-sample variations of the microphone capsules.

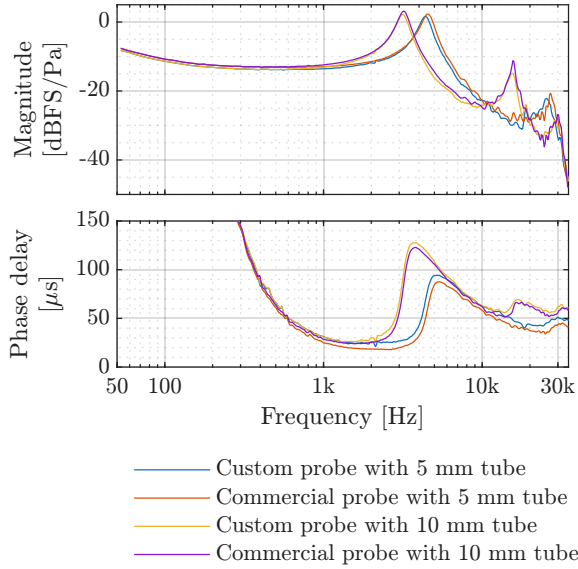


Fig. 8: IMPro responses for the test jig first channel microphone for the 5 mm and 10 mm tubes. Responses are shown for both the commercial and custom probe microphones.

3.2 DoA error analysis

To evaluate the impact of the measured RIPDs in a spatial audio capture context, DRTFs for two virtual four-microphone devices were synthesized: one with non-synchronized sequentially measured (strategy no. 4) integrated microphone characteristics and another with correct inter-channel phase-delay characteristics (strategy no. 1). IMPro responses were selected and adjusted from the full measurement dataset, which included both single-probe and probe-array asynchronous recordings, consisting of four test jig configurations, which included three distinct tube lengths and three different microphone components, and outlined in Table 3.

The IMPro responses were filtered by simulated sound scattering data of a prototype smartphone-shaped device [2] to produce two device-related transfer function (DRTF) datasets synthesizing the landscape orientation response of the virtual device rotated 360° in the horizontal plane in 1° increments.

The effect of delay estimation accuracy on DoA estimation was evaluated using a DoA estimation method based on a look-up table. Delays between all six microphone pairs were calculated from the synthesized

Table 3: Source channel and tube length data used to create the four IMPro integrated microphone responses for the virtual smartphone device.

Device channel	Test jig channel	Tube length [mm]
1	4	8.0
2	1	8.0
3	2	5.0
4	4	7.0

DRTF responses of each of the two virtual smartphone devices. The delays were calculated in the frequency range 125–500 Hz using the Generalized Cross-Correlation with Phase Transform (GCC-PHAT) method [8].

The delay measurements of the virtual device with non-synchronized sequentially measured integrated microphone characteristics were used to form a look-up table of microphone pair delays for all source directions. DoA estimates were then calculated using the virtual device with correct inter-channel phase-delay characteristics. For each evaluated direction, the source direction associated with the closest entry in the look-up table was selected as the DoA estimate using the smallest Euclidean distance over all microphone pairs.

Figure 10 shows the error in estimated direction as a function of the source direction. Direction estimation errors are largest near the $\pm 120^\circ$ azimuth directions and the maximum estimation error is about 45° . Direction errors are close to zero at the 0° and 180° azimuth directions.

4 Conclusions

We have shown that the use of a probe array in IMPro device measurements involving asynchronous probe and device recordings can successfully measure the inter-channel delays between integrated device microphones. This improved data can be used to synthesize more accurate device-related transfer functions, which offers a practical and effective alternative to traditional anechoic chamber-based measurement procedures.

In our DoA error estimation example, we have demonstrated that relative inter-channel propagation delay

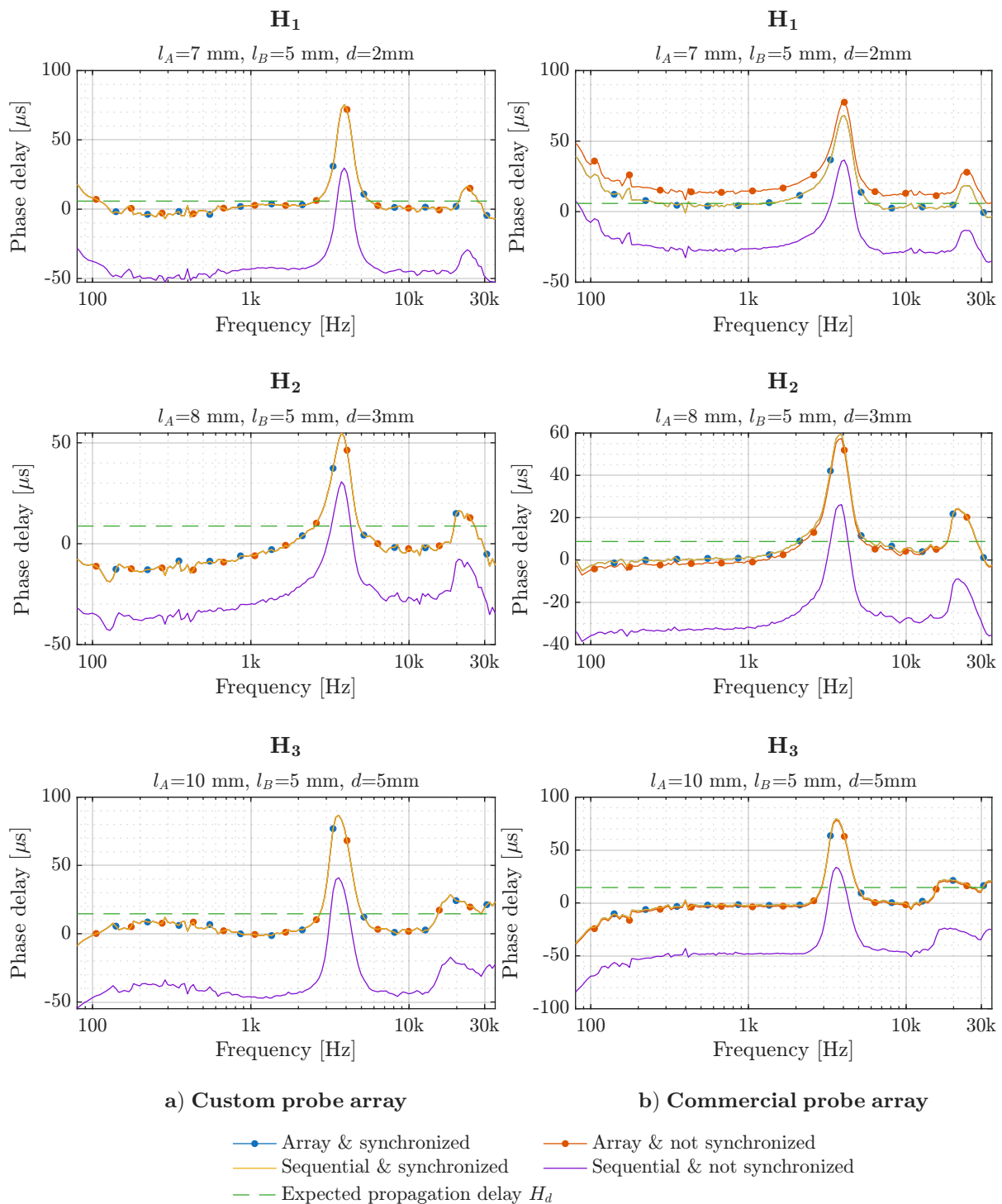


Fig. 9: Phase delay plots of H_1 , H_2 , and H_3 , showing the relative tube length inter-channel propagation delay for tubes of length l_A and l_B . Curves show the results obtained using the 4 possible data acquisition strategies and the expected propagation delay response H_d for the distance $d = l_A - l_B$.

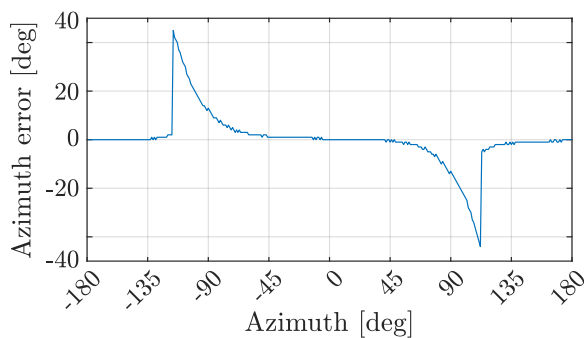


Fig. 10: Direction estimation errors of the synthesized virtual smartphone device for rotations in the horizontal plane. Zero azimuth angle aligns with the main camera optical axis direction.

variations can have a noticeable impact on the performance of spatial audio algorithms.

The improved IMPro method is particularly advantageous when microphone-to-microphone variations in electro-acoustic integration are significant or when the details of a microphone integration, such as port geometry, acoustic pathways, or mechanical couplings are not fully known or cannot be assumed to be uniform. IMPro probe array measurement provides practical isotropic characterization of integrated microphones for commercial devices with multiple microphones.

The use of custom probe microphones produced data that was sufficiently similar to that obtained by commercial probe microphones. We are unable to make any other comparisons of our custom probe microphone to commercial alternatives with the data collected.

Positioning multiple probe microphones about a device was found to be practical. However, more time and care is needed for positioning the probes, and possible repositioning iterations may be required in order to place all probes in their correct places.

Acknowledgements

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