AMBI VS. OMNI: EVALUATING THE POTENTIAL OF 3D MICROPHONE ARRAYS IN ROOM ACOUSTIC MEASUREMENTS

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Abstract

Room acoustic properties are typically assessed using omnidirectional microphones, from which room impulse responses are derived and used to calculate scalar acoustic parameters. However, spatial measurement techniques are essential for assessing sound fields in spaces equipped with active acoustics systems, since they generate direction-dependent and dynamically changing acoustic responses that cannot be fully characterized by single-point, omnidirectional measurements. In recent years, three-dimensional microphone arrays have become increasingly accessible and are widely applied in other areas of audio processing. However, their use in standardized room acoustic measurements remains limited, as existing standards (e.g., ISO 3382) are primarily based on conventional measurement approaches. In this study, a third-order Ambisonics microphone array is employed to capture spatial room impulse responses (SRIRs) under varying acoustic conditions in a space equipped with an active acoustics system. First, the omnidirectional component of the SRIRs is compared with conventional omnidirectional measurements under identical conditions. Initial results suggest that the resulting acoustic parameters are largely consistent, with only minor deviations observed under specific conditions. Subsequently, the potential of the spatial information contained in the SRIRs is examined for extended analysis. This includes the direction-dependent evaluation of established ISO 3382 parameters, such as reverberation time and clarity, enabling their representation as function of direction. The study discusses the potential role of 3D microphone arrays in future room acoustic measurement practices, and highlights the necessity of establishing three-dimensional measurement techniques to adequately assess the properties of active acoustics systems and spatially complex sound fields.

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1. Introduction

Standardized room acoustic measurements have traditionally relied on omnidirectional microphones to capture room impulse responses (RIRs), from which acoustic parameters such as reverberation time, clarity, and definition are derived according to ISO 3382 [1]. This single-point, single-capsule approach has proven robust and practical, but it inherently assumes that the sound field can be adequately described without reference to the direction from which sound energy arrives at the receiver.

Three-dimensional microphone arrays, and Ambisonics microphones in particular, open up fundamentally different ways of approaching acoustic measurement. Rather than capturing a single, direction-agnostic signal at a point in space, such arrays record the spatial structure of the sound field, making it possible to resolve how energy arrives from different directions and how this distribution evolves over time. Devices capable of capturing spatial room impulse responses (SRIRs) up to third order Ambisonics or higher have become considerably more affordable and accessible in recent years, and are already widely used in areas such as virtual reality, spatial audio production, and acoustic scene analysis [2]. However, existing standards such as ISO 3382 remain built around conventional, non-spatial measurement approaches, and simply recording an SRIR does not by itself yield new insight — dedicated analysis methods and parameters need to be designed that actually exploit the spatial information these arrays provide. First steps in this direction already exist: Di Rosario et al. [3] presented a tool for analysing SRIR measurements in auditoriums, including a proposed analysis of directional reverberation, and applied it among others to a hall equipped with an electroacoustic system. Further, spatial microphone arrays offer a high potential for simplifying measurements that conventionally require dedicated, purpose-built setups. Parameters such as the interaural cross-correlation (IACC), typically obtained with a binaural dummy head, or the lateral fraction (LF), typically obtained with a figure-of-eight and an omnidirectional microphone, could in principle be derived directly from a single SRIR capture alongside the standard omnidirectional parameters, substantially reducing the effort of measurement campaigns that currently rely on multiple microphone setups and could also increase repeatability and reliability as directions can be aligned in post processing.

Jasiński and Żera [4] reported that Ambisonics technology is broadly suitable to evaluate standard room acoustic parameters. Similarly, the present study examines the agreement between the W-channel of a compact third-order Ambisonics microphone (Zylia) and conventional omnidirectional measurement microphones, to establish whether such a device can serve as a reliable tool for everyday room acoustic measurement practice.

An even more far-reaching possibility is to represent established acoustic parameters not as scalar values per position, but as functions of arrival direction. Berzborn and Vorländer [5] proposed decomposing the sound field into a plane-wave basis to derive directional energy decay curves, enabling the quantification of anisotropic sound energy decay and its evolution over time in reverberant spaces, an approach since extended from reverberation rooms to general performance spaces. Complementing this, Penot et al. [6] noted that, although reverberant sound fields are commonly assumed to be homogeneous and isotropic, real listening environments typically exhibit neither property, and investigated how such anisotropic reverberation is perceived by listeners. These findings motivate the extension of established ISO 3382 parameters into the directional domain.

In this study, a third-order Ambisonics microphone array is used to capture SRIRs under varying acoustic conditions in a space equipped with an active acoustics system. The omnidirectional component of the SRIRs is first compared with conventional omnidirectional measurements to validate the general suitability of the array for standardized room acoustic measurement. A direction-dependent measure for clarity is introduced, and the behavior is investigated in environments with directional reverberation.

2. Method

2.1. Measurement environment and active acoustics system

The measurements were conducted in a test laboratory equipped with an active acoustics system. The room is 9.10 m by 4.70 m and has a ceiling height of 3.6 m. Its passive acoustic treatment results in a relatively short reverberation time of $T = 0.36$ s for mid frequencies when the active system is turned off.
The installed geometric hybrid active acoustics system comprised 36 loudspeakers distributed throughout the room and 12 system microphones. Four system presets were used to compare the omnidirectional microphone with the Ambisonics W channel: OFF, in which the active system was deactivated; HUB, designed to provide a natural acoustic response corresponding to a less strongly damped version of the existing room; and Symphony and Choral, two presets simulating acoustically enlarged spaces with substantially longer decay times, representing an environment suitable for symphonic music and an even larger, more reverberant space, respectively. Further, three presets denoted A, B and C, were used for the directional early-to-late energy analysis. As shown by Werner et al. [7], these presets share a similar reverberation time but differ in the spatial distribution of the reverberant energy: A evenly distributes the reverberant energy in the room, B focuses it on the side opposite the source (back heavy), and C focuses it toward the source side (front heavy).

2.2. Measurement setup

Room impulse responses were captured using two microphones: a Beyerdynamic MM1 omnidirectional measurement microphone, and a Zylia ZM-1 spherical array (19 capsules), used to obtain third-order Ambisonics RIRs. The room was excited with an NTI DS3 dodecahedron loudspeaker driven by an NTI PA3 amplifier.
Measurements were taken at two receiver positions — M1 near the room center and M2 further away — with the MM1 and ZM-1 placed as identically as possible at each position; source and receiver positions are shown in Figure 1.
Exponential sine sweeps were generated and played back in HBK Dirac 7. The MM1 signal was recorded directly in Dirac via a Focusrite Scarlett 18i20 interface. For the ZM-1, the 19 raw capsule signals were routed into Reaper and encoded to third-order Ambisonics (ACN/SN3D) using the Zylia Ambisonics Converter plugin, then fed back into Dirac via the virtual soundcard ReaRoute.
At each receiver position, this procedure was repeated for all system presets, keeping the source and receiver configuration fixed while switching presets.

2.3. Room-acoustic parameter calculation

The measured impulse responses were analyzed using an implementation in Python based on `pyfar` and `pyrato`. The omnidirectional microphone signal and

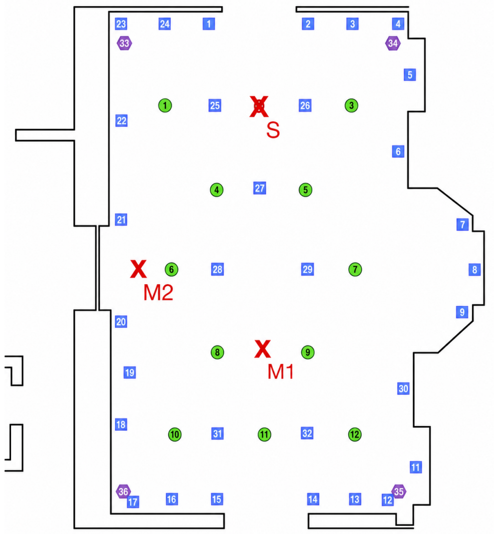


Figure 1: Floor plan of the Amadeus Acoustics Hub, showing the source position S and the two receiver positions

the zeroth-order (W) component of the Ambisonics signal were processed using the same analysis procedure. Impulse responses were filtered into fractional-octave bands (IEC 61260, filter order 14) with center frequencies from 125 Hz to 8 kHz using the fractional-octave filter bank provided by `pyfar`. For each band, a noise-compensated energy decay curve (EDC) was calculated from the backward-integrated squared impulse response using the Chu method [8] implemented in `pyrato`, which subtracts an estimate of the background noise energy before integration. EDT, T_{20} and T_{30} were obtained by linear regression of the EDC over the respective evaluation ranges and extrapolation to a 60 dB decay. Clarity was calculated as

$$C_{80} = 10 \log_{10} \frac{\int_0^{80\,\text{ms}} h^2(t)\,\mathrm{d}t}{\int_{80\,\text{ms}}^{\infty} h^2(t)\,\mathrm{d}t}, \qquad (1)$$

where $h(t)$ is the impulse response after octave-band filtering.

2.4. Comparison of the omnidirectional microphone and the ambisonics W channel

Jasiński and Żera [4] showed the general suitability of first- and third-order Ambisonics microphones, including the Zylia ZM-1, for ISO 3382 measurements by comparing their W channel with classical omnidirectional microphone measurements in five rooms of different reverberant conditions. Their measurements were carried out in ordinary rooms only. To validate their results and to extend them to a room with an active acoustics system, the same comparison was repeated here for the four presets OFF, HUB, Choral and Symphony, which cover a wide range of reverberation times within one and the same room. The deviation between the omnidirectional and the Ambisonics measurements is of particular interest for these parameters, as it directly indicates whether the array could potentially replace a dedicated omnidirectional microphone. For the reverberation time parameters, the signed relative deviation was defined as

$$\Delta T = \frac{T_{\text{Ambi},W} - T_{\text{Omni}}}{T_{\text{Omni}}} \cdot 100\,\%, \qquad (2)$$

where positive values indicate longer decay-time estimates for the Ambisonics W channel. For clarity, the signed absolute difference was used:

$$\Delta C_{80} = C_{80,\text{Ambi},W} - C_{80,\text{Omni}}. \qquad (3)$$

As a reference, the JND limits given in ISO 3382 [1] of $\pm 5\,\%$ for the reverberation times and ± 1 dB for C_{80} were included in the deviation plots.

2.5. Directional early-to-late energy ratio

To evaluate the spatial distribution of the reverberant tail, presets A, B, and C were analyzed using the SN3D-normalized, ACN-ordered third-order Ambisonics signals. As a proof of concept first-order beams pointing along the main directions (front, left, back, right, up, down) were used to calculate six directional impulse responses. Each beam was formed using max-rE weighting with unity gain on-axis, which maximizes the directional energy concentration of a first-order pattern. The beam weights w_n for the spherical-harmonic order n are given by

$$w_n = g_n\,(2n+1)\,Y_n(\Omega_0), \qquad g_n = P_n(\cos\theta_{\text{max-rE}}), \qquad (4)$$

where Y_n are the real spherical harmonics evaluated at the look direction Ω_0, P_n is the Legendre polynomial of order n, and $\theta_{\text{max-rE}} = 137.9°/(N+1.51)$ is the approximation for beamformer order N given by Zotter and Frank [9]. Since only first-order beams were used ($N = 1$), this is the only choice that fully covers the sphere with six directions: because the six look directions are related by the symmetries of the octahedron, each beam has, by symmetry, the same average power gain in an isotropic sound field, so none of the six directions is inherently favoured.

For the early energy part (0 to 80 ms) of the impulse response only the omnidirectional W channel was taken and is therefore identical for all directions. From 80 ms onward, the late energy was evaluated separately for the impulse response gained by each beam. The directional clarity was calculated as

$$C_{80}(\text{direction}) = 10 \log_{10} \frac{E_{\text{early, omni}}}{Q \cdot E_{\text{late, direction}}}, \qquad (5)$$

where Q is the directivity factor of the beam, defined as the ratio between its on-axis power gain and its average power gain over the sphere, which yields $Q \approx 3.73$ for the first-order max-rE beams used here.

The upper integration limit for the late energy was determined per band as the earlier of two criteria:

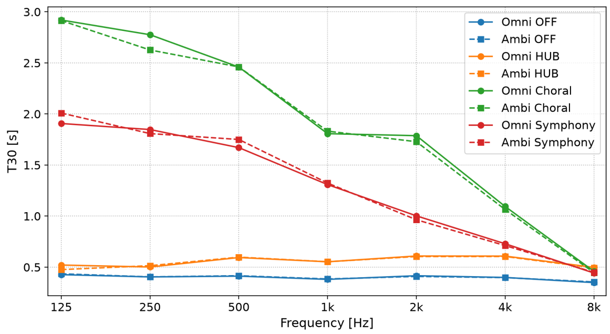


Figure 2: T_{30} obtained from the omnidirectional microphone (solid, circles) and from the Ambisonics W channel (dashed, squares), averaged over receiver positions M1 and M2.

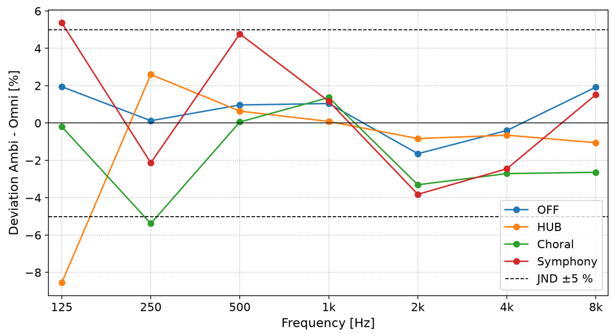


Figure 3: Relative deviation of T_{30} according to Eq. (2), averaged over receiver positions M1 and M2. The dashed lines indicate the $\pm 5\,\%$ JND.

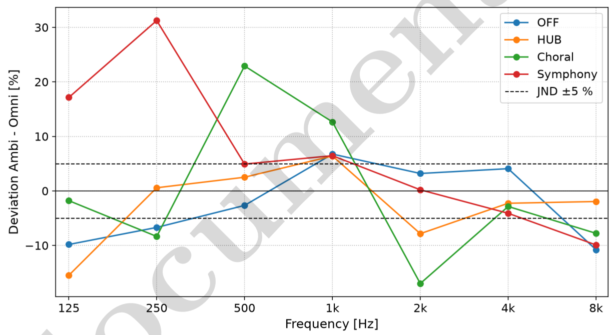


Figure 4: Relative deviation of EDT, averaged over receiver positions M1 and M2. The dashed lines indicate the $\pm 5\,\%$ JND.

the point where the smoothed envelope of the omnidirectional signal falls to within 5 dB of the estimated noise floor, or the point where the backward-integrated Schroeder decay reaches -30 dB, used as an abort criterion to avoid integrating noise-dominated parts of the decay. This directional evaluation was carried out at 500 Hz and 1 kHz.

3. Results

3.1. Reverberation time T_{30}

Figure 2 shows the absolute T_{30} values. With the active system switched off, T_{30} stays close to 0.4 s and shows almost no frequency dependence. The HUB preset lies between roughly 0.5 s and 0.6 s. The Symphony and Choral presets show a clear decrease with frequency, reaching about 2.9 s (Choral) and 2.0 s (Symphony) at 125 Hz and converging with the OFF and HUB curves above 4 kHz. For all four presets, the curves obtained from the omnidirectional microphone and from the Ambisonics W channel run closely together.

To compare the omnidirectional vs the ambisonics results, the relative deviations ΔT_{30} are shown in Figure 3. Between 500 Hz and 8 kHz, deviations stay within $\pm 5\,\%$ for all four states. Larger deviations occur for low frequencies only at 125 Hz for HUB ($-8.5\,\%$) and Symphony ($+5.4\,\%$). And at 250 Hz for Choral with about 5.3 %.

3.2. Early decay time

The relative deviations of EDT are shown in Figure 4. They are considerably larger than those of T_{30} and range from about $-17\,\%$ (Choral, 2 kHz) to $+31\,\%$ (Symphony, 250 Hz), with further values above $+20\,\%$ for Choral at 500 Hz. No consistent trend across frequency, system state or receiver position is visible.

3.3. Clarity C_{80}

Figure 5 shows the absolute C_{80} values. OFF gives the highest values across the frequency range (about 9 to 16 dB), followed by HUB. Choral and Symphony start for lower frequencies at values below 9 dB and increase toward 8 kHz, reaching similar values to OFF and HUB.

The relative deviations ΔC_{80} are shown in Figure 6. Deviations stay within ± 1 dB for most state/frequency combinations between 250 Hz and 8 kHz. The largest deviations occur at 125 Hz, with about $+1.7$ dB for HUB and -1.9 dB for Symphony. OFF approaches the JND at 500 Hz (about $+1.0$ dB) but stays within it elsewhere. Overall, C_{80} shows better agreement between the omnidirectional microphone and the Ambisonics W channel than the decay-time parameters.

3.4. Directional distribution of the late energy

Figure 7 shows polar plots of C_{80} in the horizontal plane (front, left, back, right) for presets A, B and C at 500 Hz and 1 kHz. The dashed circle marks the omnidirectional C_{80} value for reference.

For preset A (Figure 7a), the six directional values are close together at both frequencies. The spread between directions is 1.2 dB at 500 Hz and 2.3 dB at 1 kHz, with the lowest value in both bands occurring for the right direction (7.09 dB and 4.19 dB).

For preset B (Figure 7b), the back direction gives the lowest value at both frequencies (6.25 dB and 6.16 dB), while front and up give the highest. The difference between back and front amounts to 3.6 dB at 500 Hz and 2.5 dB at 1 kHz.

For preset C (Figure 7c), the pattern is reversed: back

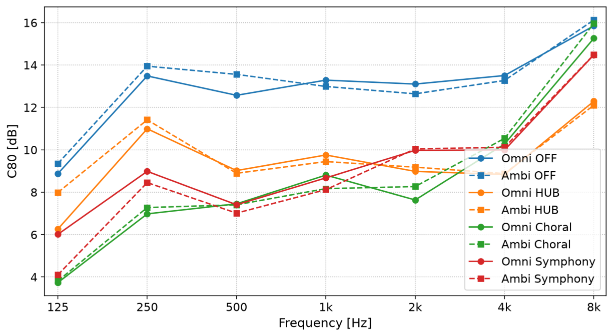


Figure 5: C_{80} obtained from the omnidirectional microphone (solid, circles) and from the Ambisonics W channel (dashed, squares), averaged over receiver positions M1 and M2.

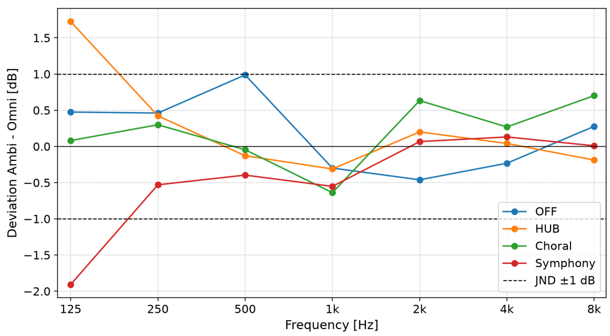


Figure 6: Deviation of C_{80} according to Eq. (3), averaged over receiver positions M1 and M2. The dashed lines indicate the ±1 dB JND.

gives the highest value in both bands (8.46 dB and 5.75 dB), while the lowest value shifts from down at 500 Hz (5.87 dB) to front at 1 kHz (3.14 dB).

The omnidirectional values alone do not reflect these directional differences. At 1 kHz, preset B gives the highest omnidirectional C_{80} (8.06 dB), followed by A (5.53 dB) and C (4.16 dB), but the direction from which the late energy arrives cannot be derived from a single omnidirectional value.

4. Discussion

The parameters derived from the Ambisonics W channel agree well with those from the omnidirectional microphone, with most deviations staying within the reference JND. Robustness follows the amount of decay range used per parameter (C_{80} best, then T_{30}, EDT worst), since shorter evaluation windows are more sensitive to small differences in noise floor or individual reflections — consistent with Jasiński and Żera [4], who likewise found the largest deviations for EDT and in rooms with short decay times. Remaining outliers occur mainly at low frequencies and in the OFF and HUB presets, where the available signal to noise ratio is smallest, likely because the two microphones reach their noise floors at slightly different times, shifting the regression window relative to the decay; placement variation may also contribute.

The directional analysis reproduces the intended spatial design of presets A, B and C purely from the measurements, without knowledge of the system settings — confirming that the geometric approach of Werner et al. [7] produces the distributions it is designed for, and that a compact Ambisonics array is sufficient to detect them, unlike the omnidirectional values. This is notable because anisotropic late energy is not specific to active acoustics: Berzborn and Vorländer [5] found it in ordinary performance spaces as well, meaning an active system merely makes anisotropy a design parameter rather than a geometric side effect. The energy-based approach used here also has a practical edge over intensity-based analysis, since Meyer-Kahlen and Schlecht [10] showed analytically that the pseudo intensity vector — widely used for SRIR analysis — has only limited degrees of freedom in the late field and thus reflects anisotropy only weakly.

Whether these differences are perceptually relevant is not addressed here. Penot et al. [6] showed that arrival direction of late energy affects envelopment, clarity and timbre even when monaural parameters stay constant, and that listeners distinguished settings with identical relative directional distributions — suggesting absolute directional energies describe perception better than relative measures. Since directional clarity here is a ratio, this limitation would need to be considered for any perceptual interpretation.

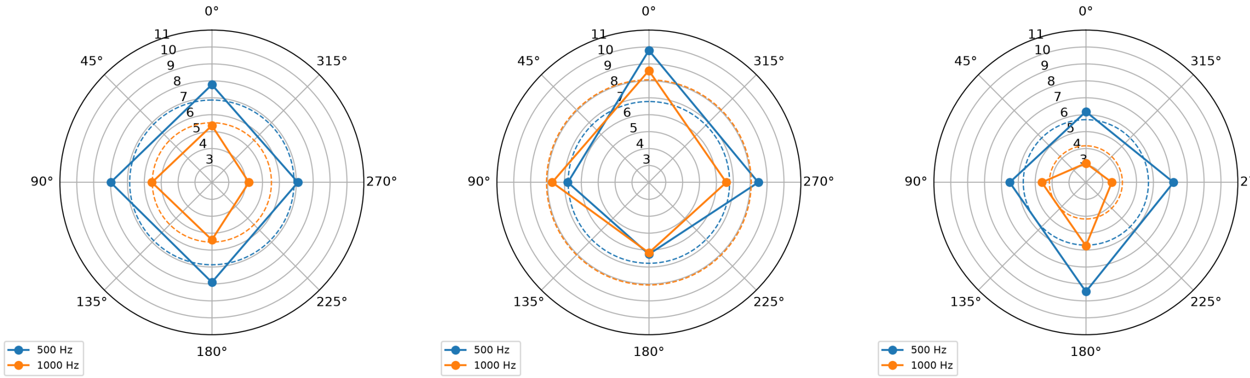
5. Conclusion

The results show that a compact third-order Ambisonics array is a suitable tool for standardized room acoustic measurement: parameters derived from its W channel agree with those from a dedicated omnidirectional microphone.

Beyond this, the directional analysis recovers the intended spatial design of presets A, B and C from the measurements alone, demonstrating that a compact array carries information that a conventional omnidirectional measurement cannot provide. The suggested directional measure of clarity reacts to directional reverberation and can be useful for quantifying the directionality of sound fields. Since anisotropic late energy is not unique to active acoustics systems but a more general property of sound fields, this method offers a practically viable way of characterizing directional behavior in both active and passive spaces.

6. Outlook

Recording SRIRs with arrays of higher order, such as a 32- or 64-channel spherical array, would allow verifying whether a finer directional resolution over a wider frequency range is achievable, and would make a direct comparison between first-order and higher-order analysis possible. For the ZM-1 specifically, repeating the measurement with the array rotated would allow on-axis and off-axis behaviour to be separated. Beyond clarity, the same SRIR data can be used to derive spatial parameters such as IACC, which would



(a) Preset A – even distributed **(b) Preset B – back heavy** **(c) Preset C – front heavy**

Figure 7: Directional C_{80} in the horizontal plane for presets A, B and C at 500 Hz and 1 kHz. The dashed circles indicate the omnidirectional C_{80} value.

show from which directions useful reflections arrive. The most important open step, however, is a listening test. Green and Kahle [11] showed that whether a reflection is consciously perceived at all depends on its direction of arrival and on the overall listening level, so a directional measure is only meaningful once it is linked to the auditory impression.

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