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Technical Note

A comparison of measured room acoustics metrics using a spherical microphone array and conventional methods ☆

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ABSTRACT

The traditional microphone configuration used to measure room impulse responses (IRs) according to ISO 3382:2009 is an omnidirectional and figure-8 microphone pair. IRs measurements were taken in a 2500-seat auditorium to determine how the results from a spherical microphone array (an mh acoustics Eigenmike-em32) compare to those from the traditional microphone setup (a Brüel & Kjær Type-4192 omnidirectional microphone and a Sennheiser MKH30 figure-8 microphone). Measurements were obtained at six receiver locations, with three repetitions each in order to first evaluate repeatability. The metrics considered in this study were: reverberation time (T30), early decay time (EDT), clarity index (C80), strength (G), lateral energy fraction (J_{LF}) and late lateral energy level (L_J). Before calculating these quantities, the IRs were filtered to equalize the frequency response of the microphones and sound source. For the spherical array measurements, the omnidirectional (monopole) and figure-8 (dipole) patterns were extracted using beamforming. In terms of repeatability, the average standard deviation of the three measurements at each receiver location averaged across all metrics, receivers, and octave bands was found to be 0.01 just noticeable differences (JNDs). The analysis comparing the measurements from the two microphone configurations yielded differences which were less than 1 JND for the majority of metrics, with a few exceptions of EDT and C80 slightly above 1 JND. Based on this case study, these results indicate that spherical microphone arrays can be used to obtain valid room IR measurements, which will allow for the development of new metrics utilizing the higher spatial resolution made possible with spherical arrays.

1. Introduction

Spherical microphone arrays contain a number of microphones arranged on the surface of a compact sphere and can be used to obtain spatial information about sound fields. The spherical configuration of the array enables a convenient way to beamform directional patterns in any direction in 3D space using a spatial Fourier transform and processing the signals in the spherical harmonics domain [1,2]. In recent years, spherical microphone arrays have begun to be utilized in room acoustics applications to analyze the directional properties of reverberant spaces [3–6]. Room impulse responses (IRs) measured with spherical arrays have been analyzed to determine the direction of arrival of early reflections in rooms [3–5]. A recent study also evaluated IR measurements obtained in performing arts spaces using a 16-channel spherical microphone array by beamforming the IRs in the azimuthal plane and comparing different audience receiver positions [6].

Previous room acoustics studies involving spherical microphone arrays have not included analyses of the IRs to calculate established room acoustics spatial metrics as defined in Annex A of ISO 3382 [7]. These metrics require measurements made using a pair of microphones, one with an omnidirectional directivity pattern and a second one with a figure-of-eight (figure-8) directivity pattern. Alternatively, these directivity patterns can be obtained from spherical microphone array measurements by extracting the zeroth (monopole) and first order (dipole) spherical harmonic components, respectively. Before this analysis can be done, however, room acoustics metrics using spherical microphone arrays must be verified against traditional methods in order to gain confidence that the measurements are consistent. This research is

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especially necessary due to the fact that previous work has shown a large variation in measured parameters made between different microphone types and with different measurement teams [8–13]. Additionally, this comparison is necessary since spherical microphone arrays are generally larger than conventional measurement microphones, and therefore may alter the sound field if the sound wave that is scattered from the array reflects off of nearby objects and returns to the microphone array [1].

Obtaining room acoustics metrics with spherical microphone arrays may offer some advantages compared to measurements made with conventional microphones. Spatial measures are typically obtained using a figure-8 microphone. Commercially available figure-8 microphones are not laboratory-grade and may not have ideal directivity, frequency response, or linearity; whereas spherical array microphones are typically constructed using laboratory-grade microphone capsules. Spherical microphone arrays also enable the researcher to rotate the figure-8 pattern in post-processing to perfectly align the pattern to the source, which could reduce measurement uncertainty. Finally, current spherical microphone array technology enables beamforming utilizing spherical harmonics up to third- or fourth-order, which can be used to create new room acoustics metrics with a much higher spatial resolution than the traditional first-order dipole.

The purpose of this case study was to compare measurements taken in accordance with the ISO 3382 standard using a traditional omnidirectional and figure-8 microphone pair with measurements taken using a spherical microphone array. This comparison is required in order to gain confidence that room acoustics measurements made with a spherical microphone array can be directly compared to measurements made with traditional methods. Once this verification is complete, new metrics with higher spatial resolution can be developed.

1.1. Room acoustics metrics

The metrics that were evaluated in this study are defined in ISO 3382 and accompanying Annex A. The omnidirectional measures are reverberation time (T30), measured from a 30 dB decay from the Schroeder backwards integrated curve; early decay time (EDT), measured from the slope of the first 10 dB decay of the Schroeder backwards integrated curve; clarity index (C80), the ratio of the early sound in the first 80 ms to the late sound; and strength (G), the energy in the room IR normalized to the level of the sound source measured at a distance of 10 m in a free field. In addition to the commonly used omnidirectional measures, metrics used to predict the spatial impression of a room are included in Annex A of ISO 3382. Spatial impression is one characteristic that has been shown to be related to overall room impression [14–16]. Previous research proposed that spatial impression should be formally divided into two distinct components [17]: the apparent source width (ASW) as being associated with the early lateral reflections, and listener envelopment (LEV), which is related to late lateral reflections [18]. A number of objective measures have been proposed to predict both ASW and LEV that utilize either directional microphones or a binaural head [19]. The two spatial metrics that have gained the largest acceptance in the architectural acoustics community are early lateral energy fraction (J_{LF}, previously LF) [20], which is used to predict ASW, and late lateral energy level (L_J, previously GLL, LG, and LG_{80}^{∞}) [18], which is used to predict LEV. Both of these metrics are included in ISO 3382 Annex A and were evaluated as part of this study. J_{LF} is the ratio of early lateral energy to total early energy:

$$J_{LF} = \frac{\int_{5\text{ ms}}^{80\text{ ms}} p_f^2(t)dt}{\int_0^{80\text{ ms}} p_o^2(t)dt}, \tag{1}$$

where $p_f(t)$ is the IR measured with a figure-8 microphone, and $p_o(t)$ is the IR measured with an omnidirectional microphone. L_J is the ratio of the late lateral energy to the normalized source energy:

$$L_J = 10\log\left[\frac{\int_{80\text{ ms}}^{\infty} p_f^2(t)dt}{\int_0^{\infty} p_{10}^2(t)dt}\right] \quad [\text{dB}], \tag{2}$$

where $p_{10}(t)$ is the IR of the sound source normalized at a distance of 10 m away in a free field.

2. Measurement uncertainty

A number of studies have shown that there is a high degree of measurement uncertainty in room acoustics metrics obtained from room IRs [8–13,21–25]. Specific sources of uncertainty and studies between measurement teams are summarized below. A common method to evaluate uncertainty is to compare measurements in terms of just noticeable differences (JNDs). The JND for each room acoustics parameter is included in the Annex A of ISO 3382 [7]: 5% for T30 and EDT, 1 dB for C80, 1 dB for G, 0.05 for J_{LF}, 0.05 for definition (D), and 10 ms for center time (T_S); the JND for L_J is not known. For the purposes of this study, the JND for G will be used for L_J.

The contributions of different sources of uncertainty to the overall measurement uncertainty has been studied in Ref. [21]. The main contributions to measurement uncertainty are source position and orientation, microphone placement and orientation, source directivity, microphone directivity, and measurement hardware frequency response. Source directivity, in particular, has been shown to be a significant portion of the measurement uncertainty as a result of non-uniform source directivity. The most common sound sources used in room acoustics are dodecahedron loudspeakers, which typically become directional above approximately 1 kHz. Therefore, the orientation of the source can yield different results in room acoustic metrics [22,23]. A second major contributor is microphone placement, where measures can vary widely even within a single seat location [24,25]. Additional sources of uncertainty include ambient room conditions (i.e. temperature and humidity), evaluation methods (e.g. different signal processing and filtering methods), room noise, and equipment noise.

Studies comparing metrics calculated from IRs obtained from different measurement teams show differences that exceed the JND of each metric in most cases [8–10]. One of the earliest studies comparing the results from four measurement teams showed that the standard deviation across the teams were around 5% to 10% for T30, EDT, D, and T_S, and around 0.5 dB for C80 and G from 1 kHz to 4 kHz, which are all on the order of 1–2 JNDs [8]. The largest differences tended to occur in the 125 Hz octave band. Additionally, larger differences were found in J_{LF} measurements with differences up to 4 JNDs at 1 kHz.

The first phase of the third round robin on room acoustics simulation programs was to collect measurement data on the space that was to be modeled [9]. T30, EDT, C80, and G measurements all showed differences well above 1 JND with the largest differences in the 125 Hz octave band. Again, the largest differences were found in the parameter J_{LF} which were on the order of 3 to 5 JNDs in various octave bands and receiver positions. As part of the third round robin study, some follow-up measurements using three figure-8 microphones of the same make and model (Neumann KM86) revealed significant differences in measurements taken with the microphones at different orientations (i.e. rotated 180°). One possible source of this measurement error was hypothesized to be due to changes in the microphone sensitivity of each diaphragm due to aging.

A third study compared measurements made in opera houses using different measurement hardware and excitation techniques