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The Sound Power as a Reference for Sound Strength (G), Speech Level (L) and Support (ST): Uncertainty of Laboratory and In-Situ Calibration

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Summary

Some room acoustic parameters require the sound power of the sound source. The Sound Strength G uses the free field sound pressure level at 10 meters distance as a reference value. Speech intelligibility parameters like the A-weighted Speech Level, $L_{p,A,S,4m}$, and the Speech Transmission Index, STI, can require an absolute source level defined at 1 m distance from the sound source. The Early and Late Support parameters use the sound level at 1 m distance as a reference level. In this paper, all proposed methods to obtain the sound power level for room acoustic applications are investigated, using various omnidirectional sound sources with a dodecahedron shape containing 12 loudspeakers. It is shown that, for octave bands 250 to 8,000 Hz, the sound power can be determined with 0.8 dB uncertainty when using precision methods (diffuse field, intensity or free field). Alternative laboratory calibration methods, that only measure in a single plane of the sound source, show deviations up to 2 dB per octave band. Different stepwise rotational averages, used in such a single plane free field method, have been investigated. It can be concluded, that the uncertainty is significantly reduced only when using 12.5 degree steps (ISO 3382-1) and when using equal-angular rotations with 5 or 7 steps. Furthermore, the uncertainty of in-situ calibration has been investigated. A comparison of results from different researchers shows that a correction factor should be applied to correct the in-situ calibration for its deviation from the laboratory calibration. For each calibration method the uncertainty is presented. Results show that some methods might be sufficiently accurate to be able to measure single number ratings for G, ST, $L_{p,A,S,4m}$ and STI with an uncertainty in the order of magnitude of 1 JND, provided that no other measurement errors are introduced in the measurement chain.

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1. Introduction

Various room acoustic parameters have been introduced, some of which have been included in the ISO standard 3382 on the measurement of room acoustic parameters [1]. Many room acoustic parameters are defined in such a way, that the sound power of the sound source is not relevant. Energy decay related parameters (EDT, T_{20} and T_{30}), energy related parameters (C_{80}, D_{50}, T_s), lateral energy measures (J_{LF}, J_{LFC}), spatial impression parameters (IACC) and the spatial decay parameter ($D_{2,S}$) all make use of a relative definition.

However, some room acoustic parameters do require knowledge of the sound power of the sound source. Level parameters (G, L_J, and $L_{p,A,S,4m}$) and stage support parameters (ST_{early} and ST_{late}) measure the amount of energy of a room impulse response within a certain time interval and/or direction, and compare it to the energy of the impulse response from the same sound source measured in the free field at a certain distance. Also, when determining speech intelligibility parameters, like STI, the signal to noise ratio is determined based on a ratio of absolute sound pressures (following ISO 16268-16 [2], only if background noise is taken into account, and following ISO 3382-3 [3], for all measurements in open plan offices). Following ISO 3382, all of these room acoustic parameters should be determined using an omnidirectional sound source. A certain deviation from omnidirectionality is allowed and the deviation limits are given in the standard.

Lundeby *et al.* [4] asked 8 different teams to determine room acoustic parameters for 10 source–receiver combinations in a 1,800 m^3 auditorium. He found a standard deviation for the level parameter Sound Strength G of only 0.2 to 0.3 dB for the octave bands 125, 1,000 and 4,000 Hz. These results would suggest that G can be measured with very high accuracy, even when using a variety of loudspeaker types (a single loudspeaker in a box, a cube with six loudspeakers and a dodecahedron with twelve loudspeakers). Unfortunately, in their paper it is not explained how the sound sources were calibrated. In theory, the relation between the sound power of a point source and its sound pressure level (SPL) in the free field is clear. How-

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ever, in earlier research we have shown that different methods to obtain the free field SPL may yield different results with deviations more than 2 dB for individual octave bands [5]. The low standard deviations found by Lundeby *et al.* [4] between 8 different measurement teams are therefore highly questionable.

The deviations in sound power determination are problematic as one would like to measure most room acoustic parameters within the limits of their Just Noticeable Difference (JND), which can be as low as 1 dB for some level parameters. It is necessary to find out when measurement methods are sufficiently accurate and which methods should be avoided. In this paper, the difference between various calibration methods, and the impact of simplifications within these methods, are investigated. This is done by using available data from literature and, to close some knowledge gaps or to check whether the findings from literature can be reproduced, by performing additional measurements or analysing shared data from other researchers. In some cases, results are only available from one single research(er) using one single loudspeaker type, which is often dodecahedrally shaped. We did not perform such extensive amount of measurements, necessary to significantly identify all uncertainty contributions in each measurement method, but the main conclusions are based on results from multiple investigations involving various researchers and sound sources. The overview presented in this paper provides valuable insight in the merits of sound source calibration for room acoustic purposes and some major problems have been identified.

In this paper, the background on the most relevant room acoustic parameters and common calibration methods is discussed in Section 2. In Section 3, the differences of various laboratory measurement methods, concerning the sound power as a reference for room acoustic parameters, are discussed. Findings from literature and new research have been combined to investigate uncertainties. In Section 4, problems with the directivity of the sound source are discussed, which is particularly important for the calibration methods that only measure in the horizontal plane of the sound source while taking rotational averages. In Section 5, in-situ measurement methods are discussed, including (floor) interference effects and variations over different positions. In Section 6, the paper will conclude with a summary and conclusions on the uncertainty that can be expected from using the available methods.

2. Background

2.1. Room acoustic parameters and sound power

The sound strength G is used to investigate the sound distribution in a concert hall or to compare the sound levels between different concert halls. Originally, Lehmann introduced the *Stärkemass* or 'Strenght Index', which was defined as the difference in SPL in the hall caused by an omnidirectional sound source on the stage, and the sound power level L_w of the same sound source [6]. Later on, G was defined as the SPL at a listener position in the hall, with reference to the SPL at 10 m distance from the same sound source in a free field. The late lateral sound energy level L_J is similar to G in its definition of the reference level. Here, the late sound energy arriving after 80 ms at a figure-of-eight microphone is compared to the total sound energy at 10 m distance at an omnidirectional microphone in the free field. For G the 10 meter distance was chosen by Barron and Lee for reasons of convenience because this choice will often result in measured values of the sound level L_p close to the reference value $L_{p,10\mathrm{m}}$ and hence values of G close to 0 dB [7]. G can either be determined using stationary noise or using impulse responses [1], where the sound pressure exposure level L_{pE} is determined (up to the time point that the energy decay, or Impulse to Noise Ratio (INR) [8], is 30 dB or lower). The single number rating for G is calculated from the average of the 500 and 1000 Hz octave band, defined by ISO 3382-1 as G_M, and the Just Noticeable Difference (JND) is 1 dB. For L_J the single number rating is calculated from the average of the 125 to 1000 Hz octave band, denoted by $L_{J,\mathrm{avg}}$. The JND for L_J is unknown.

$L_{p,A,S,4m}$ is the A-weighted SPL of normal speech at 4 meter distance from an omnidirectional sound source. $L_{p,A,S,4m}$ is used together with $D_{2,S}$, the decay of sound per doubling of the distance, to describe the decay of speech sound in an open plan office. A standardised spectral level $L_{p,S,1\mathrm{m}}(f)$ defined at 1 meter distance is used to describe the sound power of the normal speaker [3]. After A-weighting the speech spectrum, the sound level in dB(A) is predominantly dependent on the level in the 500 and 1000 Hz octave bands. The distance of 4 m is chosen as a nominal distance where the far field starts [9]. In a similar way, the absolute SPL of speech is used in the calculation of the Speech Transmission Index (*STI*), where the SPL of the received speech $L_{p,S(f)}$ and the SPL due to background noise $L_{\mathrm{eq},N}(f)$ is used to determine the signal to noise ratio (SNR). In both $L_{p,A,S,4m}$ and *STI* parameters, the sound power of the sound source must be known to be able to apply the standardised spectrum and level. The JND for the *STI* is 0.03 [10]. The impact of reverberation on *STI* is small in open plan offices, as shown by Wenmaekers *et al.* [11]. In a worst case scenario, where reverberation does not affect the *STI* calculation and the influence of background noise is fully dominant, we can translate the JND of the *STI* as a JND of the SNR in dB. In this way, the maximum possible error in Signal level (or speech level $L_{p,S}$) due to calibration uncertainty can be investigated. In this paper, the individual errors $\Delta L_{p,S(f)}$ in dB over the octave bands 125 to 8000 Hz are translated into a modulation transfer index $MTI(f)$ by $(\Delta L_{p,S(f)}+15)/30$. The $MTI(f)$ is weighted in accordance with IEC 60268-16 and the *STI* is calculated. Then, to arrive at a weighted single-number rating error, $\Delta L_{p,S,\mathrm{single}}$ is calculated as $(STI\times 30)-15$ dB. A difference of 0.03 in *STI* appears at approximately 1 dB difference in $\Delta L_{p,S}$,single.

The stage acoustic parameters Early Support, ST_{early}, and Late Support, ST_{late}, are used to investigate the ensemble conditions and perceived reverberance by musicians on

Table I. Overview of room acoustic quantities that depend on a reference level. *: because the 500–1000 Hz bands are dominant after A-weighting the speech spectrum, the 500 and 1000 Hz bands average level will be used an indicator for $L_{p,A,S,4\mathrm{m}}$. **: estimated by A.C. Gade.

Acoustic Quantity	Parameter	Reference	JND	Single Number
Sound Strength	G	$L_{p,10\mathrm{m}}$ or $L_{pE,10\mathrm{m}}$	1 dB	500–1000 Hz
Late Lateral Sound Energy Level	L_J	$L_{p,10\mathrm{m}}$ or $L_{pE,10\mathrm{m}}$	not known	125–1000 Hz
A-weighted speech level at 4 m	$L_{p,A,S,4\mathrm{m}}$	L_w or $L_{p,1\mathrm{m}}$	not known	A-weighted level*
Speech Transmission Index	STI	L_w or $L_{p,1\mathrm{m}}$	0.03 STI (= 1 dB in $\Delta L_{p,S,\mathrm{single}}$)	Weighted over 125–8000 Hz
Early Support	ST_{early} or $ST_{\mathrm{early},d}$	$L_{p,1\mathrm{m}}$ or $L_{pE,1\mathrm{m}}$	2 dB **	250–2000 Hz
Late Support	ST_{late} or $ST_{\mathrm{late},d}$	$L_{p,1\mathrm{m}}$ or $L_{pE,1\mathrm{m}}$	2 dB **	250–2000 Hz

concert hall stages. Both parameters are commonly determined at 1 meter distance from an omnidirectional sound source and measure the early or late reflected sound energy relative to the direct sound energy of the sound source [12, 13]. More recently, the extended parameters $ST_{\mathrm{early,d}}$ and $ST_{\mathrm{late,d}}$ have been introduced that can be used to study the transfer of reflected sound energy over the stage at various distances [14]. The 1 meter distance reference is chosen as it is comparable to the distance of the musical instrument to the players' ears [12] (even though other researchers suggested that this distance is smaller in many cases [15, 16]). The direct SPL at 1 m distance was intended to be the free field sound level, as explained by Gade [17]. The method described in ISO 3382 uses a reference level measured in-situ. The single number rating for the ST parameters is the average of the four octave bands 250 to 2000 Hz and the estimated JND for the ST parameters is 2 dB [18].

An overview of the parameters mentioned in this paragraph is presented in Table I. The different frequency ranges are used in the different parameters because they relate to different perceptual aspects. In this paper, the frequency ranges as suggested by ISO 3382 are used.

2.2. Calibration methods in room acoustics

A large number of methods for the determination of sound power levels of sound sources is described in the ISO 3740 series [19], ranging from reverberation room methods to intensity or pressure level measurements in a (hemi) free field. Depending on the desired accuracy, different methods can be applied. For the determination of the sound power level of an omnidirectional sound source used for room acoustic measurements, ISO 3382-1 suggests two different calibration methods. ISO 3382-3 refers to this same part of the standard and suggests determining the sound power with at least 'engineering accuracy'.

Following the first method mentioned in ISO 3382-1, one directly measures the SPL at 10 meters distance to the sound source in an anechoic room or, in case only a smaller anechoic room is available, one measures at a distance of at least 3 m (to avoid being in the near field of the loudspeaker) and translates the measured SPL to a 10 meter distance. In accordance with ISO 3382-1, the energy mean sound level needs to be determined from 29 measurements at every 12.5° step rotation of the sound source. It is remarkable that the sound power of the omnidirectional sound source, which most often has a dodecahedral shape containing 12 loudspeakers, is determined from measurements in one single horizontal plane only, see Figure 1. In contrast, the methods in the ISO 3740 series suggest measuring over an equally spaced grid around the sound source. In ISO 3382-1, no scientific study is quoted that motivates the 12.5° rotation method, nor is its accuracy discussed. Among others, this method has been applied by Barron and Lee [7], Aretz and Orlowski [20] and Dammerud [21]. In this paper, this method will be denoted the 'single plane free field method'.

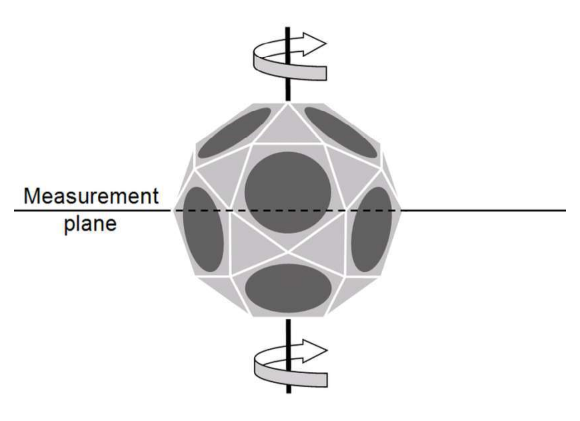

Figure 1. Side view of vertical rotation axis and horizontal measurement plane of a dodecahedron loudspeaker, used in the 'single plane free field method' for calibrating omnidirectional sound sources.

The second method described in ISO 3382-1 uses the precision method for reverberation rooms in accordance with ISO 3741 [22]. When using stationary noise, the sound power is determined following the full standard's procedure. When using impulse responses, a system calibration can be performed in the reverberation room without measuring the actual sound power. During a system calibration, the sound exposure level L_{pE} is measured in the reverberation room, then corrected for the amount of

Table II. Overview of calibration methods using for room acoustic parameters.

Calibration method	Standard	Procedure	Averaging
1. Single plane free field method (ISO 3382-1, Annex A)	none	SPL measured in an anechoic room at any distance > 3 m and translated to the SPL at 10 m distance	Average taken from 29 rotations in the horizontal plane with steps of 12.5°
2. Reverberation Room (ISO 3382-1, Annex A)	ISO 3471	SPL and T measured in a reverberation room of at least 200 m^3 for octave bands $\geq$ 125 Hz	SPL measured over 30 seconds for 6 microphone positions (if standard deviation is below 1.5 dB)
3A. In-situ on stage original (ISO 3382-1, Annex C)	none	The direct SPL/SEL measured in-situ from the measured impulse response using a 0–10 ms window at 1 m source-receiver distance	Single measurement at random angle relative to the omnidirectional sound source
3B. In-situ on stage update [17]	ISO 3471	idem 3A, with additional correction for 1 m distance SPL derived from a sound power measurement in a reverberation room	Single measurement at fixed angle relative to the omnidirectional sound source
3C. In-situ on stage by others [24, 25]	none	The direct SPL/SEL measured in-situ from the measured impulse response using a 0–3.5 or 0–5 ms window at 1 m source-receiver distance	Single measurement at random fixed angle relative to the omnidirectional sound source

absorption in the room and used as a reference for any future sound exposure level measurements (comparing relative levels). According to ISO 3741:1999, in octave bands, the uncertainty in terms of the standard deviation of reproducibility is equal to or less than 2.5 dB for 125 Hz, 1.5 dB for 250 Hz, 1 dB from 500 Hz to 4,000 Hz and 2 dB for 8,000 Hz (in the 2010 edition of ISO 3741 the octave band values are no longer mentioned). Among others, this method has been applied by Gade [23], Virjonen *et al.* [9] and Beranek [24].

Essentially, the Support parameters ST_{early} and ST_{late} as described in ISO 3382-1, use a third method to determine the sound power level of the sound source. A reference level is determined in-situ from the impulse response measured at 1 m distance using a 0-10 ms window. Within this 0-10 ms time interval, the floor reflection is included which introduces an error in the determination of the direct sound. Also, errors due to loudspeaker directivity are being introduced because of the use of only one single measurement. Gade [17] suggests to compensate for these errors by first determining the SPL at 1 meter distance based on a sound power laboratory measurement. After that, the measured SPL at 1 meter distance is determined in-situ on a reflective surface and for a certain fixed angle or aiming point relative to the omnidirectional sound source. The difference between these two values could be applied to the ST_{early} and ST_{late} as a fixed correction factor for future in-situ measurements. After performing this procedure once, there would no longer be the need for calibrating the sound source in the laboratory (in the short term). It should be noted that this correction procedure is not mentioned in ISO 3382-1.

Similar in-situ methods have been used by various researchers to measure G. Beranek [24] notes that all researchers mentioned in his paper used an in-situ calibration measuring the sound pressure level at 1 meter distance, except for the Takenaka R&D institute who used a reverberation room calibration. Dammerud and Barron [25] used a reference microphone at 1 meter during their scale model measurements, as the used spark source could not reproduce the same output power for every measurement. They extracted the direct sound by windowing over the 0 to 3.5 ms interval of the impulse response. San Martin *et al.* [26] used a similar approach on concert hall stages by windowing over the 0 to 5 ms interval. An overview of all mentioned calibration methods is presented in Table II.

2.3. Signal processing in-situ measurements

In case of source and receiver heights of 1.0 m, the floor reflection will arrive 3.6 ms after the direct sound, and for the 250 Hz octave band, which is the most critical in the 250–2,000 Hz frequency range, these two components will be smeared out over the whole time interval 0–10 ms due to the band filtering. So, it seems to be impossible to separate the direct sound and floor reflection by windowing. Actually, earlier research by the authors [14] has shown that, to reduce the error in determining the sound level of the direct sound separately from a signal with direct sound and a single equally loud reflection to ≤ 0.1, ≤ 0.5 and ≤ 1.0 dB, a minimum distance between direct sound and reflection of 17, 12 and 9 ms is required respectively for the separate octave bands 250, 500, 1,000 and 2,000 Hz (see Annex for the type of signal processing used). When measuring sound levels, it is also necessary to take into account the size of the wavelength and it is recommended to use a time window of at least one corresponding wavelength. For the 250 Hz octave band with lower edge frequency at 176 Hz this suggests that the time window should at least be 6 ms and for the 125 Hz octave band with lower edge frequency at 88 Hz at least 11 ms. So, it seems that a minimum time window of 11 ms is needed for highly accurate measurements starting from the 125 Hz octave band, while room reflections should not arrive before 17 ms. This again shows that the floor reflection cannot be excluded.

Other elements of signal processing exist that might cause variation of results from different researchers.
Among others, the determination of the impulse response starting point can be done in various ways, which might influence results from in-situ calibrations. Also, as pointed out by Lundeby *et al.*, the method of filtering can be of influence on results of level calculations. Uncertainty introduced by signal processing is mostly relevant for judging reproducibility and less relevant for judging repeatability. In our paper, we assume that the uncertainty contribution of the signal processing is part of the whole measurement procedure and is therefore included in the analysis. Detailed analysis of uncertainty due to signal processing is outside the scope of our paper, but would be interesting for further research.

3. Laboratory calibration measurements

3.1. Precision methods

The uncertainties in the determination of the sound power (or reference SPL) of sound sources have been studied under laboratory conditions by Vorländer and Raabe [27]. They organised a round robin among 8 laboratories during which the sound power of a B&K 4204 reference sound source was measured in hemi-anechoic and in reverberant conditions. The uncertainty due to the use of different types of signal processing was included in the research. They concluded that, in general, both methods yield almost exactly the same results, except in the frequency ranges below 100 Hz and above 10 kHz. The maximum standard deviation σ and reproducibility limit R (probability level of 95% using a coverage factor of 2.8) of both methods are 1.0 dB and 2.8 dB in the 125 Hz octave band and 0.3 dB and 0.8 dB in the 250 to 8,000 Hz octave bands. The reproducibility is similar to the values suggested by ISO 3741:1999.

To the knowledge of the authors, no literature exists about the stability of dodecahedron loudspeakers, which is known to be a critical design element for the type of sound sources. Sound power measurements (at 120 dB sound power level) performed by the authors in a 90 m^3 reverberation room, repeated 10 times over four years using a dodecahedron loudspeaker B&K 4292, a B&K 2734 amplifier and a B&K 4189 microphone on a rotating boom, showed a standard deviation of 0.3 dB in the separate 250 to 8,000 Hz octave bands (the 125 Hz octave band could not be evaluated as the room volume was too small). The standard deviation of our measurement with the dodecahedron sound source is similar to the standard deviation found by Vorländer and Raabe for the reference sound source. It shows that, even over a four year period, the stability of a dodecahedron loudspeaker, in this case a B&K 4292, can be as high as a reference sound source type B&K 4204, provided all other used measurement equipment is highly stable too.

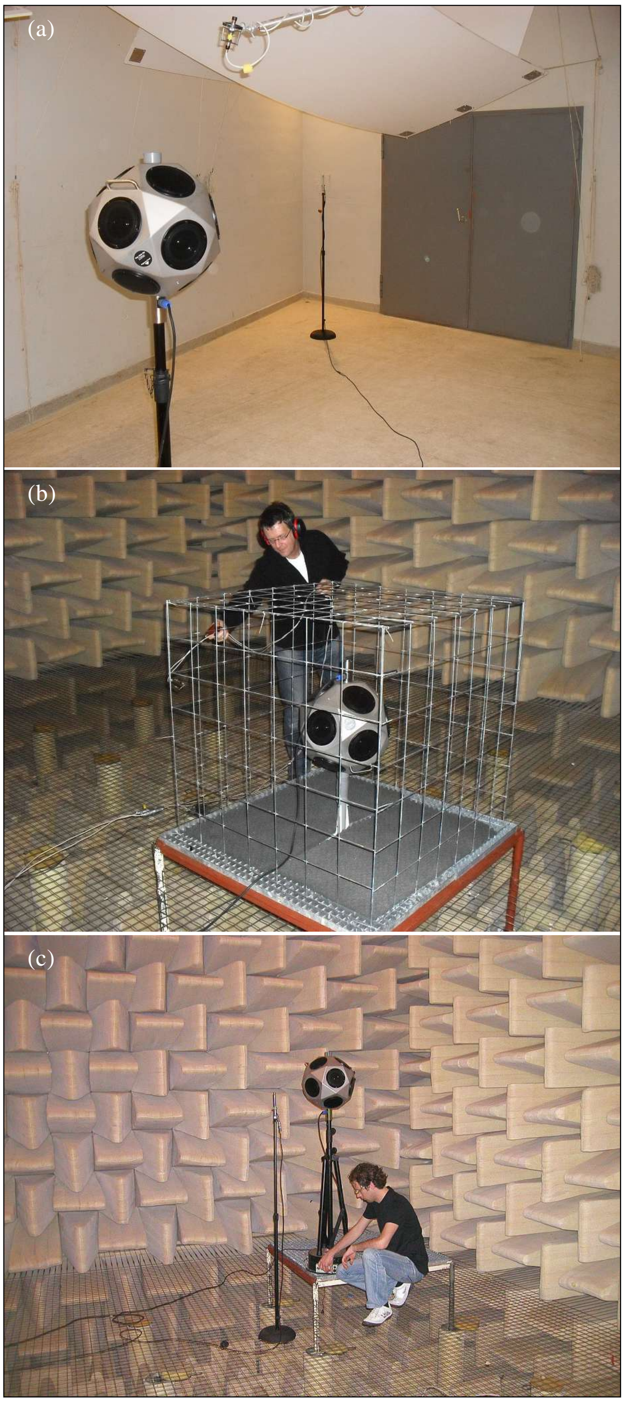

Figure 2. (a) Measurement setup in the reverberation room (using a reference source); (b) Measurement setup in the anechoic room using the intensity probe (a metal grid was used to define the scanning surface); (c) Measurement setup in the anechoic room using a omnidirectional microphone and a turntable (single plane free field method).

Furthermore, the difference between two types of precision calibrations has been investigated for the dodecahedron loudspeaker type B&K 4292, to investigate whether the difference would fall within the reproducibility limits as found by Vorländer and Raabe and mentioned in ISO 3741:1999. The sound power was determined in a 200 m^3 reverberation room in accordance with ISO 3741, see Figure 2a, and in an anechoic room via a sound intensity measurement using a sweep scan method following ISO 9614-3 [28], see Figure 2b (see Annex for details). Note that the intensity measurement used by us is different from the sound level measurement used by Vorländer and Raabe, although both are executed in a (hemi)anechoic room. Our measured results for the direct reverberation method and anechoic intensity method are presented in Figure 3a as average sound power levels relative to the average result of both measurement methods. The maximum difference between L_w for the methods individually and their average L_w is at most 0.3 dB over the 250–4,000 Hz octave bands with a standard deviation of 0.5 dB over the individual receiver positions or scanning surfaces. In the 125 and 8,000 Hz octave bands, the maximum difference is larger, up to ±1.0 dB with a standard deviation up to 1.0 dB. For the 125–4,000 Hz octave bands, the difference in our results are well within the reproducibility limits of R = 0.8 dB at 250–8,000 Hz and R = 2.8 dB at 125 Hz as found by Vorländer and Raabe. We can conclude that the difference in results from our two different measurements can be attributed to each test methods' precision.

3.2. Full sphere versus single plane

Besides the reverberation room precision method, ISO 3382-1 recommends performing a sound power measurement in an anechoic room, where the average level is determined from 12.5° rotation of the sound source, denoted here by the 'single plane free field method'. Unlike the intensity measurement, where a full sphere around the source is measured, in the ISO 3382-1 method, only the horizontal plane is measured (see Figure 1). To find out if an error is introduced by measuring in a single plane instead of measuring around a full sphere, we performed measurements using the single plane free field method at 1 m and 7 m distance from the physical centre of the omnidirectional dodecahedron sound source in an anechoic room. We compared the results to the intensity measurement presented earlier, which takes into account all directions. A noise signal was recorded at both distances simultaneously while rotating the sound source using a turntable, see Figure 2c (see Annex for details). The deviation in measured sound power at both distances from the results of the intensity measurement is presented in Figure 3b. It is shown that the results for the two measured distances follow a similar trend. The average over all octave bands is equal for both distances. The deviation of the results using the single plane free field method from the results from the intensity measurement is above 0.5 dB up to 2.1 dB for almost all octave bands, see figure 3b. Surprisingly, for the frequency range below 500 Hz where the dodecahedron sound source is expected to be fully omnidirectional, the deviation is 0.8 dB on average. Note that the expected reproducibility for precision calibration methods is 0.8 dB for 250 and 500 Hz. This means that the deviation up to 500 Hz, that we found comparing the intensity method and the single plane free field method, can be attributed to the overall precision of the measurement method. However, the larger deviation above 500 Hz might

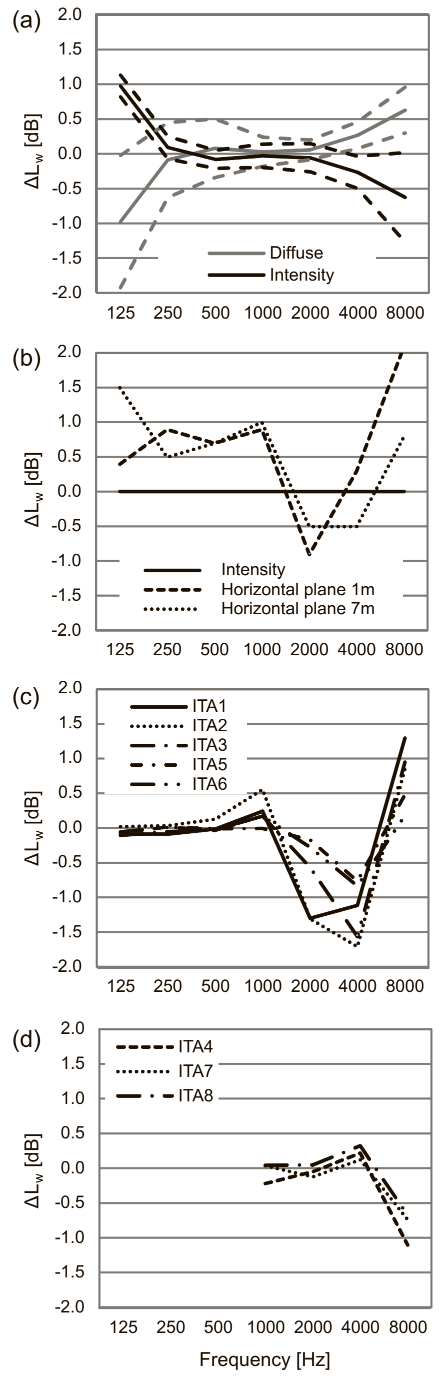

Figure 3. (a) Comparison of the sound power levels, measured in diffuse field using a omnidirectional microphone and anechoic conditions using an intensity probe, relative to the mean. (b) Comparison of the sound power level measured at 1 m and 7 m distance in the horizontal plane in an anechoic room, relative to the sound power level measured using an intensity probe over the full sphere in an anechoic room. (c) The deviation between the full sphere average and single plane average for various moderate size dodecahedron loudspeakers (with a section of 300-400 mm). (d) The deviation between the full sphere average and single plane average for various small size dodecahedron loudspeakers (section approximately 100 mm) that are used in a three way loudspeaker setup.

Table III. Uncertainty factors and calculated uncertainty for the precision method and single plane free field method. *: under the assumption that the deviation in different octave bands is correlated **: estimated by the average over the octave bands ***: offset and deviation at 95% confidence level and 2.8 coverage factor. ll: lower limit; ul: upper limit.

	Octave band with mid frequencies [Hz]							Single number ratings average*			
	125	250	500	1000	2000	4000	8000	125–1000	250–2000	500–1000	*STI*
$\sigma_{\text{precision}}$	1	0.3	0.3	0.3	0.3	0.3	0.3	0.5**	0.3	0.3	0.4**
$\text{offset}_{\text{plane}}$	0	0	0	0.2	-0.9	-1.1	0.8	0	-0.2	0.1	-0.3
σ_{plane}	0.1	0.1	0.1	0.2	0.6	0.5	0.4	0.1	0.1	0.1	0.1
$U_{95\%,\text{precision}}$	**±2.8**	**±0.8**	**±0.8**	**±0.8**	**±0.8**	**±0.8**	**±0.8**	**±1.4**	**±0.8**	**±0.8**	**±1.1**
$U_{95\%,\text{plane}}$***	**0**	**0**	**0**	**0.2**	**-0.9**	**-1.1**	**0.8**	**0**	**-0.2**	**0.1**	**-0.3**
	±2.8	**±0.9**	**±0.9**	**±1**	**±1.9**	**±1.6**	**±1.4**	**±1.4**	**±0.9**	**±0.9**	**±1.2**
$U_{95\%,\text{plane}}$, ll	-2.8	-0.9	-0.9	-0.8	-2.8	-2.7	-0.6	-1.4	-1.1	-0.8	-1.5
$U_{95\%,\text{plane}}$, ul	2.8	0.9	0.9	1.2	1.0	0.5	2.2	1.4	0.7	1.0	0.9

be caused by the simplification of measuring only a single plane instead of measuring a full sphere.

To investigate whether the high frequency deviation between the full sphere and single plane measurement found for the B&K 4292, presented in Figure 3b, is representative for dodecahedron loudspeakers in general, directivity data for various dodecahedron loudspeakers have been analysed which were measured by the Institut für Technische Akustik (ITA), RWTH Aachen (sources denoted ITA1 to ITA4 are described in [29]). The directivity was measured with a 5 degree grid over half the sphere, using a similar setup as described in Leishmann *et al.* [30], Section II. The emitted sound power, averaged over the full sphere, is determined by weighting over the surface area per grid point as described in Leishmann *et al.* [30], Section IV-B, equations 3 to 6. The emitted sound power, averaged over a single plane, was derived from the 72 measurements in the horizontal plane in the base of the half sphere. The calculated deviations between the full sphere average and single plane average are presented in Figure 3c for various moderate size dodecahedron loudspeakers (with a diameter of 300-450 mm) and in Figure 3d for various small size dodecahedron loudspeakers (diameter approximately 100 mm) that are used in a three way loudspeaker setup for the 2 kHz octave band and higher. For the moderate size dodecahedrons, a similar frequency trend is found as presented in Figure 3b. Now, we can conclude that the single plane method introduces a systematic error with a slight variation over different sound sources with similar size.

3.3. Discussion on laboratory calibration measurements

The uncertainty of the precision calibration methods, to determine the sound power of a highly stable omnidirectional sound source, is within 0.8 dB for the octave bands 250–8,000 Hz. However, in the 125 octave band, the deviation is found to be > 1.0 dB which is larger than the JND in case of G. The absolute deviation between a full sphere average (any precision method) and the single plane average (as suggested by ISO 3382-1) is significant for frequency bands 2,000–8,000 Hz with errors up to 2.1 dB for various measured dodecahedron loudspeakers. This systematic deviation can be attributed to the geometrical simplification in the measurement method.

To determine the total uncertainty for each method, models are defined that show how the different identified sources of uncertainty propagate through the measurement procedure. Because the number of number of data points in the Vorländer and Raabe study and our studies are limited, it is not possible to determine its distribution. However, following Vorländer and Raabe, we have no reason to doubt whether data would not be normally distributed. The standard deviation is expanded with a coverage factor of 2 multiplied by a factor $\sqrt{2}$, recommended for cases with a small amount of data. This way, we can expect to arrive at a level of confidence of approximately 95%.

The uncertainty of the precision method and single plane free field method can be expressed by

$$U_{95\%,\text{precision}} = \pm 2.8\sqrt{\sigma^2_{\text{precision}}}, \tag{1}$$

and

$$U_{95\%,\text{plane}} = \text{offset}_{\text{plane}} \pm 2.8\sqrt{\sigma^2_{\text{plane}} + \sigma^2_{\text{precision}}}, \tag{2}$$

where $U_{95\%,\text{precision}}$ is the uncertainty of the precision method at 95% confidence level in dB (coverage factor 2.8), $\sigma_{\text{precision}}$ is the maximum standard deviation of the precision methods in dB taken from Vorländer and Raabe [27], $U_{95\%,\text{plane}}$ is the uncertainty of the single plane free field method at 95% confidence level in dB, and $\text{offset}_{\text{plane}}$ and σ_{plane} is the average systematic error and standard deviation due to geometrical simplification for 6 moderate size dodecahedron loudspeakers in dB.

Table III shows the values for the parameters used in Equation (1) and (2) and the calculated uncertainty $U_{95\%,\text{precision}}$ for the precision method and $U_{95\%,\text{plane}}$ for the single plane free field method. It seems that for the room acoustic parameters mentioned in Section 2 and presented in Table I, determining all separate octave band values within an JND limit of 1 dB (uncertainty at 95% confidence level) is not possible when using either the precision methods or the single plane free field method for calibration. For the single number ratings G, $L_{p,A,S,4m}$, ST_{early} and ST_{late}, a calibration can be performed with an uncertainty

$\leq$ 1 JND using either a precision calibration method or the single plane free field method. For *STI*, the uncertainty is slightly larger than the JND.

4. Uncertainties due to directivity

In the previous section, some directivity characteristics of the dodecahedron sound source were already revealed in the difference between a sound power measurement averaged over the full sphere and averaged over a rotation in a single plane only. In this section, the impact of sound source directivity on room acoustical measurements, and sound source calibration in particular, is investigated.

4.1. Background on polyhedron loudspeakers and directivity

Recently, the properties of omnidirectional sound sources have been investigated in more depth. Leishmann *et al.* [30] compared the directivities of various regular polyhedron loudspeakers (RPL). They conclude that none of the investigated RPL's are being consistently exceptional in omnidirectional behaviour above their ‘cut-off frequency’, the frequency above which the directivity increases rapidly (see [30] for the definition of ‘cut-off frequency’). Among others, the reduction in omnidirectional behaviour is caused by the spread of the individual loudspeakers relative to the wavelength and by the break up phenomenon on the individual loudspeakers’ cone. The tetrahedron, with four loudspeakers, showed the best performance in the 4 kHz band. The dodecahedron was also found to be a good choice, among other things due to its highest cut-off frequency (1.463 Hz for a 14.6 cm radius) and the most uniform radiation in the 2 kHz octave band. An advantage of the dodecahedron shape, is that the increase of the number of loudspeakers will result in a higher (possible) sound power. It is striking, that the icosahedron shape with 20 loudspeakers, the type that was used by Gade [23], did not show a more uniform radiation than any other RPL with a lower amount of loudspeakers.

Lundeby *et al.* [4] raised the problem of the effect of the directivity of the dodecahedron and the cube loudspeaker on measured room acoustic parameters. They indicate that, for 18 rotation steps of 20°, a standard deviation of almost 0.4 dB in G can be found at the 4 kHz octave band. Actually, San Martín *et al.* [31] found that, for single measurements in a concert hall at 18 meter distance, deviations in all room acoustic parameters, except T_{30}, were above the JND for random orientations of two different sound sources at octave bands with mid-frequencies above 1 kHz. Also, for 24 measurements taken in the horizontal plane (see Figure 1), over a 120° area in steps of 5° using both sound sources, the standard deviation at 2 and 4 kHz is larger than one JND for G. San Martín *et al.* conclude that the uncertainty is not sufficiently reduced when an average value is taken over 3 rotations, as suggested by ISO 3382-1 for field measurements (mentioned authors state that it is common practice to average within a 120° area in steps of 40°). As mentioned before, for sound source calibration, ISO 3382-1 recommends using 29 steps of 12.5°.

The possibility of averaging over multiple rotations with equally sized steps (for instance 4 steps of 90 degrees or 6 steps of 30 degrees) has been investigated by the authors, and our first results were presented in [32]. The maximum sound level deviation from the sound level determined from a full rotation average was determined for various equal-angular step averages. For every possible single rotation (= 1 step), and for every possible multiple rotation averages over equal-angular steps up to a number of 8 steps with any random initial aiming point, the maximum deviation in sound level from the full rotation average was determined at various source-to-receiver distances in a concert hall. An even distribution of the steps over the full rotation was chosen to take into account small differences in sound power by the different loudspeakers (instead of rotating within a single 120° area). It was concluded that, when choosing any of the 1, 2, 3, 4 or 6 equal-angular rotation averages, the maximum deviation was not significantly reduced. Surprisingly, when using an average over 5, 7 or 8 equal-angular rotations, the maximum possible deviation from the full rotation average could be dramatically reduced, far below the JND up to the 4 kHz octave band for all source-to-receiver distances. The dodecahedron loudspeaker has rings of 3 or 6 loudspeakers distributed along the axis of rotation. Possibly, the number of 5 and 7 equal-angular rotations both work because these are prime numbers resulting in a non-symmetrical distribution of measurement points. (These results are only based on one condition, a random concert hall. To confirm the validity of the equal-angular averaging method under different conditions, similar results will also be presented in the end of this section for anechoic conditions using multiple sources).

Investigations were continued by Martelotta [33], who looked at the possibilities of finding an optimal choice of (relatively small) angles for a two or three step rotation average with any random starting point. For his study, he measured room impulse responses for every 5° step over 120°, similar to San Martín *et al.* [31]. He concludes that two measurements, spaced by 60°, or three measurements, spaced by 30°, similarly result in the lowest standard deviation from the average compared to single measurements (using any of the discrete 5° steps as the initial aiming point) in room acoustical parameters G, C_{50}, L_F and EDT. For a G measurement at 10 meter distance in a 1,200 m^3 auditorium, the standard deviation, averaged over 2 and 4 kHz, was reduced from 0.67 dB for a single measurement to 0.25 dB and 0.31 dB for the two or three step rotation average.

4.2. Comparison study of single plane rotational averaging methods

Table IV gives an overview of findings on deviations due to directivity and source rotation. It can be concluded that, for judging level related parameters in separate octave bands $\geq$ 2 kHz and at a single position in a hall, the standard deviation due to source directivity can be larger than the JND. An even larger uncertainty can be expected

Table IV. Overview of findings on directivity and source rotation.

Authors	Orientation and averaging	Conclusions	Distance	Denoted
Lundeby *et al.* [4]	18 rotation steps of 20°	σ of almost 0.4 dB at 4 kHz	auditorium, distance not stated	-
San Martín *et al.* [31]	2 sources with random orientation	absolute deviation in all room acoustic parameters (except T_{30}) above the JND for bands > 1 kHz	concert hall at 18 m distance	-
San Martín *et al.* [31]	24 single measurements over an 120° area in steps of 5°	σ over rotation results at 2 and 4 kHz above JND	concert hall at 18 m distance	'single'
San Martín *et al.* [31]	3 rotation average within a 120° area in steps of 40°	σ not significantly reduced	concert hall at 18 m distance	'0-40-80'
ISO 3382-1 [1]	29 rotation average in steps of 12.5°	deviation unknown	> 3 m in anechoic room	'29x12.5'
Hak et al. [32]	2 to 8 equal-angular rotation average	maximum deviation reduced far below the JND for all octave bands by averaging over 5, 7 or 8 equal-angular rotations	concert hall at 1, 5 and 18 m distance	'2EA' to '8EA'
Martelotta [33]	2 or 3 rotation average within 120° area	optimal choice is 60° spacing for 2 rotation average or 2x30° spacing for 3 rotation average	auditorium at 10 m distance	'0-60' '0-30-60'

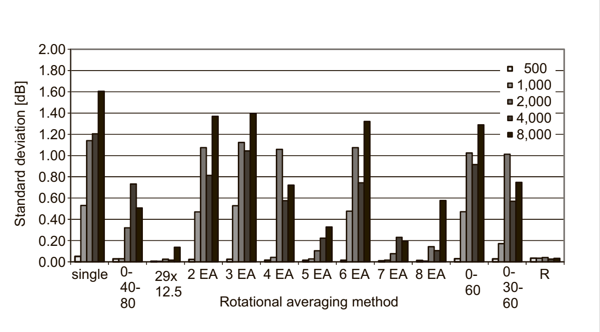

Figure 4. Standard deviation of the sound level by stepwise rotations, for a B&K 4292 measured at 7 m distance in an anechoic room, in single octave bands from 500 to 8,000 Hz for various averaging methods (see Table IV for explanation of methods). R: Repeated measurements without rotation.

when measuring the sound level close to the sound source, which is relevant for this paper. However, there is no agreement on which type of rotation average should be used to find a sufficiently reliable average over the horizontal plane (while ignoring the fact that a single plane average is not the same as a full sphere average). To investigate the various rotational averaging methods, impulse response measurements have been performed by the authors in an anechoic room at 7 m distance using a dodecahedron loudspeaker B&K Type 4292 (see Annex for more details). For every rotation of 5°, an impulse response was determined resulting in 72 measurements. Then, for all averaging methods presented in Table IV, every possible average in sound level was determined (for instance, in case of a '3 rotation average within a 120° area in steps of 40°', the average could be determined 24 times) and its absolute deviation from the average over all 72 measurements is calculated. Linear interpolation was used when needing angles in between the 5° step. Over all these possible absolute deviations within a certain rotational average method, the standard deviation has been determined for each separate octave band from 500 to 8,000 Hz.

Results are presented for the individual octave bands in Figure 4 for the B&K 4292. The standard deviation increases with frequency up and until 2 kHz, while variations in the 2, 4 and 8 kHz bands are of the same order of magnitude. To confirm that the results found for the B&K 4292 are representative for dodecahedron loudspeakers in general, the ITA directivity data for various dodecahedron loudspeakers as presented in section III, has been analysed and the average standard deviations for the 2, 4 and 8 kHz octave band are presented in Figure 5a for the moderate size dodecahedron loudspeakers and in Figure 5b for the small size dodecahedron loudspeakers. The standard deviation of 72 repeated measurements without rotation was found to be below 0.03 dB, proving that the deviations found are indeed caused by directivity variations.

4.3. Discussion on uncertainties due to directivity

From our results of deviation in sound level for the various single plane averaging methods as discussed in the previous paragraph, it can be concluded that an accurate estimation of the single plane average in single octave bands above 500 Hz is not possible using a single random measurement. The deviation from a full single plane average is reduced significantly, only for the ISO 3382-1 method ('29x12.5') and the equal-angular rotations using 5 and

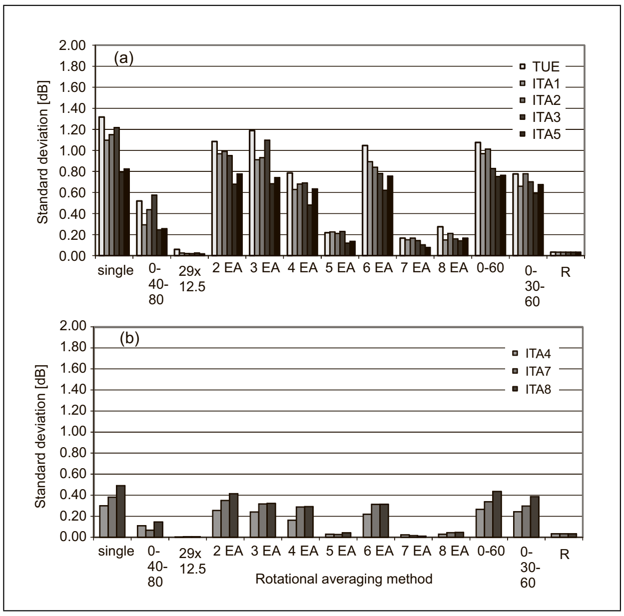

Figure 5. Average standard deviation of the sound level by step-wise rotations for 2, 4 and 8 kHz for various loudspeakers: (a) moderate size dodecahedron loudspeakers (b) small size dodecahedron loudspeakers. R: Repeated measurements without rotation.

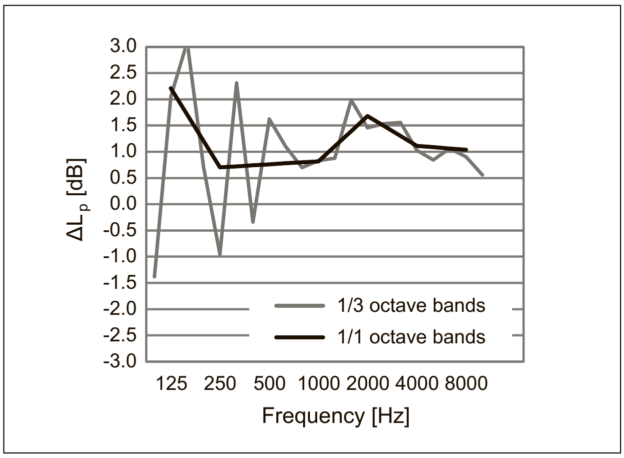

Figure 6. Effect of floor interference: difference in SPL between the average of two on stage measurements and a measurement in an anechoic room. Results averaged over a full rotation in the horizontal plane while producing a noise signal.

7 steps (‘5EA’ and ‘7EA’). For the 5 steps equal-angular rotation, the standard deviation introduced is 0 dB in the octave bands up until 1 kHz and 0.1, 0.2 and 0.3 dB at 2, 4, and 8 kHz respectively. It should be noted that, even though the result of a multiple step rotation average may approach the result of a single plane average, results can still deviate up to 2 dB from a full sphere average as mentioned in Section 3. For laboratory calibration purposes, it is therefore recommended to either measure a full sphere average if one is interested in accurate separate octave band measurements, or measure as many steps as possible (with 29 steps σ is below 0.1 dB) to determine the single plane average if one is only interested in the single number ratings mentioned in section IIIC. However, as we will discuss in the next section, a single plane rotational average with less averaging steps (only 5) can be a practical tool when calibrating in the field.

5. Field calibration measurements

The possibility of performing calibrations in the field has been investigated. The deviation of in-situ calibration compared to laboratory calibration has been reported by various researchers.

5.1. Interference by the floor reflection

Gade stated in the appendix of his report on ‘Acoustical Survey of 11 European Concert halls’ [23] that at first, he used an in-situ calibration at 1 meter distance on stage to be able to measure G, while applying a time window to filter out the direct sound together with the floor reflection. He corrected the calibration level based on the theoretical effect of the floor reflection. Afterwards, when comparing the in-situ calibration to a reverberation room calibration, he concluded that the theoretical correction did not predict the actual deviation accurately. As Gade noted, the floor reflection does not increase the sound level equally in all frequency bands. Due to comb filtering, some frequencies will be amplified while others are cancelled out. Figure 6 shows the difference in SPL between the average of two on stage measurements and a measurement in an anechoic room in one-third-octave bands and full octave bands, performed by the authors of this paper at 1.5 m transducer heights. The effect of interference can be clearly observed up to 500 Hz. Above 500 Hz, an average increase in SPL is found of 1.1 dB. The interference effect is not visible in the full octave band data.

Beranek [34] also reports the difference between an in-situ measurement using stationary noise measured with two microphone positions on either side of a dodecahedron sound source, and a calibration performed in a reverberation room, see Table V. Hak *et al.* [5] showed results for various cases, among which are measurements at 1 meter distance on stage of two concert hall stages, see Figure 7. A full rotation average was taken using stationary noise and an 8 equal-angular step rotation average was taken using impulse responses. It should be noted that in the latter, actually a system calibration was performed and the source to receiver distance was determined from the impulse response, causing a 15 cm deviation in distance determination. More in-situ measurement were compared to a calibration in an anechoic room by Dammerud [35] for G_{0-10} using 29 averages of 12.4° steps in the anechoic room and 4 single measurements at 1 meter distance on 8 different stages. A single measurement was taken per position with the same rotation of the sound source relative to the microphone for all measurements, as suggested by Gade [17]. The various deviations found are summarised in Table V together with an average offset and standard deviation for the measurements that used a correct source-receiver distance. All researchers used a 0–10 ms time window on a stage with objects or surfaces beyond 4 m dis-

Table V. Overview of errors found by using an in-situ calibrations. *: The physical distance was 1.0 m, but the distance determined from the impulse response and used in the system calibration was 0.85 m. ΔL_w: ΔL_w (error in L_w by in-situ calibration); 1.: Theoretical [23]; 2.: Reverberation Room vs Stage [23]; 3.: Reverberation Room vs Stage [34]; 4.: Precision vs Stage, Noise [5]; 5.: Precision vs Stage System cal. [5]; 6.: Anechoic vs 8 Stages [35]; Avg: Average over 2, 3, 4 and 6 ($\text{offset}_{\text{insitu}}$); Std: Standard deviation over 2, 3, 4 and 6 (σ_{insitu}).

				Octave band with mid frequencies [Hz]						Average	
ΔL_w	Int. [ms]	h [m]	d [m]	125	250	500	1000	2000	4000	500–1000	250–2000
1.	0–10	1.2	1	-4	1.7	-0.2	0.6	0.4	0	0.2	0.6
2.	0-10	1.2	1	0	2.5	1.1	0.5	0	0	0.8	1
3.	0-inf	1.5	1	2.7	2.2	1.7	1.1	0.9	0.4	1.4	1.5
4.	0-inf	1.5	1	2.9	1.2	1	1.3	0.1	0.3	1.2	0.9
5.	0-inf	1.5	1*	-1.5	0	0.1	-0.1	0.6	0.8	0	0.2
6.	0-10	1.0	1	-2.2	2.7	0.3	1.1	1	0.7	0.7	1.3
Avg				- **	2.2	1.0	1.0	0.5	0.4	1.0	1.2
Std				2.4	0.7	0.6	0.3	0.5	0.3	0.3	0.3

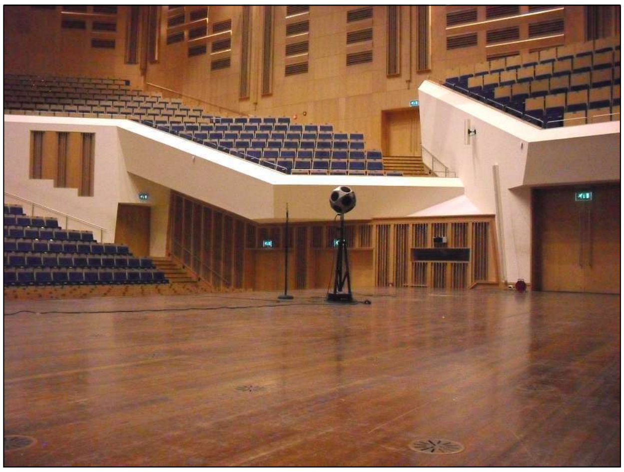

Figure 7. In-situ measurement setup on a concert hall stage with a source-receiver distance of 1 m.

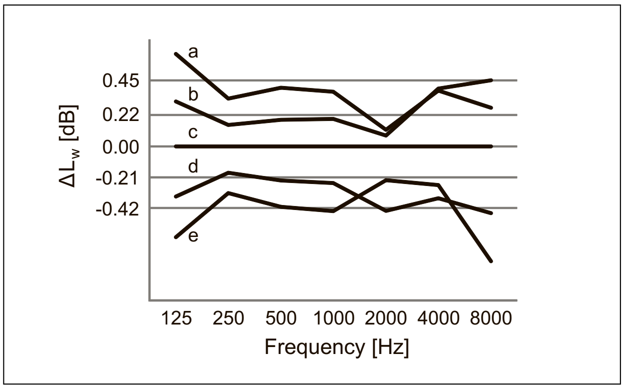

Figure 8. Sound level per frequency measured on a concert hall stage at a distance of a: 0.950, b: 0.975, c: 1.000, d: 1.025 and e: 1.050 meter distance, normalised to the 1.000 distance measurement, together with theoretical values derived using the inverse square law: 0.45 dB, 0.22 dB, 0 dB, -0.21 dB and -0.42 dB respectively.

tance, windowing out room reflections and reducing the maximum error by windowing to 0.1 dB (see Section 2.1). It is likely that the floor reflection is an important cause for these errors. The variation in the measurements might be explained by directivity problems of the sound source, by different types of omnidirectional sound sources and by different transducer heights. Other possible causes of error might be microphone misplacements and other unknown variations due to moving the sound source and microphone. These possible causes of error will be discussed in the next two paragraphs.

5.2. Microphone misplacement

The error due to transducers 'misplacement' was investigated by Gehe in a master thesis [36]. He found that the error in G_{0-10}, due to his ±1 cm error in sound source to microphone distance, would be negligible. Earlier, Gade [17] already concluded that a distance error of up to 30 cm, would lead to an error in the *ST* parameters of maximum 1 dB. Obviously, such a large error in distance is never made when performing measurements accurately. To investigate the actual deviation in measured sound level due to misplacement of the microphone, the authors of this paper measured the sound level using impulse responses, windowed for 0–10 ms, on a concert hall stage at a distance d of 0.950, 0.975, 1.000, 1.025 and 1.050 meter distance in steps of 2.5 cm (see Annex for more details). To reduce the error due to directivity deviation, a 5 equal-angular stepwise rotation average was used. The transducers height was varied from 1.0 m, 1.2 m to 1.5 m. Figure 8 shows the results for a 1.2 m transducer height together with theoretical values based on the inverse square law $20\,\lg(d)$. It is clear that the measured results deviate from the theoretical results, possibly due to the floor reflection, but the results are close to the theoretical values for the 250 to 1,000 Hz octave bands. These results show that accurate placement of the transducers is necessary for direct field calibrations. When the microphone placement is done within 1 cm, the maximum error can be expected to be below 0.1 dB and can therefore be neglected.

5.3. Variation over different positions and the influence of objects

Gehe [36] also looked at the variation in measured *ST* reference level at different positions on stage. For 13 mea-

Table VI. Overview of standard deviation of in-situ calibrations at different positions on stage. A: Gehe [36]: with risers (13 positions, rotation aimed); B: Dammerud [35]: no risers (4 positions, rotation aimed); C: Dammerud [35]: with risers (4 positions, rotation aimed); D: Concert hall, empty stage (4 positions, rotation random); E: Concert hall, empty stage (4 positions, 5 step average); F: Concert hall, stage with chairs (4 positions, 5 step average).

				Octave band with mid frequencies [Hz]						Average	
ΔL_w	Int. [ms]	h [m]	d [m]	125	250	500	1000	2000	4000	500–1000	250–2000
A	0-10	1.0	1.0								0.2
B	0-10	1.0	1.0	0.2	0.2	0.1	0.1	0.3	0.2	0.1	0.1
C	0-10	1.0	1.0	0.5	0.5	0.3	0.2	0.3	0.4	0.3	0.2
D	0-10	1.35	1.0	0.1	0.1	0.1	0.4	2.4	1.6	0.3	0.6
E	0-10	1.35	1.0	0.1	0.1	0.0	0.1	0.2	0.6	0.1	0.1
F	0-10	1.35	1.0	0.5	0.3	0.2	0.8	1.0	0.8	0.5	0.5

surements spread over a stage, the standard deviation in G_{0-10} was only $\Delta\sigma_{250-2000} = 0.2$ dB. The variation of G_{0-10} over various positions was also determined for the data from Dammerud [35] by the authors of this paper. The average standard deviation in G_{0-10} over only 4 measurements is found to be $\sigma_{250-2000} = 0.1$ dB for 2 stages without risers (in this context, risers are devices to create height differences on the stage), and $\sigma_{250-2000} = 0.2$ dB for 6 stages with risers. In both cases, such low standard deviations are achieved, as long as the exact same orientation of the dodecahedron sound source towards the microphone is used, and measurements on risers are performed with both transducers on the same riser (and same height). We performed a similar study for various sets of our own measurement data of stage acoustic measurements using a dodecahedron loudspeaker. During the measurements, no special attention was given to aim the loudspeaker towards the microphone accurately, because a 5 equal-angular step rotation average was used as a method to improve accuracy, see Section 4. On one stage, the effect of chairs on the measured deviation was investigated.

In Table VI, all available results of per octave band are presented. A maximum $\sigma = 0.6$ dB per octave band and $\sigma = 0.2$ dB for single number ratings is reached on stages without risers, when aiming the sound source to the microphone, or taking a 5 equal angular step rotation average. Risers introduce a slight increase in uncertainty with a $\Delta\sigma_{250-2000} = 0.1$ dB, while chairs in (very) close proximity to the transducers increase the uncertainty only moderately by $\Delta\sigma_{250-2000} = 0.4$ dB. As expected, single measurements show a larger deviation at frequencies above 500 Hz when the omnidirectional sound source is not aimed at the microphone correctly: a single measurement results in an $\sigma_{250-2000}$ of 0.6 dB while a 5 equal angular step rotation average results in an average $\sigma_{250-2000}$ of 0.1 dB. Adding chairs in close proximity to the transducers results in a $\sigma_{250-2000}$ of 0.5 dB.

5.4. Discussion on field calibration methods

It can be concluded, that the difference in laboratory and field calibration methods found by different researchers varies considerably. The variance in the measurements by different authors cannot be explained by the error due to time windowing (maximum error 0.1 dB) and microphone misplacement (maximum error 0.1 dB with 1 cm accuracy). Performing multiple in-situ measurements in various halls using the same equipment results in a standard deviation of 0.1–0.6 dB per octave band (on a flat stage floor), which includes the time windowing uncertainty, microphone misplacement uncertainty and the uncertainty due to the source aiming for single measurements or the horizontal plane averaging. It is likely that the largest part of the deviations found between laboratory and field calibration methods can be attributed to the floor reflection. This means that a correction for the floor reflection is the most important step to reduce the error. The correction should be determined by comparing the in-situ sound power to a laboratory sound power using precision methods.

To determine the total uncertainty for the in-situ methods, a model is defined that shows how the different identified sources of uncertainty propagate through the measurement procedure. While including a coverage factor of 2.8, the in-situ method can be expressed by an offset and an average standard deviation by

$$U_{95\%,\mathrm{insitu}} = \mathrm{offset}_{\mathrm{insitu}} \pm 2.8\sqrt{\sigma^2_{\mathrm{insitu}} + \sigma^2_{\mathrm{precision}} + \sigma^2_{\mathrm{repositioning}} + \sigma^2_{\mathrm{rotation}}}, \tag{3}$$

and with laboratory correction,

$$U_{95\%,\mathrm{insitu,corrected}} = \pm 2.8\sqrt{\sigma^2_{\mathrm{precision}} + \sigma^2_{\mathrm{repositioning}} + \sigma^2_{\mathrm{rotation}}}, \tag{4}$$

where $U_{95\%,\mathrm{insitu}}$ is the uncertainty of the in-situ method at 95% confidence level in dB, $\mathrm{offset}_{\mathrm{insitu}}$ and σ_{insitu} is the average systematic error and standard deviation due to in-situ calibration for 4 different researchers, $\sigma_{\mathrm{precision}}$ is the standard deviation of the precision methods, $\sigma_{\mathrm{repositioning}}$ is the standard deviation of 4 repeated measurements over different stages and $\sigma_{\mathrm{rotation}}$ is the standard deviation of the rotational averaging method (with a fixed aiming point $\sigma_{\mathrm{rotation}}$ is assumed to be 0).

The calculated uncertainty for the in-situ method, without and with laboratory correction, are shown in Table VII in case of using a 5 equal-angular step rotation average.

Table VII. Uncertainty factors and calculated uncertainty for in-situ method, without and with laboratory correction using precision methods. Avg: Single number ratings average (the 125-1000 Hz and *STI* average were not calculated due to a lack of sufficient data); **: offset and deviation at 95% confidence level and 2.8 coverage factor; ***: deviation at 95% confidence level and 2.8 coverage factor.

	Octave band with mid frequencies [Hz]						Avg	
	125	250	500	1000	2000	4000	500–1000	250–2000
$\text{offset}_{\text{insitu}}$	0	2.2	1.0	1.0	0.5	0.4	1.0	1.2
σ_{insitu}	2.4	0.7	0.6	0.3	0.5	0.3	0.3	0.3
$\sigma_{\text{precision}}$	1	0.3	0.3	0.3	0.3	0.3	0.3	0.3
$\sigma_{\text{repositioning}}$	0.2	0.2	0.1	0.1	0.3	0.2	0.1	0.1
σ_{rotation}	0	0	0	0	0.1	0.2	0	0
$U_{95\%,\text{insitu}}$**	**0**	**2.2**	**1**	**1**	**0.5**	**0.4**	**1.2**	**1**
	±7.3	**±2.2**	**±1.9**	**±1.2**	**±1.9**	**±1.4**	**±1.2**	**±1.2**
$U_{95\%,\text{plane}}$ ll	-7.3	0	-0.9	-0.2	-1.4	-1	0	-0.2
$U_{95\%,\text{plane}}$ ul	7.3	4.4	2.9	2.2	2.4	1.8	2.4	2.2
$U_{95\%,\text{insitu-corrected}}$***	**±2.9**	**±1**	**±0.9**	**±0.9**	**±1.2**	**±1.2**	**±0.9**	**±0.9**

It is clear that actual in-situ calibrations should be avoided for accurate level measurements because the uncertainty of individual octave band values and single numbers ratings for *G* and *ST* parameters is (much) larger than the parameters' JND. However, the in-situ method with laboratory correction as proposed by Gade, where a fixed correction value is used for the difference in laboratory and field calibration (see section IIB), seems promising in terms of being both a reasonably accurate and practical method for the single number ratings. Aiming the sound source to the microphone, or taking a 5 step rotation average without aiming, both are an effective method to control the deviation in measured reference level between different positions on stage as long as the microphone is placed at the correct distance within 1 cm. The introduction of risers does not appear as a concern for measuring the reference level, but, chairs close to the transducers should be avoided. To avoid the introduction of any other uncertainties, the signal processing should be kept identical after determining the fixed correction. It should be noted, that the in-situ method was not tested for calibration inside office spaces and therefore no results are presented for *STI*.

6. Conclusion

The results from above-mentioned existing and new research illustrate the concern about the accuracy of calibrating the dodecahedron loudspeaker as an omnidirectional sound source for room acoustical measurements of Sound Strength (G), Speech Level (L) and Support (ST) type of parameters. When measuring the sound power produced by a dodecahedron loudspeaker as an omnidirectional sound source, the effect of its directivity cannot be neglected and many other errors can be introduced, especially when calibrating in-situ. We can discriminate between three groups of calibration methods, each with a different uncertainty for different frequency bands and for the single number ratings for G, L_J, ST, $L_{p,A,S,4m}$ and STI. For each method and parameter, the uncertainties are summarized in Table VIII.

6.1. Precision methods

A laboratory calibration using precision methods like the reverberation room or intensity method results in an uncertainty of 2.8 dB at 125 Hz and 0.8 dB in the frequency range 250–8000 Hz. The most practical method to achieve a full sphere average is probably the reverberation room method as mentioned in ISO 3382-1, as was also recently suggested by Beranek and Nishihara [37]. For single number ratings, the uncertainty varies between 0.8 and 1.4 dB. The precision methods can be sufficiently accurate to be able to calibrate the sound source for measuring the room acoustic parameters G, ST and $L_{p,A,S,4m}$ because their JND's are larger than the uncertainty, except for the separate 125 Hz octave band. Single number ratings for parameters that are sensitive for the large uncertainty at the 125 Hz octave, like the STI and L_J have an uncertainty > 1 dB. For measuring *STI*, the uncertainty of the precision method is slightly larger than the JND. This holds for the worst case scenario where the room acoustics has no influence (anechoic room). In practice the uncertainty due to calibration for measuring *STI* will be (just) below the JND.

6.2. Single plane free field method

The method mentioned in ISO 3382-1, where the sound power is determined from 12.5 degree steps while rotating in the horizontal plane, is conceptually clear but it results in a systematic error. Above 1000 Hz, we showed deviations up to 2 dB per octave band between the single plane free field method and a full sphere measurement based on measurements of 9 different dodecahedron loudspeakers. It is clear that the deviation can be significantly improved by reducing the dodecahedron's diameter, but a sound power measurement should always cover the full sphere if one is interested in separate octave bands. For measuring single number ratings for G, ST, and STI, the uncertainty of a single plane average is on average 33% more than the precision methods.

Table VIII. Summary of measurement uncertainty at 95% confidence level of different calibration methods for moderate size dodecahedron loudspeakers. Precision method ISO 3740: reverberation room or intensity probe over sphere or free field over sphere. Single plane free field method: as suggested by ISO 3382-3, using a full rotation average or 29 steps of 12.5 degrees. In-situ measurement: on a stage floor without risers or chairs, 0-10 ms time window, microphone placement accuracy 1 cm, a fixed source to microphone aiming point or 5 equal-angular rotation average. In-situ corrected: As in-situ measurement with additional correction for difference between laboratory precision measurement and in-situ measurement. *: The maximum uncertainty over all octave bands is shown, which is dominated by the 125 Hz octave band. For uncertainties per octave band, see Table III and Table VII. **: The uncertainty presented for *STI* holds for the worst case scenario when the room acoustics has no influence. The uncertainty due to calibration for measuring *STI* might be lower than presented. ***: The two figures represent the offset and the random deviation.

Type of calibration	Uncertainty				
Frequency	octave bands*	L_J	*ST*	G, $L_{p,A,S,4\mathrm{m}}$	*STI***
JND	1–2 dB	-	2 dB	1 dB	1 dB
Precision method ISO 3740	≤ ±2.8	±1.4	±0.8	±0.8	±1.1
Single plane free field method	≤ ±2.8	0 ±1.4***	-0.2 ±0.9***	0.1 ±0.9***	-0.3 ±1.2***
In-situ measurement	≤ ±7.3	-	1.2 ±1.2***	1 ±1.2***	-
In-situ corrected	±2.9	-	±0.9	±0.9	-

6.3. In-situ measurement

We have shown that an in-situ calibration at 1 m distance is not accurate with un uncertainty of ±7.3 dB for separate bands and +2.4 dB for single number ratings *G* and *ST*. The systematic deviation between the in-situ measurement and a laboratory calibration can be corrected if the error is known for the particular sound source and transducers' height. This can be useful in circumstances where the actual sound power of the source is difficult to reproduce for each different measurement condition. The correction between the laboratory calibration and in-situ calibration can be determined using a full rotation average (using a 12.5° steps average resulting in 29 measurements or using an average over 5 equal-angular rotation steps) or, by determining the correction between the laboratory calibration and the in-situ measurement at 1 m for a fixed sound source aiming point and fixed height (as suggested by Gade [17]). Results from various researchers have shown, that the single number ratings of measured results using both the rotational average or fixed aiming point method can be reproduced with 0.3 dB standard deviation over different measurement points on a single stage, with and without risers, and over stages in different halls. However, the in-situ method including laboratory correction should only be used for measuring single number ratings for *G* and *ST* and it should not be used in case one is interested in separate octave bands.

6.4. Conclusion

Based on the JND for single number ratings, an uncertainty <1.0 dB would be desired for measuring *G* and *STI* and an uncertainty < 2.0 dB for measuring ST_{early} of ST_{late}. It is clear that even the most accurate calibration processes described in this paper have uncertainties that are in the same order of magnitude of the parameters' JND. This might seem as if these calibration processes are sufficiently accurate. However, it should not be overseen that performing an accurate sound power calibration is just the first step in taking an accurate measurement of the room acoustic parameters. For instance, the directivity of the dodecahedron sound source will still influence the measurement result with errors well above 1.0 dB [4, 30, 31, 32]. With current available measurement methods, it still might not be possible for room acoustical parameters, that use the sound power as a reference level, to be measured accurately enough.

Appendix

Measurement equipment

For our measurements the same measurement set was used. The power amplifier had a built-in white noise generator. For every measurement this noise generator was set to exactly the same value, so the sound power level of the omnidirectional sound source was always the same. The sound source was a 12 loudspeaker omnidirectional sound source (dodecahedron) with a diameter of approx 40 cm. The measurement equipment consisted of the following components:

- sound source: omnidirectional (B&K Type 4292), directivity in compliance with ISO 3382;
- signals: stationary white noise and an exponentially swept sine;
- input/output: USB audio device (Acoustics Engineering - Triton);
- power amplifier: (Acoustics Engineering - Amphion);
- turntable: 80 s for one rotation (B&K Type 2305);
- microphone: 1/2" omnidirectional ICP (B&K Type 4189);
- sound intensity probe: (B&K Type 3520);
- software: DIRAC (B&K Type 7841).

Diffuse-field measurement conditions:

The diffuse-field measurements were carried out in the reverberation room (200 m^3) of the Faculty of Applied Sciences of the Delft University of Technology. All sound power measurements were done according to ISO 3741. According to this standard two source positions and four microphone positions were used for the direct method. For the system calibration measurements (impulse response measurement using e-sweeps and deconvolution) two sound source positions and three microphone positions were used. For each situation the measurement results were averaged over the microphone and sound source positions.

Sound Intensity measurements:

The sound intensity measurements were carried out in the anechoic room of the Faculty of Applied Sciences of the Delft University of Technology. The measurements were performed according to ISO 9614-3 using a metal mesh cube with dimensions 1.05 × 1.05 × 1.05 m^3 and a mesh size of 15 × 15 cm^2. Using the sweep scan method all individual surfaces were scanned in two directions and averaged to one intensity measurement. The sound intensity of the bottom surface was determined by turning the omnidirectional sound source upside down. The total sound power level is obtained by summing the 6 separate sound intensity results.

Free-field measurement conditions:

The free-field measurements were also carried out in the anechoic room of the Faculty of Applied Sciences of the Delft University of Technology. In this room a measurement is performed at 1 m distance (near field) and 7 m distance from the centre of the omnidirectional sound source. For both distances full rotational measurements were performed using stationary white noise while rotating the sound source around its vertical axis using a turntable with a rotation speed of 360°/80 s. For the stepwise rotational measurements, exponential sweep signals were used to determine an impulse response.

In situ measurement conditions:

The measurements in situ were carried out on the stage of the symphonic concert hall and the chamber music hall of the Frits Philips Muziekcentrum Eindhoven. The (near-field) measurements are performed at a distance of 1 m from the centre of the omnidirectional sound source. During the measurements the stages were unoccupied.

Signal processing

The impulse response is calculated through deconvolution of the room's response to a stimulus signal with the stimulus signal itself. The result is a time domain signal which is filtered using band-pass filters as recommended by ISO 3382-1 and using the reverse filtering technique. The filters are IEC 61260-compliant full and third octave frequency band filters. To enable accurate measurements of very short reverberation times, time reversed filtering is used. Following ISO 3382-1 the impulse response starting point is determined from the broadband impulse responses and defined as the point where the signal level first rises above 20 dB below the maximum level. However, in all free field measurements presented in this paper, the source to receiver distance was measured by the distance between the physical centre of the dodecahedron sound source and the microphone (without using information from the impulse response).

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