SOUND STRENGTH MEASUREMENTS USING A PRE-CALIBRATED OMNI-DIRECTIONAL SOURCE

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1 INTRODUCTION

Most room acoustic parameters are derived from the shape and slope of the measured energy decay curve, regardless of the actual sound level. However, several parameters, such as Sound Strength G and Speech Transmission Index STI, are based on the actual sound pressure level at the receiver position and can only be derived using a calibrated measuring system. The ISO 3382-1 standard describes two methods for calibrating a measuring system in well-known environments: a *Reverberation* or an *Anechoic chamber*[1]. Using these methods, it is not necessary to know the actual sound pressure levels involved in the parameters, but the relative difference from a reference value.
In both cases, the equipment is first calibrated in the test chamber. Afterwards, the calibrated equipment is moved to the room under testing, for the actual measurements. Any settings and parts of the equipment used in the calibration chamber must be identical to those used for the field measurements. This restriction may lead to errors in the measured results, due to accidental or necessary changes in the measurement setup. An effective solution has been presented by Christensen et al.[2], by adding an extra step on the calibration procedure. The method is called *Two-step calibration* and it registers the levels at the calibration chamber and compensates for them in case they have been changed in the room to be tested.
The proposed method removes the necessity of having strictly fixed equipment between the test chambers and in the ordinary room, but it does not remove the requirement of using a reverberation or anechoic chamber for the first part of the calibration. Given that these chambers are typically very difficult to access, calibration remains generally a tedious process for many acousticians that wish to perform a fast measurement of G and STI.
This paper presents a procedure where the acoustician can use calibration data from a reference source, provided that they use a ‘copy’ of that reference in the measured room. The presented method is inherently the Two-step calibration method, in which the first step in the calibration chamber does not need to be repeated by the acoustician. The proposed procedure could be applied to any commercially available source that is produced in series, provided that its directivity pattern remains the same across all copies. In that sense, sound sources with multiple loudspeaker drivers such as dodecahedrons may not suit the method. Typically, the drivers have varying sensitivities, and thus varying output levels. The overall directivity pattern of the source is affected by the sensitivity of each driver, so it becomes more uncertain with many drivers. Conversely, if the source consists of a single driver, the directivity pattern will remain generally the same, while the overall level can be adjusted by the two-step calibration method.
In this paper, the proposed method is evaluated using several copies of Odeon Omni, which is a single-driver portable source. The pre-calibration is first performed for all copies in a reverberation chamber, and the measurement of G in an auditorium is investigated using the pre-calibrated copies.

2 THEORY

Henceforth in this article, we focus on the calibration of G. The findings can be easily applied to STI as well. Sound Strength G quantifies the influence of the room in the perceived loudness and describes the amplification applied to the source by the room. It is defined as the logarithmic ratio of the sound energy of the measured impulse response at any position in the room, to that of the sound energy of the impulse response at 10 m distance from the source, in free field[1]:

$$G = 10\log_{10}\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10}^2(t)dt} \quad \text{(dB)} \tag{1}$$

where $p(t)$ is the instantaneous sound pressure at any position and $p_{10}(t)$ is the instantaneous sound pressure at 10 m distance from the source in free field.
Theoretically, G requires knowledge of the actual sound pressure levels involved in the equation above. However, thanks to the calibration procedure, it can be instead calculated from the relative levels measured inside a reverberation chamber or an anechoic chamber and the room to be tested.

2.1 One-step Calibration Method

Since the procedure in both chambers is similar, in the rest of the paper we focus on the calibration inside a reverberation chamber. The following formula gives G calculated from the relative level in the chamber L_{pE}^{DiffCh}, the level in-situ L_{pE} and the properties of the chamber (reverberation time T and volume V):

$$G = L_{pE} - L_{pE}^{DiffCh} - 10\log_{10}\frac{0.16V}{T} + 37 \quad \text{(dB)} \tag{2}$$

This can be re-written as:

$$G = L_{pE} + \Delta L^{DiffCh} \quad \text{(dB)} \tag{3}$$

Where ΔL^{DiffCh} is the calibration adjustment:

$$\Delta L^{DiffCh} = L_{pE}^{DiffCh} - 10\log_{10}\frac{0.16V}{T} + 37 \tag{4}$$

To perform the calibration, a series of impulse response measurements is first taken inside the chamber at random positions, according to the guidelines described in ISO 3382. Then, an average L_{pE}^{DiffCh} is calculated from the impulse responses, for each octave band separately. Together with the properties of the chamber, the calibration adjustment ΔL^{DiffCh} is derived and can be used in Eq. (3) for the calculation of G in-situ.
The process so far is simple, as long as the whole measuring equipment and gains remain the same. The equipment typically includes an omnidirectional source, possibly a microphone amplifier, a loudspeaker amplifier, a laptop, a microphone, cables etc. However, this strict requirement is typically the main source of errors in calibrated G measurements. Even if all gain settings have been noted, this information can often be missed, especially if the calibration was done long before the actual measurement. Moreover, changes of gains might be desirable if the user realizes that the current settings are not optimal for the field measurements.

2.2 Two-step Calibration Method

To make the calibration more robust and accurate, a two-step calibration method was proposed by Christensen et al[2]. The method introduces an extra step in the calibration procedure, but offers greater flexibility and compensates for accidental changes in the gains or the equipment. The only remaining prerequisite is that the directivity of the calibrated source must be identical to that of the source used for field measurements. The rest of the equipment and settings can be different.
The first step in this method is identical to the procedure mentioned in Sec. 2.1. The second step consists of a reference impulse response measurement inside the calibration chamber (reverberation or anechoic) and an impulse response measurement in-situ. These two measurements are performed at the same distance and direction from the source, in order to truncate both impulse responses at the same well-defined part of the direct sound. This part is eventually independent of the room and exclusively dependent on the source. The purpose is to derive any level difference that has occurred in the final output of the source (and equipment), and compensate for that. The process is illustrated

in Figure 1. To ease this process the microphone should be placed as close as possible to the source. With the new reference levels of the second step, G is calculated as:

$$G = L_{pE} + \Delta L^{DiffCh} + (L_{pE}^{C,2^{nd}} - L_{pE}^{M,2^{nd}}) \quad \text{(dB)} \tag{5}$$

Where $L_{pE}^{C,2^{nd}}$ is the 2nd-step reference level, measured at a fixed point in front of the source in the calibration chamber, while $L_{pE}^{M,2^{nd}}$ is the 2nd-step reference level measured at the same point in front of the source, in the room to be tested. This fixed point ensures that the microphone captures always the same part of the source directivity pattern, which is assumed to change uniformly with the level. If there is no change in the reference levels, then Eq. (5) is simplified to Eq. (3). As noted in Figure 1, the process is done for every octave band separately. It should be emphasized that the microphone measures an overall level that consists of the contribution from the source and contributions from the rest of the equipment. As long as the source - i.e. the directivity pattern - remains the same, it is possible to track any changes in the overall level/octave, at the specific microphone position. However, if the source changes, then the directivity pattern might not be the same at the microphone position, making it impossible to make a reliable calibration. In addition, it is recommended to obtain more than one measurement at the same distance and direction, by re-positioning the microphone manually. The levels $L_{pE}^{C,2^{nd}}$ and $L_{pE}^{M,2^{nd}}$ will be an average from all the measurements, thus reducing any errors from imprecise positioning.

3 USING A PRE-CALIBRATED SOURCE

The two-step calibration method is already a significant improvement to the one-step calibration method. However, even the one-step method is demanding, given that it requires a special room (reverberation or anechoic) which is not readily available for most end users. It would be more convenient to remove the necessity of the first step, by using a pre-calibrated source that comes in identical copies. In that case both the calibration adjustment ΔL^{DiffCh} as well as the 2nd step reference level in the calibration chamber $L_{pE}^{C,2^{nd}}$ can be known and supplied by the manufacturer of the source. Eq. (5) can be rewritten as:

$$G = L_{pE} - L_{pE}^{M,2^{nd}} + \left[\Delta L^{DiffCh} + L_{pE}^{C,2^{nd}}\right] \quad \text{(dB)} \tag{6}$$

where the part in brackets is known from the pre-calibration of a reference source. G can then be derived by measuring the relative levels in-situ L_{pE} and the correction $L_{pE}^{M,2^{nd}}$ at a fixed distance from the source, specified by the manufacturer.

The pre-calibration procedure is reliable only if the source consists of a single driver, because this ensures that the directivity pattern remains the same across the copies of the production series. The single-driver source used in this paper is *Odeon Omni* which was first presented in Euroregio/BNAM 2022[4]. A photo of the source is shown in Figure 2. A single full-range loudspeaker driver is mounted between the cabinet and an acoustic doughnut-like shaped lens, that has been optimized for omnidirectional high-frequency radiation (between 63 Hz and 8 kHz), according to ISO 3382[1]. Apart from having a single driver, Odeon Omni has rotational symmetry in the horizontal plane. This makes it easier to obtain the 2nd-step levels $L_{pE}^{C,2^{nd}}$ and $L_{pE}^{M,2^{nd}}$, since an exact direction is not crucial any more (see Figure 1). Only the distance needs to be fixed. Still, more than one measurement is recommended in order to obtain an average. These can be performed at random angles from the centre of the source on the horizontal plane.

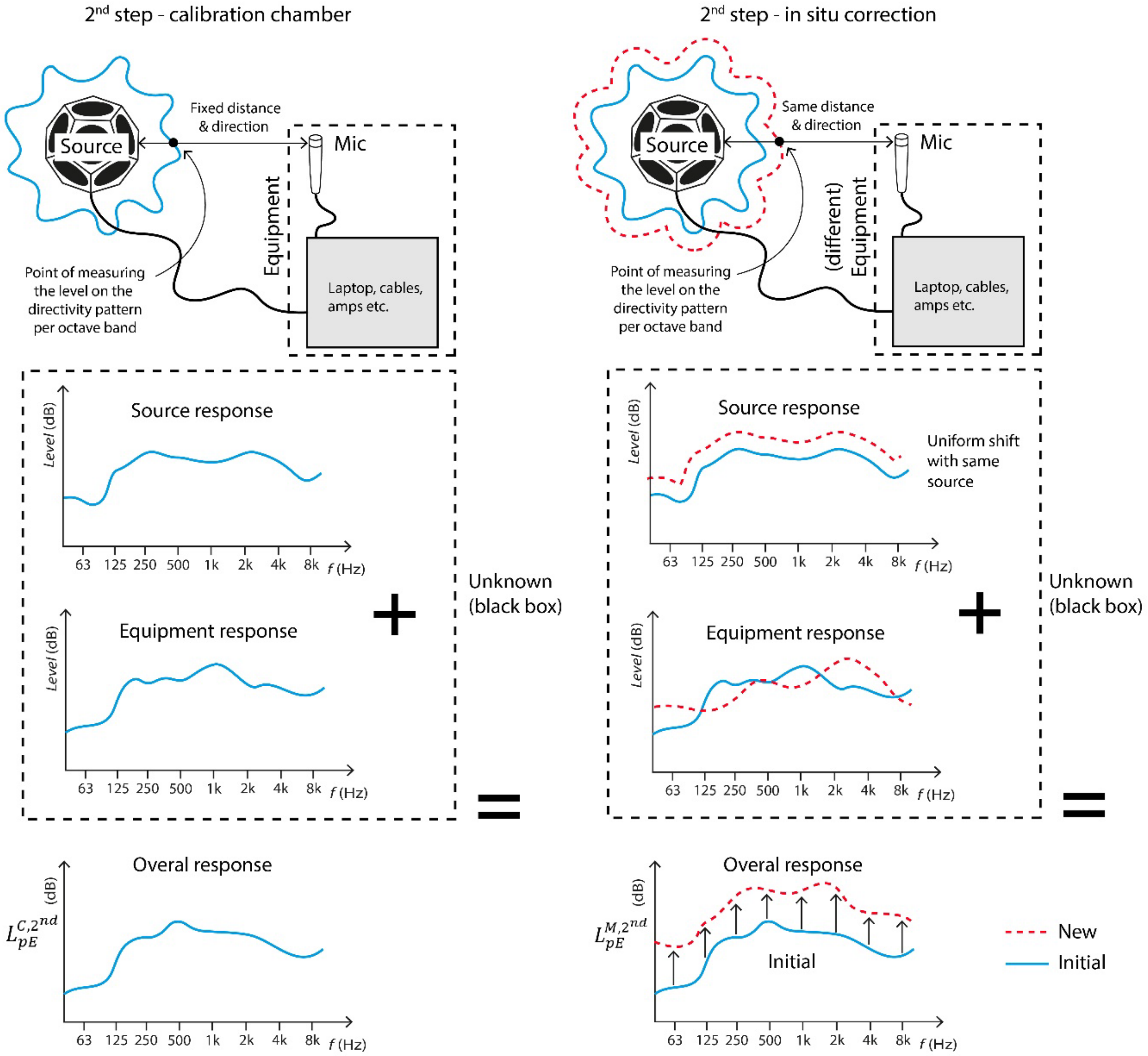

Figure 1: Illustration of the 2nd step calibration method, that consists of a measurement inside the calibration chamber and an in-situ correction. In this example, the gain of the source has been increased in-situ, while parts of equipment (such as a cable or the microphone) have changed.

3.1 Deriving the pre-calibration file

A calibration file is derived for Odeon Omni in the main reverberation chamber at the Acoustic Technology group of the Technical University of Denmark. The calibration file consists of the calibration adjustments plus the 2nd-step reference levels $\left[\Delta L^{DiffCh} + L_{pE}^{C,2^{nd}}\right]$ as presented in Eq. (6). The process from section 2.1 was followed for three random copies of Odeon Omni - instead of one, using the same measurement chain. This was done in order to compare the responses from all three copies and evaluate how close they are to each other. Moreover, a calibration from the average of the three sources can reduce measurement uncertainties.

First, the impulse responses from 24 source-receiver combinations (4 sources – 6 receivers) were measured with the sweep signal facilities in the ODEON software[6]. From these, the reverberation time and the level were derived to be used in Eq. (4) for calculating the calibration adjustments ΔL^{DiffCh}.

The levels of the second step $L_{pE}^{C,2^{nd}}$ were derived from impulse response measurements at 8 positions around the source, at a radius of 70 cm from its centre on the horizontal plane. The summation of ΔL^{DiffCh} and $L_{pE}^{C,2^{nd}}$ at each octave band is shown in Table 1. The results confirm that all three copies lead to very similar recorded levels. The standard deviation (STD) is around 0.5 dB at the 63 and 125 Hz octave bands and well below 0.3 dB at the rest octave bands, which shows that the average can be used safely for the final calibration file. As expected, the highest STD, as well as the maximum difference (between Omni A and Omni C) occur at the lowest octave band. This is probably because the measuring conditions are less stable (lower signal-to-noise ratio, poorer sensitivity of the microphone and lower modal density in the reverberation chamber).

Table 1: Calibration values plus 2nd-step ref. levels in dB for each Omni source, together with their average, STD and max difference in the reverberation chamber.

$\left[\Delta L^{DiffCh} + L_{pE}^{C,2^{nd}}\right]$	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Omni A	-1.57	-3.33	-0.93	1.38	3.75	6.81	10.07	12.97
Omni B	-2.22	-4.03	-1.54	0.78	3.37	6.40	9.81	12.81
Omni C	-2.90	-4.34	-1.47	0.74	3.31	6.23	9.48	12.73
Average	**-2.23**	**-3.90**	**-1.31**	**0.97**	**3.48**	**6.48**	**9.79**	**12.84**
STD	0.54	0.42	0.27	0.29	0.19	0.24	0.24	0.10
Max diff.	1.33	1.01	0.61	0.64	0.44	0.58	0.59	0.24

4 EVALUATION

The pre-calibration method was evaluated with a series of measurements in the *Auditorium 034* at the Technical University of Denmark (Figure 4). Four source-receiver combinations were used (1 source – 4 receivers), as illustrated in Figure 5. Each series of measurements was performed three times using three different Odeon Omni sources*, with the calibration file derived in Section 3.1.

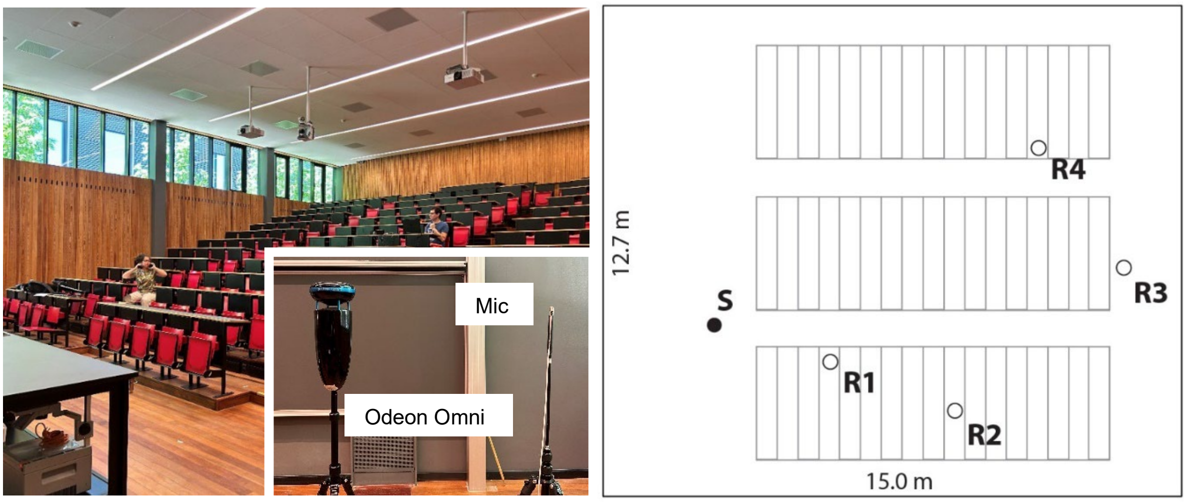

*Figure 2: **Left:** A photo of the auditorium 034 at DTU, used for the evaluation of the pre-calibration method. At the lower corner, one Odeon Omni is shown, together with the microphone during the in-situ correction. **Right:** An approximate overview of the source and receiver positions in the room.*

* Since the measurements were performed later than the calibration, one of the sources was replaced with another copy in the room under testing (Omni A → Omni D).

4.1 In-situ correction

Before executing the measurements, an in-situ correction was performed for each source, according to Sec. 2.2. The microphone was placed at 6 positions around the source at a radius of 70 cm from the centre, on the horizontal plane. For each position, a short impulse response was recorded using a sweep signal of 4 s. The objective was to capture the same part of the direct sound as in the calibration chamber therefore neither a long impulse is needed, nor a long sweep. The latter would be necessary to achieve higher signal-to-noise-ratios[5], but when the microphone is very close to the source, then a short sweep is adequate. On top of that, it was found that longer sweeps in ODEON are more sensitive to distortion at the early part of the impulse response, which can make the detection of the onset time less accurate. This can lead to unreliable calculation of the level of the direct sound, and therefore false in-situ correction.

Table 2 shows the average measured levels from the 6 microphone positions, for each source and octave band from 63 Hz to 8 kHz. In addition are shown the standard deviation (STD) and the final calibration adjustments, which consist of the values in the calibration file (Table 1) minus the in-situ correction: $\left[\Delta L^{DiffCh} + L_{pE}^{C,2^{nd}}\right] - L_{pE}^{M,2^{nd}}$ (see Eq. 6). It can be seen that the STD values are well below 1 for almost all bands and sources, meaning that the 6 measurements around the source give a similar level. This is expected because of the symmetry of the Odeon Omni source on the horizontal plane[4].

All in-situ correction measurements were performed with the same gain. Therefore, any differences in level between the sources is attributed to their possible mechanical variations (different sensitivity of the driver, small variations of the body and lens, small variations in the electronic components etc.). Despite these variations, the measured average levels from the three sources are quite similar (within about 1 dB difference for each octave band). This shows that the three items tested have highly reproducible characteristics.

Table 2: In situ correction performed for the three Omni items with 6 measurements around each source. The table presents the average relative level, the STD and the final calibration adjustment $\left[\Delta L^{DiffCh} + L_{pE}^{C,2^{nd}}\right] - L_{pE}^{M,2^{nd}}$.

		63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Omni B	Avrg.	-30.60	-22.63	-17.25	-15.87	-10.87	-6.55	-11.87	-12.91
	STD	0.16	0.14	0.12	0.10	0.12	0.12	0.31	0.31
	Adjst.	**28.37**	**18.73**	**15.94**	**16.84**	**14.35**	**13.03**	**21.66**	**25.75**
Omni C	Avrg.	-31.01	-23.45	-18.38	-17.11	-12.04	-7.47	-11.91	-13.66
	STD	0.09	0.10	0.09	0.07	0.10	0.10	0.67	0.55
	Adjst.	**28.78**	**19.55**	**17.07**	**18.08**	**15.52**	**13.95**	**21.70**	**26.50**
Omni D	Avrg.	-30.2	-22.9	-18.15	-17.13	-11.81	-6.70	-10.82	-12.47
	STD	0.16	0.10	0.10	0.08	0.12	0.12	1.07	1.04
	Adjst.	**27.97**	**19.00**	**16.84**	**18.10**	**15.29**	**13.18**	**20.61**	**25.31**

4.2 Measurements in an auditorium

The measurements with the (in-situ) corrected and calibrated sources were performed with sweep signals whose length was 16 s, at the four receiver positions shown in Figure 2. Due to the Bluetooth transmission, any output gain adjustment is done digitally within from ODEON, and without hardware settings involved. This makes it possible to compensate for adjustments during different measurements - without affecting the calibration - and it eliminates the possibility of accidental

changes. Throughout the measurements, the gain varied digitally from -18 dB to -12 dB, with 0 dB being the maximum level. The reason for varying the gain was to obtain a higher signal-to-noise ratio (SNR) when needed and avoid overload (by reducing it) when microphone and source were closer to each other.
The calibrated G measurements for all receivers and sources, per octave band are shown in Figure 3. In three of the four measurement positions, G is 5 to 7 dB higher at 63 Hz compared to the other octave bands. This is typical in a room with heavy wall constructions because the acoustic treatment gives very little absorption at low frequencies. The exception in Figure 3 is the position R2, which is in a distance from the wall that is close to a quarter wavelength at 63 Hz. This can explain why the sound pressure at 63 Hz is lower than in the other positions. Table 3 shows the STDs of the average G values from all three Omni sources at each receiver position.

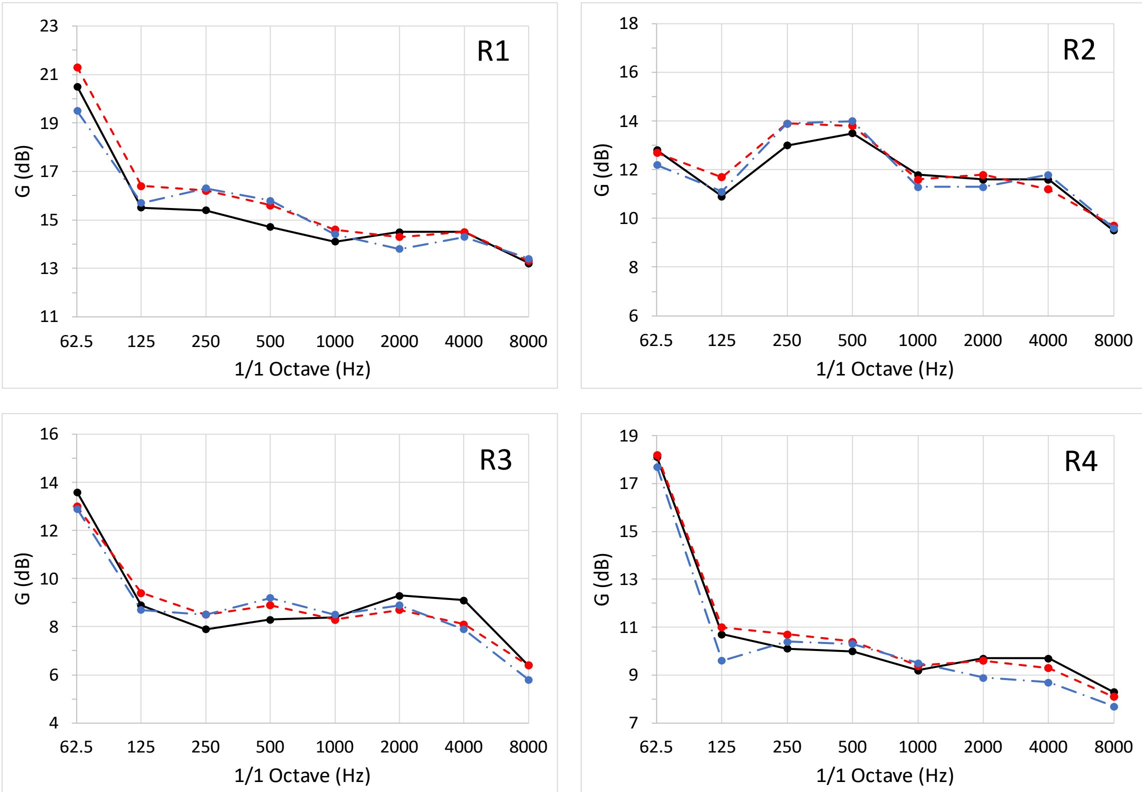

Figure 3: Calibrated G measurements at the four source-receiver combinations in Auditorium 034 (according to the layout of Figure 2). All G axes have a fixed range of 12 dB, with varying limits. ***:Omni B**, **:Omni C**, **:Omni D**.*

Table 3: STD (dB) of the average G values from all there Odeon Omni copies, at each receiver location.

	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
R1	0.74	0.39	0.40	0.48	0.21	0.29	0.09	0.08
R2	0.26	0.34	0.42	0.21	0.21	0.21	0.25	0.08
R3	0.31	0.29	0.28	0.37	0.08	0.25	0.52	0.28
R4	0.22	0.60	0.24	0.17	0.12	0.36	0.41	0.25

Overall, there is a good agreement between the measurements with all three sources. Most of the maximum deviations are within 1 dB, which is the Just Noticeable Difference (JND) of G[6]. The maximum value occurs for R1 at 63 Hz, where the signal-to-noise-ratio is typically lower, but this is still well below 1 dB.
The results of Figure 3 and Table 3 show that the proposed method of measuring G with a pre-calibrated source leads to highly reproducible results with different copies of the source. Any small differences between the measurements can be attributed to uncontrolled factors, such as background noise fluctuations - which may result in some distortion, changes in the exact position of the microphone or changes of position of the acousticians inside the room.

5 CONCLUSION

The paper presents a pre-calibration method that aims to make calibrated room acoustic measurements easier for the end user, by eliminating the need for a reverberation or anechoic chamber. The study has been focused on measurements of Sound Strength, G.
Using a sound source that has consistent directivity characteristics, it is possible to perform the calibration once, for a reference 'copy' of the source, and apply the calibration to any other copy directly during the field measurements. This is done by means of the in-situ recalibration method[2] which registers the actual level of the reference source and the level of the copy during the field measurements.
The method was evaluated using Odeon Omni, a portable omnidirectional source, that uses a single loudspeaker driver and has consistent directivity across all copies of the production series. First, a single pre-calibration file was derived by averaging the calibration values from three copies in the reverberation chamber. It was found that the three sources could produce repeatable levels, within 0.5 dB STD. Then an in-situ recalibration was applied on three different copies, during G measurements in an auditorium, to compensate for any shifts in gains between the pre-calibration file and the copies.
The results showed very good agreement between the three copies, within 1 dB STD, at all receiver positions and octave bands. This demonstrates that pre-calibrated G measurements are possible when using a single-driver source, leading to reproducible results for the copies of the source. However, a possible future study could involve more copies, and more measuring points in a test room, to derive more reliable statistical conclusions.

6 REFERENCES

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