inter noise
2013 | INNSBRUCK | AUSTRIA
15.-18. SEPTEMBER 2013
NOISE CONTROL FOR QUALITY OF LIFE

The practical application of G and C_{50} in classrooms

Jack Harvie-Clark[1], Nicholas Dobinson[2]

[1] Apex Acoustics Ltd

[2] Apex Acoustics Ltd

ABSTRACT

Reverberation time remains the primary indicator of room acoustic response. However, previous work has shown that reverberation time alone can be insufficient to describe the acoustic conditions in non-diffuse environments, especially in classrooms where the majority of absorption is typically on one surface. Alternative parameters have been proposed to evaluate the acoustic response of such rooms: Strength, G, and Speech Clarity, C_{50}. These correlate better with loudness and speech intelligibility, in the absence of background noise, than reverberation time and distance from the source. There is currently little guidance on the spatial distribution of source and measurement positions or the averaging of measured values for these parameters. This paper investigates the practical use of G and C_{50} to describe the acoustic response of classrooms. Measurements and modeling are used to investigate the spatial variation with frequency, source position, measurement distance, and room size. Correlation between modeled and measured values is investigated. Guidance on source and receiver positions is proposed to achieve consistent results, so that the parameters Strength and Speech Clarity may usefully describe the room response rather than one particular measurement set up.P

1. INTRODUCTION

Reverberation time is an enduring and intuitive descriptor of the room acoustic response. It is used not only as a criterion for room conditions, but also to infer the speech intelligibility and the relationship between sound pressure and sound power level in a room. For rooms with a linear decay, the reverberation time has deserved its provenance.

Typical classrooms have the majority of the absorption concentrated on one surface, the ceiling; this causes a significantly non-linear time decay, and hence the acoustic response is not well described by the reverberation time. Reverberation time is convenient, but not necessarily accurate for determining the purpose for which the acoustic response is sought. The main purposes for determining the acoustic response in classrooms are speech intelligibility and loudness. As speech intelligibility is a function of background noise as well as room response, it is more convenient to separate these aspects of acoustic performance, to use separate descriptors for room acoustic response and for background noise.

The parameters Speech Clarity, C_{50} and Strength, G, have been proposed as measures of the quality of the acoustic response with which we are concerned in classrooms. These are defined in ISO 3382-1 [1]; however, as the purpose of ISO 3382-1 is for the measurement of parameters for

[1] jack.harvie-clark@apexacoustics.co.uk
[2] nicholas.dobinson@apexacoustics.co.uk

performance spaces, the descriptions are not well suited or defined for measurements in ordinary rooms used for speech. This paper seeks to determine how these parameters may be used in ordinary rooms such as classrooms.

2. BACKGROUND

Sabine's relationship for reverberation time was developed empirically in the 1890s, relating the rate of decay of sound to the amount of absorption within a space and the volume. It is implicit in the concept that the decay of sound is exponential, or linear when the sound level is plotted in decibels. Schroeder's reverse integration technique [2] made measurements simpler to undertake.

Reverberation time is defined in ISO 3382-1 as the duration required for the space-averaged sound energy density in an enclosure to decrease by 60 dB after the source emission has stopped. It is more commonly measured over a 20 or 30 dB range, denoted T_{20} and T_{30} respectively, starting from 5 dB below the initial level and extrapolated to the time for the decay over the 60 dB range. The T_{20} value is generally preferred [16, 18], as it relates more closely to the earlier portion of the decay, but it is noted [1] that the rate of the first 10 dB of the decay is more closely related to perceived reverberance, which can be measured by the EDT.

Many eminent researchers [3, 4, 5] have proposed modifications to the Sabine relationship, and Standards have been developed [6], in an attempt to calculate the reverberation time in rooms with uneven distribution of absorption, in more highly damped rooms, or in larger rooms intended as performance spaces [7]. Similarly, parameters to describe the degree of non-linearity of a decay curve have been proposed [18]. Attempts to describe the effect of diffusing elements such as furnishings on the measured reverberation time have illustrated the incongruous relationship between the sound pressure and sound power levels [10]. However, rather than more accurately predict a measure of acoustic response which does not correlate with those aspects with which we are concerned - loudness and speech intelligibility - the present work seeks to determine if G and C_{50} may be more usefully and practically employed.

3. ROOM ACOUSTIC RESPONSE

When considering an impulse response, the integration of the total energy received at a given location is proportional to the Strength, G, whereas Speech Clarity, C_{50} is controlled by the ratio of the energy arriving in the first 50 ms to the remaining energy arriving. To some extent, the tail of the decay curve is used to determine the reverberation time, T_{20}. As the T_{20} is the measure of the decay when the sound level is between 5 and 25 dB below the initial level, it cannot describe the acoustic conditions under which the most important part of the signal for speech and loudness is transmitted; we are more concerned with that part of the sound that has a higher signal level.

3.1 Definition

G is defined [1] as the integration of the total energy received at a given receiver position from a given source location, for an omni-directional source as required for precision measurements, divided by the received energy at 10 m in a free field. Although it may be derived from an impulse response measurement, it is generally more convenient to measure static sound levels; either way a calibrated source is required.

The value of G varies between source and receiver position combinations, but may also be averaged for a number of source positions and receiver positions. An average of some type is desirable, as there may always be anomalies at particular source and receiver locations. In Annex A of [1], the definition of G is derived for static levels as:

$$G = L_p - L_w + 31 \quad (1)$$

Where G is the Strength, L_p is the sound pressure level, and L_w is the sound power level of the source. G is defined as the arithmetic mean of the values in the 500 Hz and 1 kHz octave bands, but the concept may be extended to other frequency bands. To aid comparison with conventional considerations and reverberation time, this quantity may be compared with the terms of classical diffuse field theory, where the diffuse field sound level may be described as:

$$L_p = L_w + 10.\log\left(\frac{4}{R_c}\right) \quad (2)$$

Where L_p and L_w are as above, R_c is the room constant. Comparing Eq. 1 and Eq. 2, Strength G is related to Room constant, R_c, as:

$$G = 37 - 10.\log(Rc) \quad (3)$$

Hence where the room constant may be considered as the effect of the room in reducing the sound pressure level from a given source, the Strength is the direct opposite, where a higher value represents a higher sound pressure level for a given source sound power. A common simplification for the room constant under diffuse field conditions is to the absorption area:

$$Rc \approx S.\alpha = A \quad (4)$$

And where, according to the Sabine relation:

$$A = 0.16\left(\frac{V}{T}\right) \quad (5)$$

This relationship established by Sabine is utilised in many Standards for determining noise levels in rooms. Under diffuse field theory, the room constant is a simple function of reverberation time and room volume, and hence, by substituting Eq. 5 and 4 into Eq. 3, so is the value of G relating to the diffuse field level, denoted $G'_{diffuse}$ to avoid confusion:

$$G'_{diffuse} = 45 + 10.\log\left(\frac{T}{V}\right) \quad (6)$$

Although this relation may be an adequate model in rooms where the diffuse field theory is a good model, it has been demonstrated that this relation is far from true for many types of rooms. It has been suggested [8] that in concert halls these parameters may be adequately predicted, statistically, from the reverberation time, volume, and source-receiver distance, based on Barron's revised theory [7], but on the basis of the following discussion this is not pursued further.

3.2 Just noticeable difference

The just noticeable difference (JND) indicated [1] for auditoria is 1 dB for both G and C_{50}; the JND in classrooms is not known. This sets the desirable level of accuracy required in determining the values of these parameters to be better than 1 dB.

3.3 Conditions in a classroom

Nilsson has presented measurements in 17 classrooms [11] in three different conditions, including classrooms with suspended absorbent ceilings with and without and furniture, and classrooms without suspended absorbent ceilings or furniture. These measurements indicate that the measured value of G may be frequently 5 dB or more below the value that would be predicted assuming diffuse field theory from the measured reverberation time ($G'_{diffuse}$), and in some cases more than 10 dB, in classrooms with suspended ceilings but not furniture.

This effect has been investigated previously, notably by Nilsson et al [12, 13]. These authors describe the sound field in a simple room with an absorbent ceiling as being composed of a grazing component (sound in the horizontal plane), and a non-grazing component (in the vertical direction). Nilsson has proposed two-system SEA model [14] to represent the grazing and non-grazing sound fields, with redistribution of power between each field controlled by the quantity of diffusing elements or surfaces. During the sound decay, high frequency energy in the non-grazing field is more quickly reduced by the highly absorbent ceiling, while sound in the grazing field is less efficiently absorbed by the ceiling. Different ceiling types (e.g. mineral wool ceiling tiles or perforated plasterboard) are demonstrated to have different efficiencies in absorbing grazing sound at different frequencies. Nilsson has demonstrated [12] how the non-grazing field may dominate overall sound levels due to a constant excitation of the room.

The explanation for the change in slope of a sound decay is due to the transition from non-grazing field to grazing field control. Thus the initial decay is controlled by the non-grazing field, which dominates steady state sound levels, but this is more quickly exhausted by the higher levels of absorption at normal incidence. The reverberation time measured between -5 and -25 dB for the T_{20} may be substantially controlled by the grazing field, which persists for longer in the absence the same level of absorption. Thus the reverberation time does not reflect the rate of absorption of sound energy during the initial part of the decay, nor under steady state excitation of the room, which is effectively the condition at the point at which the sound decay starts. This is a convincing argument to explain the discrepancy between the measured Strength in a room, G, and $G'_{diffuse}$ based on the measured reverberation time, in non-diffuse rooms.

3.4 Spatial variation with distance and source position

In a Sabine space with a diffuse sound field, beyond the critical distance sound levels are dominated by the reverberant field not the direct sound. In more heavily damped rooms, however, it is observed that sound levels do decay significantly from the source. This has been noted by many observers, and calculation models such as Barron's revised theory [7] for performance spaces, or measures based on raising the room constant to a power of the ratio of source to receiver distance and mean free path (mfp). Luykx [8] has proposed measuring at a distance of the mfp to evaluate G in sports halls.

The aim of this investigation is to determine if there is a single value that may be associated with a classroom type room, rather than a particular pair of source and receiver locations. If the parameter may be used in specifications and evaluation of room response, a consistent method for determining the values is required. The spatial variation with distance from the source and variation with source location are considered in this paper.

4. METHOD

Detailed measurements in four classroom type rooms and one sports hall are presented, with acoustic modeling of those rooms in CATT. With the modeling corroborating the measured results, further investigations are undertaken in the software. Mathematical models for the expected values of G and C_{50} based on the architectural features are not proposed; rather, values are determined directly from modeling. The rooms are illustrated in Figures 1and 2.

Figure 1: Room A, similar to room B

Figure 2: Room C, similar to room D

Strength and reverberation time have also been measured in a sports hall, before and after remedial absorbent treatment to reduce the reverberation. A dodecahedron loudspeaker was used with ARTA software to measure room impulse response. Static sound levels were used to measure G. Measurements were made with the speaker at the approximate position of a teacher in front of the class, and measurements were made at measured distances towards the rear of the class. The speaker was always more than 1 m from any wall, and measurements were made starting 1 m from the speaker, and then at 0.5 m intervals, and not less than 1 m from any wall, at a height of 1.2 m above the floor. The room characteristics are summarised in Table 1 below.

Table 1: Room characteristics

Room ref	Floor area / m	Mean soffit height / m	**mfp**	**Notes**
A	66	3.5	3.6	Absorbent rafts, wall panels; furnished
B	60	3.5	3.6	
C	36	2.65	2.4	Absorbent ceiling (some tiles missing); partial furnishing
D	36	2.65	2.4	
E	262	6.6	6.6	Sports hall before & after treatment; empty

5. MEASURED SPATIAL VARIATION

Results are presented for the frequencies most important for speech, the 500 Hz, 1 kHz and 2 kHz octave bands. Although octave bands were measured from 63 Hz - 8 kHz, the results in other octave bands are more variable than the results in the frequencies presented, and being less relevant are omitted for brevity and clarity. The distance is non-dimensionalised by dividing by the mean free path (mfp) for each room. All graphs are plotted with a 10 dB range on the y-axis, so the results may be compared visually. The critical distance based on the measured mid-frequency reverberation time is around 0.3 mfp, such that all measurements are at greater distance from the source. The dotted lines represent the value of $G'_{diffuse}$, calculated according to Eq. 6 above, for the measured (spatially averaged) reverberation time.

The colours used are: Red: 500 Hz; Green: 1 kHz; Blue: 2 kHz.

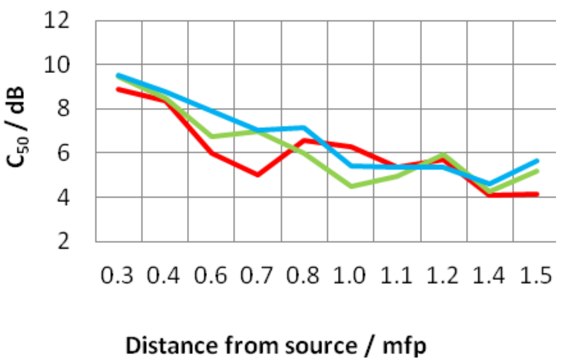

Figure 3: C_{50}, Room A

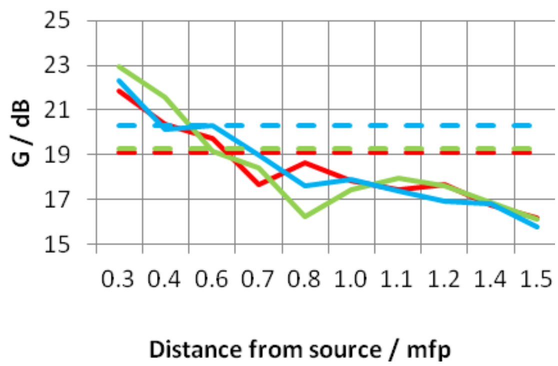

Figure 4: G, Room A

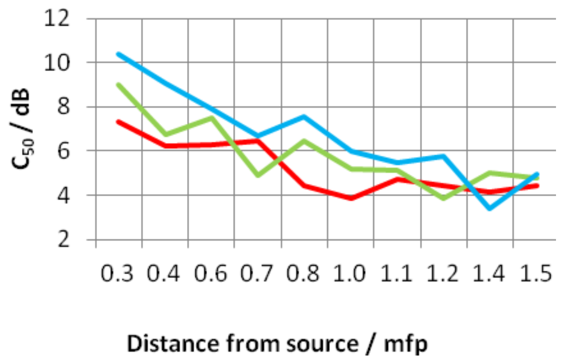

Figure 5: C_{50}, Room B

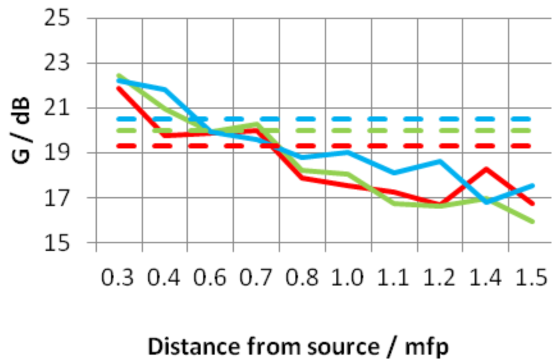

Figure 6: G, Room B

5.1 Discussion

The results in Rooms A & B show an initial decay in G of around 10 dB / mfp, up to a distance of around 0.7 or 0.8.mfp; at greater distances, the decay with distance appears to be lower, and variable. C_{50} also decreases with distance from the source, but at a slightly lower rate. The decay exhibited in Rooms C & D follows approximately the same pattern, shown overleaf.

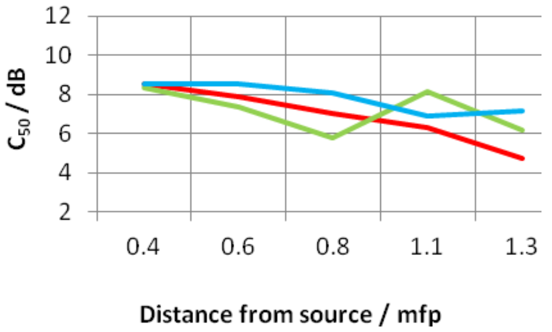

Figure 7: C_{50}, Room C

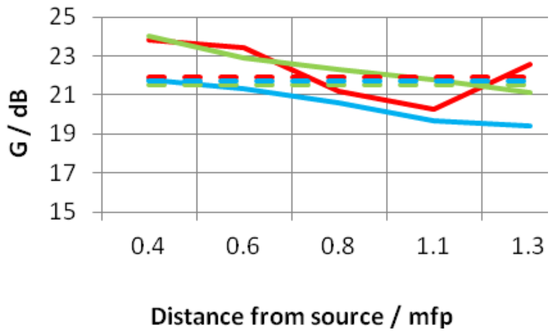

Figure 8: G, Room C

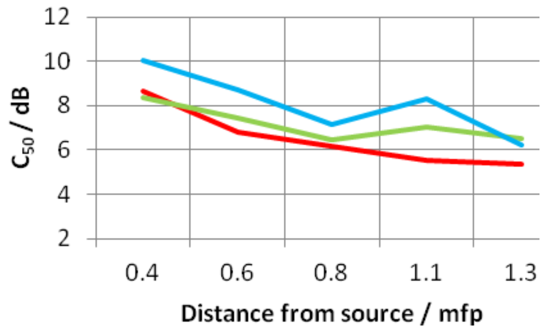

Figure 9: C_{50}, Room D

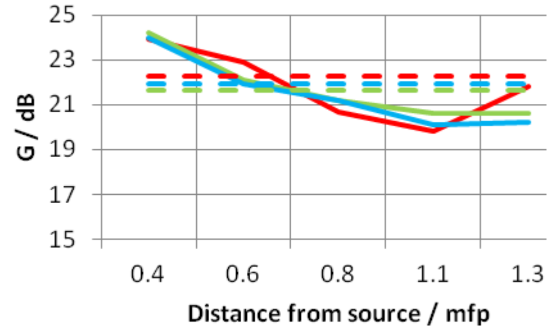

Figure 10: G, Room D

5.2 Spatial variation in sports hall

Measurements were carried out in a sports hall before and after retrofitting with absorbent panels to control excessive reverberation. The spatial variation in the sports hall also shows a clear change in slope at a distance of around 0.7 to 0.8 mfp from the source in Figure 11 prior to treatment, but this change of slope is not so evident in the decay following treatment, Figure 12, where the G continues to decrease more significantly with distance. The critical distance prior to treatment, based on the measured mid-frequency reverberation time, is 0.18 mfp, and 0.28 mfp following treatment.

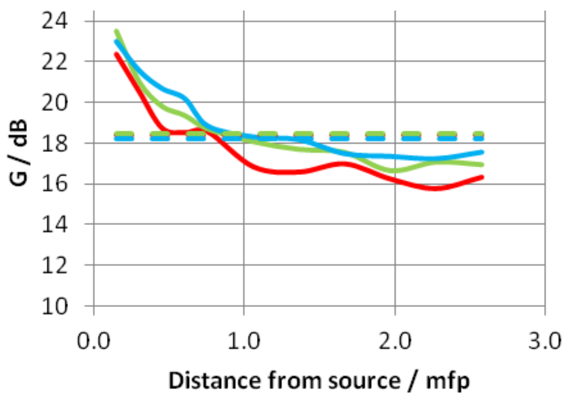

Figure 11: G, Room E, T_{mf} = 3.7 s

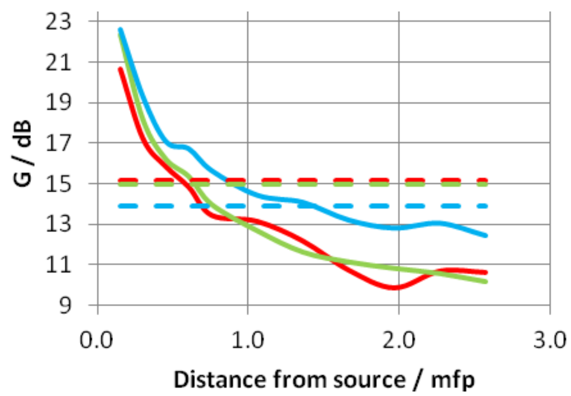

Figure 12: G, Room E, T_{mf} = 1.6

5.3 Summary of measurements

On the basis of reviewing the three relevant octave band levels for speech presented in the measured levels above, it is suggested that the arithmetic mean value of these may be combined for brevity and efficiency, justified theoretically according to Barron [15].

6. MODELLING OF MEASURED LEVELS

Modeling of Rooms A, B, C, and D is carried out using CATT Acoustic. Standard values are used for scattering and absorption coefficients – the models are not optimised to reproduce the measured values more precisely. The arithmetic mean of the 500 Hz, 1 kHz and 2 kHz octave bands is presented as a single mid-frequency value.

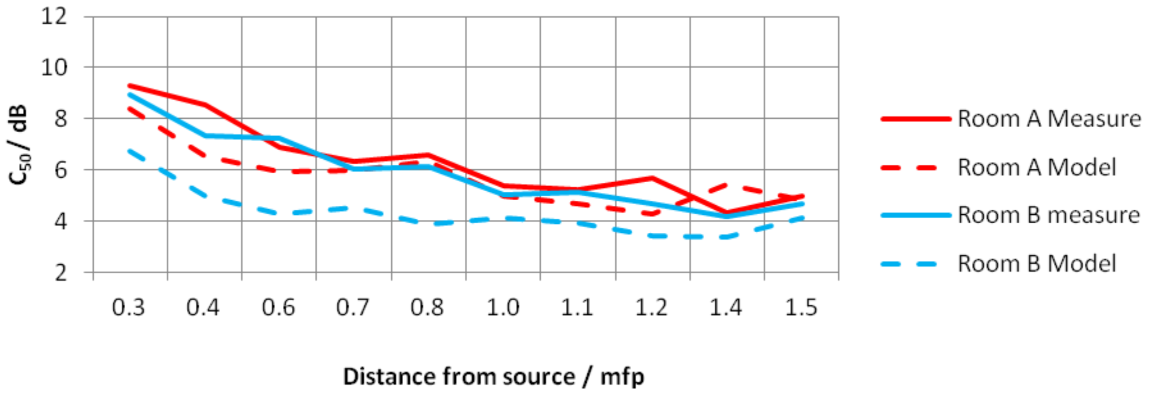

Figure 13: Rooms A ($p = 0.05$) and B ($p = 0.00$), spatial variation of $C_{50\ mf}$

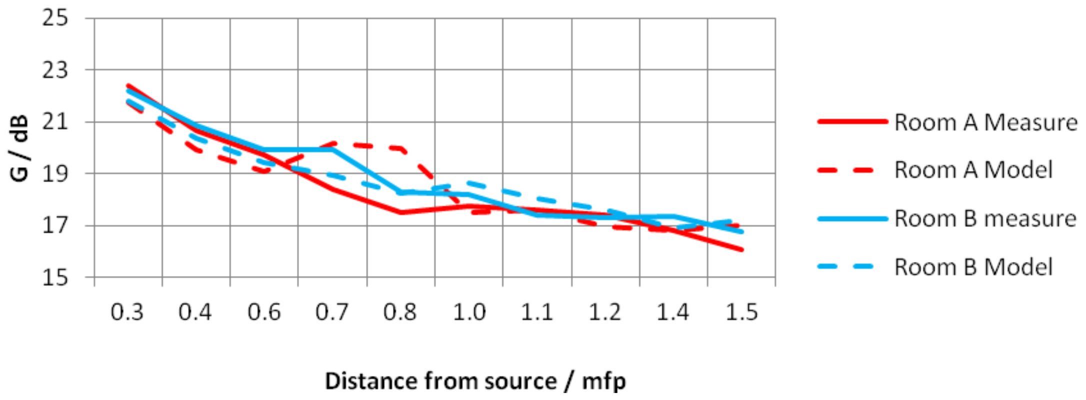

Figure 14: Rooms A ($p = 0.50$) and B ($p = 0.57$), spatial variation of G_{mf}

The Figures above indicate that the modeling of G appears reasonably accurate in both rooms, particularly beyond the distance of the mfp from the source. The modeling of C_{50} appears similarly accurate in room A, but systematically different in Room B. Figure 15 indicates that C_{50} is reasonably well represented by the modeling, whereas Figure 16 indicates that G is less well correlated.

A paired t-test analysis is also used to assess the accuracy of the modeled results; the p-values are indicated in the figures. The statistical results correlate with the visual impression of the results in the graphs, where in some cases there appear to be systematic differences between the parameters. A p-value of more than 0.05 indicates that the difference between the measured and modeled values is not statistically significant. When subject to the same t-test, T_{20} differs significantly between measured and modeled results in more rooms than the other parameters.

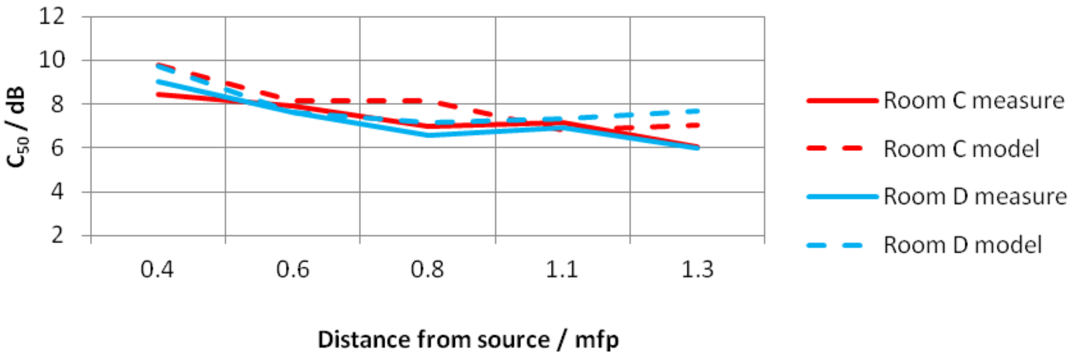

Figure 15: Rooms C ($p = 0.09$) and D ($p = 0.08$), spatial variation of $C_{50\ mf}$

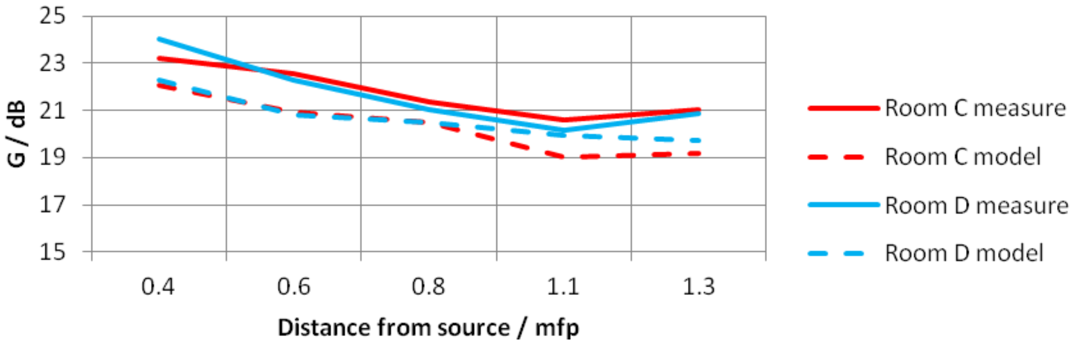

Figure 16: Rooms C ($p = 0.00$) and D ($p = 0.02$), spatial variation of G_{mf}

7. VARIATION OF SOURCE POSITION

The variation of source position is investigated using the modeled rooms, and comparing the modelled results for two distinctly different source positions – in the middle of one side, and towards the corner. Results are compared for measurement positions beyond the mfp from the source. Source and measurement positions are illustrated in Figures 17 and 18.

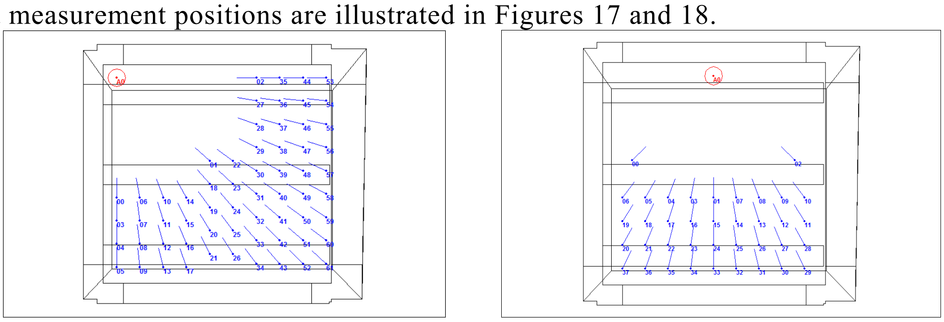

Figure 17: Room A varying source (red circle), and receiver positions (blue streak)

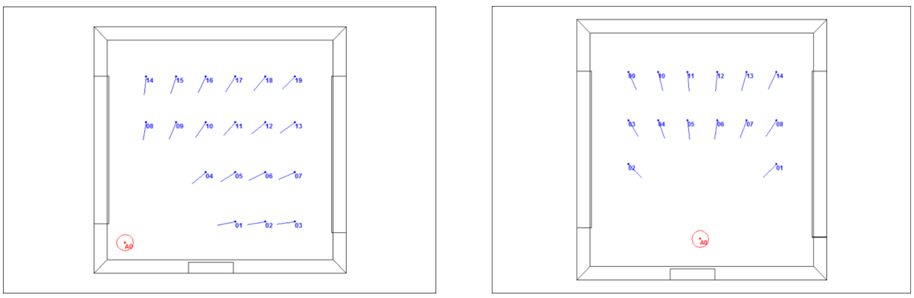

Figure 18: Room C varying source (red circle), and receiver positions (blue streak)

An independent value t-test is performed to identify the significance of differences in results when source position varies. The results are shown in Table 2 below:

Table 2: Significance of difference between two source positions

Room	Parameter	Source position	Mean / dB	SD / dB	p-value
A	C_{50}	Corner	4.8	0.9	0.15
		Mid-side	4.5	0.7	
	G	Corner	16.8	0.7	0.08
		Mid-side	16.6	0.5	
	T_{20}	Corner	0.6	0.0	0.70
		Mid-side	0.6	0.0	
B	C_{50}	Corner	4.3	0.7	0.76
		Mid-side	4.3	0.8	
	G	Corner	17.7	0.5	0.19
		Mid-side	17.5	0.5	
	T_{20}	Corner	0.6	0.0	0.58
		Mid-side	0.6	0.0	
C	C_{50}	Corner	7.55	0.80	0.25
		Mid-side	7.27	0.53	
	G	Corner	19.41	0.64	1.00
		Mid-side	19.41	0.44	
	T_{20}	Corner	0.43	0.01	0.70
		Mid-side	0.43	0.01	
D	C_{50}	Corner	6.93	0.74	0.16
		Mid-side	6.80	0.50	
	G	Corner	19.32	0.63	0.06
		Mid-side	19.69	0.44	
	T_{20}	Corner	0.46	0.01	0.70
		Mid-side	0.46	0.02	

In all rooms the criteria for statistical significance of difference has not been met for all three parameters, and the null hypothesis is accepted. This means that the difference between levels for different source positions tested is not statistically significant, although there may be significant differences for other source position variations.

8. ANTICIPATED SPATIAL VARIATION AND AVERAGING

The spatial variation associated with G may be expected to be the same as for static sound levels within a room. This is described by equation 4.5 of the Nordtest report [16] for frequencies above the Schroeder frequency and a point sound source. In the octave bands considered here, the expected spatial variation of sound levels in rooms A and B is marginally less than 2 dB, and in rooms C and D a little more than 2 dB. The modeled results for G, at a distance greater than the mfp, however, have spatial standard deviations between 0.5 and 0.9 dB for both speaker positions in both rooms, as shown in Table 2. It is therefore suggested that the same quantity of spatial measurements as for a field sound insulation test [17] would be appropriate – i.e. a minimum of two source positions and five measurement positions at each. Further statistical investigation of this is required to determine the uncertainty of measurement in various room types. A moving microphone measurement is not suitable if arithmetic averaging of different positions is used, as a moving microphone will determine the energy-averaged value.

The measurement uncertainty associated with decay rate measurements is discussed in Annex A of ISO 3382-2 [18], and some methods for evaluating non-linear decays are discussed in Annex B of that Standard. However, these assessments limit themselves to effects on the reverberation time, T_{20} and T_{30}, and do not discuss aspects of the form of the reverberation decay in the terms discussed here.

The type of spatial averaging that is appropriate for a parameter should suit its intended purpose and use. Barron [15] has discussed the averaging of parameters in concert halls, and concludes that while averaging values across octaves may be theoretically valid, spatial averaging can obscure the information for which the parameters were sought. As G describes the loudness between a given source and receiver position, multiple receiver positions represent the range of values that may be experienced by people in the room. If we limit the usefulness of this parameter to the experience of sources and receivers separated by at least the mfp in classrooms, then spatial arithmetic averaging is considered appropriate, such that the range of values are given equivalent weighting in decibels. Although energy or logarithmic averaging of sound levels is appropriate for the purposes of evaluating the energy in a room, that is not the purpose for this parameter. As the purpose of the parameters is to describe the typical adverse conditions between a speaker and listener in the room, basing the parameters on greater separation is more appropriate – the Speech Clarity between people in closer proximity is less affected by the room, and therefore of less interest.

C_{50} describes the shape or relative proportions of the decay curve, and hence the spatial variation describes how these proportions vary with distance from the source. In view of the spatial decay of Strength, it may be considered that direct sound and early reflections are much more significant than later reflections, and the diffuse sound field is less dominant than classical theory would suggest. The non-grazing field may be more responsible for early sound closer to the source than at greater distances. A theoretical assessment of the anticipated spatial variation in C_{50} is not known [15]. In the rooms tested, C_{50} follows a similar spatial pattern to G, and hence may be similarly controlled by the room features and distance from the source, although the measured and modeled standard deviation of C_{50} is marginally higher than that for G..

ISO 3382-2 [18] indicates that for precision level measurements of reverberation time in ordinary rooms, a minimum of 12 source – microphone combinations are required, with at least two source positions. Given the greater standard deviation of C_{50} compared with reverberation time in the rooms studied, it is suggested that this provision should be the minimum requirement for measurements of C_{50}.

9. SOURCE CALIBRATION

Discussion of the accuracy of calibration for G has been carried out by Hak et al [19]; the uncertainty of the calibration can be a significant part of the overall uncertainty. For these measurements, the sound source was calibrated in a reverberant room with the use of equation A.5, ISO 3382-1, as more formal means were not available. The average difference in the results in Rooms A & B between those measured and modeled for G are -0.2 and +0.1 dB respectively, and hence are not indicative of a systematic error that could occur through calibration. The average difference of results in Rooms C and D are +1.4 and +1.0 dB. These variations are significant in terms of the JND, and may not be adequate for reliable use. Further work is required to qualify the uncertainty associated with the field calibration of the source, which is one of the major constraints in the use of G.

10. SOUND INSULATION MEASUREMENTS

When conducting a sound insulation test to ISO 140-4 [17], the measured reverberation time is used to standardise the receiver room levels. If the reverberation time does not accurately describe the relationship between the sound energy transmitted into the receiving room and the resulting sound pressure level, the adjustment for room conditions will be incorrect. Thus the apparent sound insulation measured and calculated in this way will not be consistent with perceived conditions. The discrepancy between G and $G'_{diffuse}$ is illustrated to vary by between 1 and 3 dB in the rooms measured, although this effect is anticipated to be greater in empty rooms greater than 3 m in height with simple absorbent ceilings. Measurements presented in the literature indicate greater differences between G and $G'_{diffuse}$ as discussed previously; this issue has also been investigated in previous work [20].

11. CONCLUSION

It has been illustrated how reverberation time, T_{20}, by virtue of its definition, may not describe the aspects of classroom acoustic response in which we are interested - primarily loudness and speech clarity. Strength, G, and Speech Clarity, C_{50}, represent these types of acoustic response, but are subject to greater spatial variation with distance from the source than reverberation time. It is suggested that the distance between source and receiver positions should be greater than the mean free path, and that the arithmetic mean of measurements provides a suitable definition. It is suggested that a minimum of two source locations and five microphone positions at each is appropriate for measuring and defining G; a minimum of two source locations and twelve source-microphone combinations is proposed for C_{50}. Receiver locations should represent potentially occupied positions only. Further work is required to determine suitable design values for these parameters and modeling techniques to design rooms appropriately.

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