Clarity & Strength in non-diffuse fields: comparison with diffuse field models

Jack Harvie-Clark
Apex Acoustics, Gateshead, UK

Felix Larrieu
Apex Acoustics, Gateshead, UK

Nicholas Dobinson
Apex Acoustics, Gateshead, UK

Daniel Wallace
Apex Acoustics, Gateshead, UK

Summary

Clarity, C_{50}, and the useful to detrimental ratio, U_{50} have been proposed by Pelegrin et al in a model for determining room requirements that meet both listeners' and talkers' needs in rooms for speech, such as classrooms. The model is based on diffuse field assumptions; however, it is well known that rooms where the majority of absorption is on the ceiling exhibit reverberation times that can significantly exceed values that are calculated assuming diffuse field conditions.

Preliminary measurements in rooms with adverse acoustic conditions suggest that excessive reverberation times do not cause measured values of Strength to increase from those calculated assuming diffuse field conditions and the average absorption coefficient. However, measurements indicate that Clarity is more closely associated with the measured reverberation time rather than that calculated assuming diffuse field conditions. Development of the model for background noise within the rooms, from younger students and in rooms with lower reverberation times is also discussed.

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1. Introduction

According to Peutz [1], there are three aspects of the acoustic response of classrooms that should be considered:

- Acoustic comfort for the talker;
- Speech intelligibility for the listeners;
- Control of noise generated by students.

There is a separate issue of controlling background noise from external sources or building services that is not directly controlled by the room acoustic response.

A sophisticated model has been proposed by Pelegrin Garcia et al [2] to describe a method for evaluating the preferred range of acoustic conditions for both talkers and listeners in rooms for speech, such as classrooms. This model enables consideration of the overlapping ranges of acoustic response to provide conditions that may be both reasonably comfortable for the talker, and in which sufficiently good intelligibility may be achieved. The significant advantage over earlier conceptions of acoustic requirements is the simultaneous consideration of more than one aspect of acoustic response. In order to build this model, it is necessary to make a series of assumptions regarding the acoustic response of the room to both speech from the talker and noise generated within the room.

Currently criteria for classrooms are based on reverberation time, rather than parameters which relate more closely with users requirements. Therefore if it is possible to develop models which can simply and reliably describe users' requirements for speech intelligibility, talker comfort, and control of background noise with simple design parameters, this would be of huge benefit to the acoustic designer. In pursuit of this understanding, this paper presents measurements of Strength and Clarity in classrooms and compares the results with predicted values based on measured reverberation time and material absorption coefficients.

2. Theory

The model presented by Pelegrin is based on a number of assumptions that are discussed below. The spatial variation of reverberant sound from a point source follows Barron's revised theory [3], with the substitution of the Eyring equation for reverberation time as proposed by Nijs and Rychtáriková [4]. This is represented by the following equation:

$$L_{p,bar} = L_w + 10\log(Dir + Diff_{bar}) \tag{1}$$

Where:

$$Dir = \frac{Q}{4\pi d^2}$$

and

$$Diff_{bar} = \frac{4(1-\alpha)^{fb.d/mdp}}{A}$$

Intelligibility is represented by the unfavourable ratio parameter U_{50}. This is a modification of Clarity, C_{50}, to include the background noise in the late energy, arriving after 50 ms, which provides masking to the signal portion of the sound arriving before 50 ms after the direct sound. The model assumes that the decay of sound is linear, such that Clarity can be calculated on the basis of the reverberation time alone. As it is the room response that is investigated here, the predictions for Clarity are investigated disregarding the effect of background noise generated by the students, such that with the definition of Clarity from ISO 3382-1:

$$C_{50} = L_{p,early} - L_{p,late} \tag{2}$$

Using Barron's revised theory from Eqn (1) and integrating to 50 ms:

$$L_{p,early} = L_{w,sp} + 10\log\left(Dir + Diff_{bar}.\left(1 - e^{\frac{-0.69}{RT}}\right)\right) \tag{3}$$

$$L_{p,late} = L_{w,sp} + 10\log\left(Diff_{bar}.e^{\frac{-0.69}{RT}}\right) \tag{4}$$

Where $L_{w,sp}$ is the sound power level of speech

The background noise generated by the listeners is based on measurements of university students as described by Hodgson et al [5]. Other sources of information on background noise levels are also considered here.

3. Measurements

Aspects of the suitability of the assumptions in typical classrooms are investigated with two types of measurements. In the first type of measurement, the spatial variation of sound from an omni-directional source is investigated; the agreement between theory and measurements is considered, and the potential to determine in-situ conditions for both Strength and Clarity from simple design data is discussed. Strength is used in the model to determine the signal level of the talker arriving in the first 50 ms, and also the later arriving energy. Thus it is necessary to evaluate Strength before Clarity can be predicted.

In the second type of measurement, the potential to characterise a room with a single value of Clarity, C_{50} by measurement is investigated. Guidance on source location and measurement positions is proposed, and again, the potential to predict the measured values from simple relations between the mean absorption coefficient and room geometry are investigated. Measurements were conducted in normally furnished, unoccupied classrooms. The ceiling height was 2.7 m, and the ceiling was a Class A absorber, with some additional sound absorbent panels on the walls at high level.

Spatial variation of acoustic descriptors

To investigate the spatial variation of the acoustic descriptors, an omni-directional speaker was located 1 m from two walls in one corner of the room. Measurements were made along the line of the diagonal, towards the opposite corner, at measured distances. Measurements of Strength, G, were made using static sound levels, and using the calibrated source. The source has previously been calibrated using the guidance in ISO 3382-1 in a reverberant room. Measurements of Clarity, C_{50}, were made by measuring the impulse response using a swept sine method, with Arta software and the same omni-directional source. The measurements in progress are illustrated in Figure 1.

Figure 1: Measurements in the room

Spatially averaged levels

To investigate the possibility of a single spatially-averaged value representing the room, it is necessary to define an area over which the measurements are made. Inspection of the spatial decays indicates that the greatest distance that can practically be accommodated should be used, to represent a worst case condition, ie when the talker and listener are separated by the largest practical distance. This is achieved by considering measurements beyond a distance d_{min}, where d_{min} is 0.6 times the square root of the floor area, such that:

$$d_{min} = 0.6 * \sqrt{S} \qquad (5)$$

The results of the measurements at different positions are arithmetically averaged. The available area for measurements beyond the distance d_{min} is illustrated schematically in Figure 2.

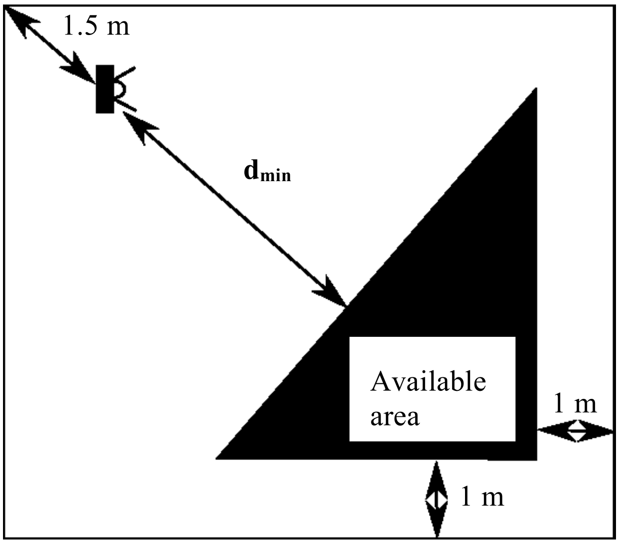

Figure 2: Available area for spatially averaged levels

The results of the spatially average levels indicate that that beyond this minimum distance, the natural variation in levels is often as significant as the decay due to increased distance. Previous measurements of spatially averaged levels of Strength and Clarity [6] have indicated good agreement with those predicted with similar theory to that presented here, based on measured reverberation time.

4. Results for spatial variation

The spatial variation of Strength with distance, plotted as the distance divided by 0.6 times the square root of the floor area, is shown in Figure 3.

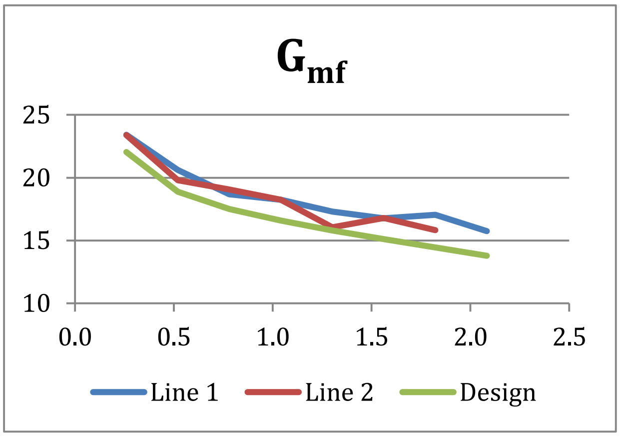

Figure 3: Spatial variation of mid-frequency Strength for both lined; “Design” is based on absorption coefficients

The spatial variation of Clarity in the 500 Hz octave band with distance is presented in Figure 4, and the variation in the 4 kHz band in Figure 5.

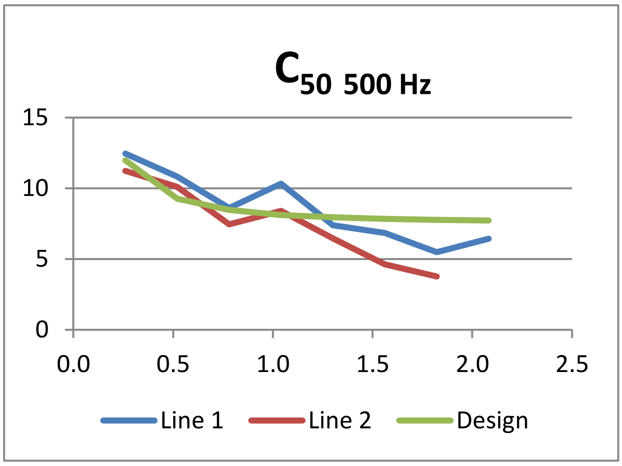

Figure 4: Spatial variation of Clarity in the 500 Hz band

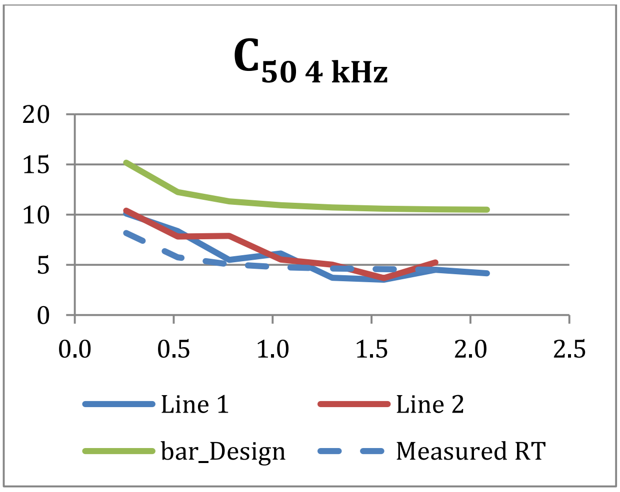

Figure 5: Spatial variation of Clarity in the 4 kHz octave band, and that calculated based on the measured RT

5. Results for spatially averaged values

The results for the spatially averaged values are shown in all octave bands between 125 Hz and 4 kHz for reverberation time T_{20}, Figure 6, Strength, G, Figure 7, and Clarity, C_{50}, Figure 8.

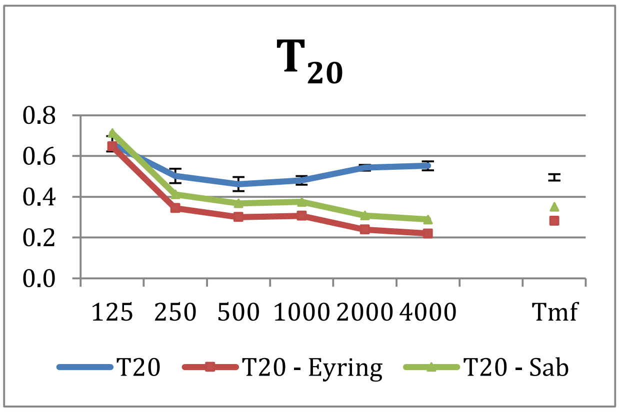

Figure 6: Measured and calculated values of T_{20}, based on Sabine and Eyring equations, and the standard deviation measured.

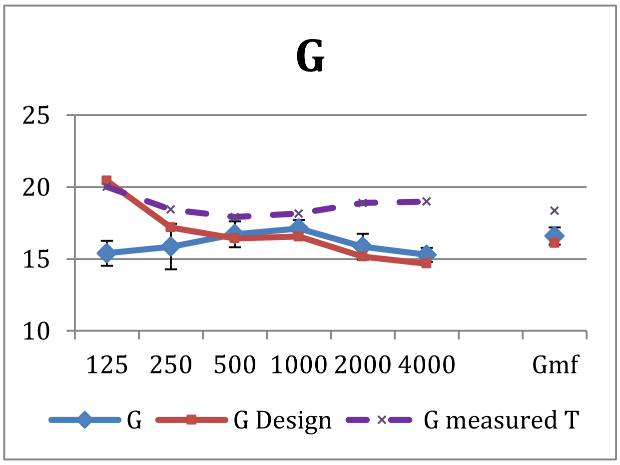

Figure 7: Measured and calculated values of G, based on the absorption coefficients (G Design) and measured reverberation time (G measured T)

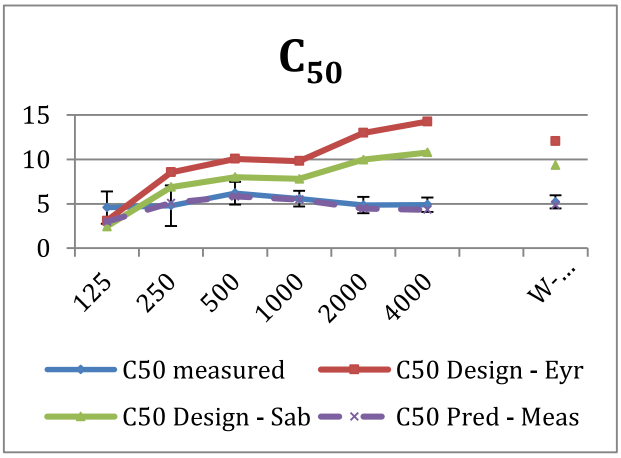

Figure 8: Measured and predicted values for Clarity, based on Eyring & Sabine calculated reverberation time, and based on measured reverberation time

6. Discussion

Reverberation time

The measured values for reverberation time, T_{20}, Figure 6, illustrate a common occurrence in classrooms, where the majority of the absorption is concentrated on one surface; the values in the higher octave bands exhibit significantly higher values than are calculated with the diffuse field assumptions of the Sabine or Eyring equations.
This effect has been well documented, especially by Nilsson [7], who has developed a model to describe the grazing and non-grazing sound fields. It is not known if this model can predict other quantities such as Strength and Clarity with sufficient accuracy; this is an area for further work, especially in light of the following discussion.

Strength

It is notable that the measured values for Strength shown in Figure 3 and Figure 7 correlate well with calculated values based on the average absorption coefficients, despite the higher measured reverberation times above 1 kHz. This has been noted previously, especially of measurements in sports halls [8]. Thus it may be considered that Strength can be well predicted on the theoretical basis presented here with knowledge of the average absorption coefficients alone, despite higher reverberation times in practice.

Clarity

Consideration of the effect on Clarity, however, is different. Where the reverberation time is reasonably well predicted with the simple assessment, so is Clarity, as illustrated in Figure 4. But above the 1 kHz frequency band, predicted values of Clarity are significantly less than those predicted based on the average absorption coefficient. Figure 5 illustrates the divergence in the spatial variation, and Figure 8 illustrates the divergence between predicted and measured values at higher frequencies.
It is also noted in Figure 8 that Clarity appears to be well predicted with the measured values of reverberation time across the whole frequency range. This would not necessarily be anticipated, as the characteristic of the sound field above 1 kHz would be double-sloped in the decay, such that reverberation time would not be expected to be a good predictor of Clarity based on a linear decay. Clarity in octave bands up to 4 kHz is

important for speech intelligibility according to Marshall, as described in [6].

Noise from students

In the model presented by Pelegrin, the model for the background noise generated by the students [5] is similar to that presented by Rindel [9], in that within the dynamic sound source level there is a decrease of approximately 6 dB for a halving of the reverberation time. Measurements made during the Essex Study [10] are not directly comparable as the background level during lessons is expressed as the statistical level, $L_{A90,\ T}$, rather than that part of the sound attributable to the students during discourse by the teacher. However, those measurements were notable in that the background level dropped by 9 dB with halving of the reverberation time from 0.8 to 0.4 seconds; this was associated with the change of behavior that was noted from the qualitative results in those rooms with the lowest reverberation times. It is therefore suggested that there may be considerable benefit for the accuracy of the model to undertake further work to determine the noise level generated by different aged pupils in different acoustic environments.

7. Conclusions

The overall goal of developing simple design tools that enable robust prediction of the acoustic qualities in which we are interested – speech intelligibility, talker comfort and control of background noise – remains elusive. However, the measurements suggest that Strength can be well predicted with the amount of absorption within the room, regardless of the reverberation time measured; this is a significant finding.

On investigating Clarity, correlation with the measured reverberation time would not necessarily be anticipated, given that the model for Clarity is based on a linear decay, whereas non-linear decays are likely where the reverberation time significantly exceeds diffuse-field models. Despite this, measured values of Clarity were found to follow predicted values based on the measured reverberation time. This suggests that a more sophisticated model of calculating reverberation time may prove advantageous.

The development of the model for noise generated within the room, for younger students and in rooms with lower reverberation times, would also assist in making the model more robust.

Acknowledgement

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