THE DIFFUSE SOUND FIELD AND ITS RELEVANCE FOR CONCERT AUDITORIA

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1 INTRODUCTION

For most of us, our first encounter with the concept of a diffuse sound field is when we are introduced to the theory behind the Sabine equation. However emboldened by the ability to predict reverberation time (RT), we probably imagine that the diffuse requirement can be mostly ignored. Then once we start using a computer simulation models, we discover that many predicted RTs differ from the Sabine values. The reasons for this are generally a poor state of diffusion; in fact most spaces in real life are not particularly diffuse! This paper will discuss the nature of diffusion, the requirements for diffusion, and the situation in concert halls, both subjective and objective. Overall, there is the question of whether a diffuse sound field is a suitable goal for concert hall design.

Defining a diffuse sound field is difficult[1]. Perhaps the most straightforward definition of a diffuse sound field at a point is that the acoustic energy flux density through the point is equally distributed over all directions. The consequences of a diffuse field are more easily described:

Sound in all directions during decay
Linear decay
Uniform sound level throughout the space <u>during</u> <u>decay</u>
RT equations predict correctly
Revised theory predicts correctly

The link between a diffuse sound field and linear decays comes from the derivations of the standard Sabine and Eyring RT equations, for whose derivation it is necessary to assume a diffuse sound field.

The requirements of a space to achieve a diffuse sound field are:

Proportionate space
Uniform absorbent treatment on all surfaces
A lot of scattering treatment
No focusing

We are all familiar with how this is achieved in a reverberation chamber, where a diffuse sound field is a requirement. However what is interesting here is that an auditorium does not have a uniform distribution of absorbing treatment, but rather a concentration of absorption on the floor. In spite of that, behaviour as if it were a diffuse sound field is not uncommon. That statement needs qualifying: more precisely in auditoria we often find the characteristics of a diffuse sound field, such as a linear decay, but conformity with behaviour as a diffuse field occurs at different degrees of diffusion depending on which objective measure one is looking at.

From a subjective point-of-view, listeners can respond to the directional distribution of arriving sound and to the linearity of decays. However regarding these two aspects, in neither case are listeners especially sensitive. One can summarise subjective response as follows:

Listeners like to be surrounded by sound but otherwise they are relatively insensitive to direction
Poor sensitivity to linearity of decays

The case for designing a diffuse sound field is thus fairly weak from a subjective perspective. The evidence concerning directional sensitivity comes from work by Damaske[2], which showed that as long as reverberant sound arrives from four roughly orthogonal directions, listeners feel surrounded/enveloped by sound.

2 DETECTING THE STATE OF DIFFUSION

Though the definition of a diffuse sound field in terms of directional uniformity is conceptually uncomplicated, it does not lend itself to a straightforward measurement procedure. The consequences of a diffuse field might be used as measures of diffuseness, though more research is needed to substantiate them as reliable measures. The following have been tried:

Decay linearity, such as T_{20}/T_{30}
RT equation predicts correctly
Normalised standard deviation of RT
Standard error of late level

In each case further comments are necessary. Measuring decay linearity using T_{20}/T_{30} depends on a good signal-to-noise ratio, to avoid contamination by background noise. An alternative measure would be the ratio of mean EDT to mean RT (omitting under balcony seat positions); this does not work if reflecting surfaces are specifically directing reflections onto seating areas[3]. An example where mean EDT/RT indicates good diffusion is the St David's Hall, Cardiff (p.196 of ref. 4), which is a terraced hall with a scattering ceiling.

Checking correct prediction by RT formulae is very straightforward when using computer simulation models since they provide computed RTs as well as Sabine calculations. For real auditoria the comparison depends on accurate absorption figures for room surfaces, in particular absorption by seating.

Davy *et al.*[5,6,7] have developed formulae for the expected standard deviation (SDev) of RT measured in many positions in a space with a diffuse sound field (see Appendix). To assess the degree of diffusion, a normalised value can be used as the ratio between measured SDev and theoretical. Figure 1 illustrates normalised values in three British concert halls constructed between 1991 and 1997. There is an immediate oddity about these values, namely the significant rise in the normalised standard deviation of RT (NSDRT) at 2kHz. This has been attributed to the breakdown of omni-directionality of a standard dodecahedron loudspeaker above 1kHz, which has been confirmed from RT measurements made with a significantly smaller dodecahedron loudspeaker[8]. Returning to Figure 1, NSDRT values at 500 and 1000Hz do appear to reflect the expected degrees of the states of diffusion in the three halls. The measured range of NSDRT in a total of 7 concert halls (as measured by the author) is 0.73 to 1.60. One can suggest a criterion of less than a value of 1.10 for good diffusion. Further evidence of the suitability of NSDRT as a measure of diffuseness has been found in acoustic scale models[9,10,11].

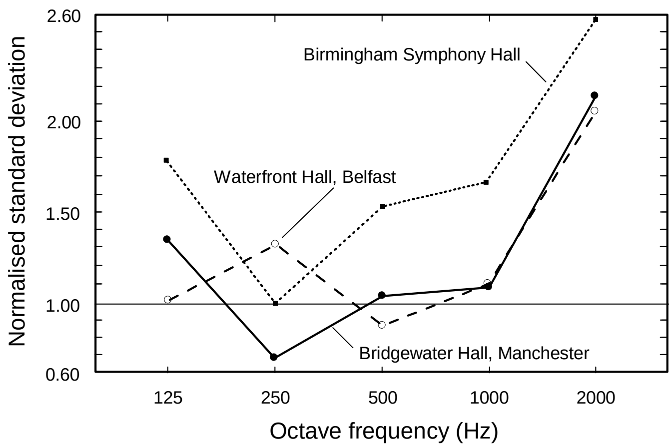

Figure 1. Measured values of the NSDRT in three large British concert halls.

Schroeder[12] and Lubman[13] independently proposed an equation for the standard deviation of sound pressure level in a diffuse sound field (see Appendix). Lubman measured this deviation (SDev) in several reverberation chambers, finding that measured values were generally slightly larger than theory. The standard deviation however referred to a diffuse field in a reverberation chamber, in which the reflected sound level is basically constant throughout the space. In auditoria, it has been shown[14] that the reflected level decreases with distance; the relevant scatter in this case is better assessed by the scatter about the line-of-best-fit, which is known as the standard error (SE) of estimate[15]. (The relevant difference here between reverberation chambers and auditoria is the mean absorption coefficient, which is very small in reverberation chambers.) A comparison has been made between the Lubman/Schroeder theory and measured SE in a diffuse model space which included absorbing treatment[9]. Good agreement was found, not with the reflected sound level, but with later sound after 200ms. In all real concert auditoria, the measured SE for late sound after 80ms was found to exceed the theoretical value. However comparison between measured SE at mid-frequencies and the Lubman/Schroeder prediction suggests this as a possible measure for the state of diffusion; subtracting the theoretical value (SDev) from the measured SE provides a normalised measure (in dB). This last can be called the Normalised Standard Error for Late Level (NSELL). The measured range of NSELL in 25 concert halls is 0.12 to 1.23dB; one could propose a maximum value of 0.20dB for a diffuse sound field.

Studying measured values of the NSDRT and NSELL in concert halls, there appears to be a benefit from looking at both figures to judge the state of diffusion. But without an unambiguous measure for diffusion, these normalised quantities remain speculative.

3 REVISED THEORY OF SOUND LEVEL AND DIFFUSE SOUND FIELDS

As mentioned above, the revised theory of sound level resulted from the observation that the reflected level decreases with distance in concert spaces. The theory is based on two simple assumptions: that reflected sound cannot arrive before the direct sound and that the instantaneous sound level during a linear decay in a room is uniform throughout the space. These assumptions result in integrated impulse responses as shown in Figure 2. The consequence of this approach is that the reflected sound level decreases linearly as a function of source-receiver distance. The theory provides predictions for the early, late and total sound levels, as well as the early-to-late index (see Appendix); the temporal boundary for music is usually taken as 80ms after the arrival of the direct sound. The predictions are a function of only auditorium volume, reverberation time and source-receiver distance.

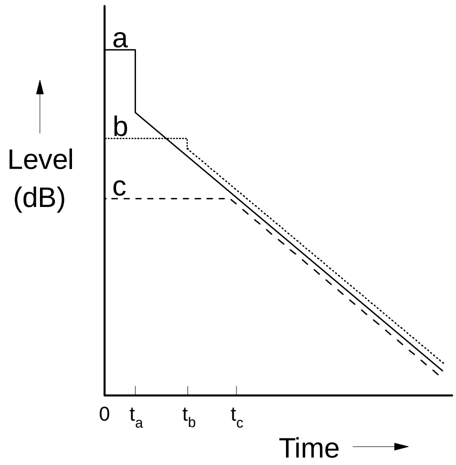

Figure 2. Integrated impulse curves at three receiver distances from the source in a room. Curve ‘a’ represents the position closest to the source, with travel time t_a for the direct sound. The time origin at t = 0 is the time when the sound is emitted from the source. According to the second assumption above, the diagonal lines are superimposed but have been separated here for clarity.

A late realisation has been that because we are dealing with linear decays and ‘uniform’ level throughout the room during the decay, we are considering a diffuse sound field. Measurements in a diffuse model space have shown that it exhibited basic revised theory behaviour[9]. This leads to the recognition that in a space with a diffuse field, for a particular volume and RT, there are unique values for total sound level (G) and early-to-late index (C_{80}). This translates subjectively into a unique loudness and clarity, both a function of source-receiver distance. Figure 3 shows predicted values as a function of source-receiver distance for different auditorium volumes in diffuse sound fields (with RT = 2.0s), while Figure 4 shows equivalent values for three RT values (for volume of 10,000m^3). These can be compared with subjective criteria for G and C_{80}.

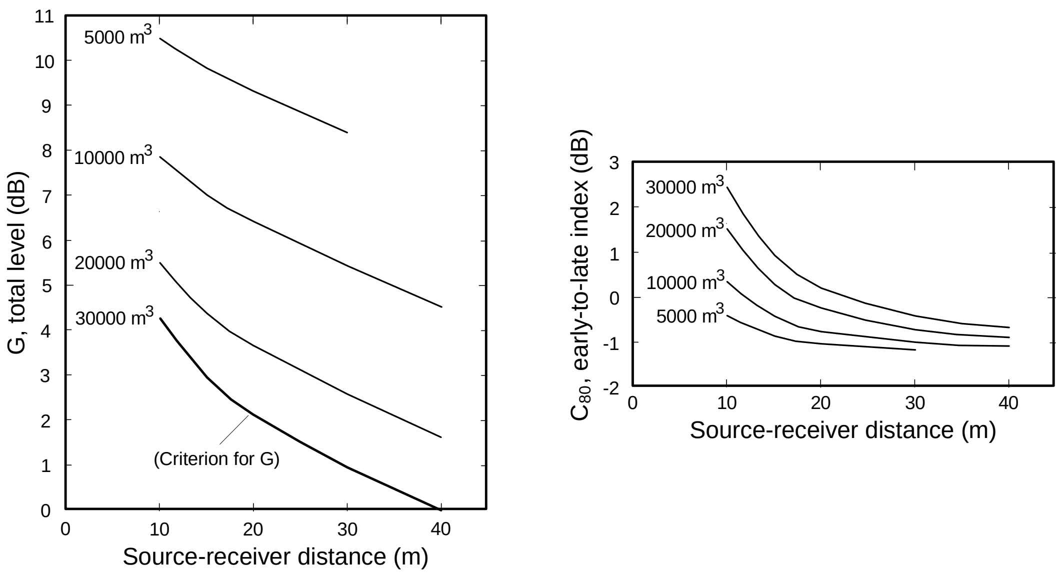

Figure 3. Predicted values of total sound level, G, and early-to-late index, C_{80}, as a function of hall volume according to revised theory (assumed RT = 2.0s).

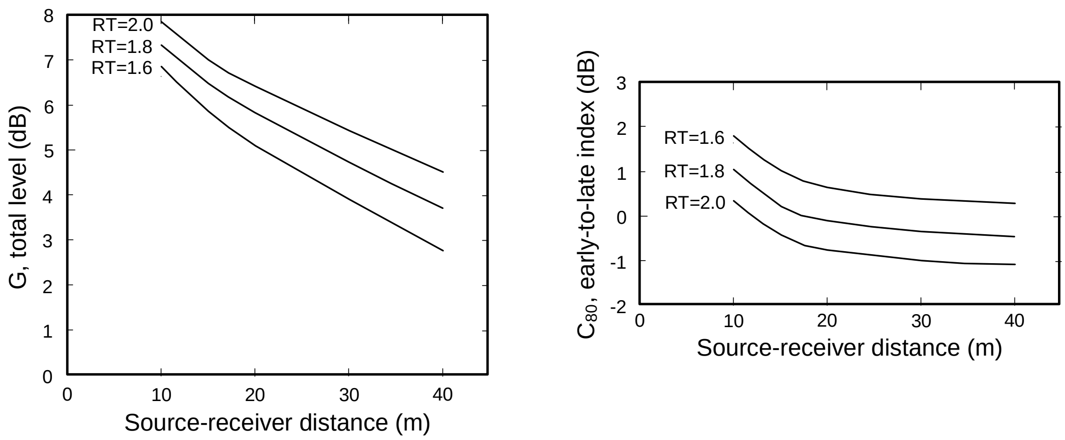

Figure 4. Predicted values of total sound level, G, and early-to-late index, C_{80}, as a function of reverberation time according to revised theory (assumed auditorium volume 10,000m^3).

There is also convincing evidence that the scatter of sound level at individual positions is least in a diffuse sound field[9,15]. This is a consequence of the Lubman/Schroeder analysis mentioned above. Thus not only are unique values of G and C_{80} predicted for diffuse sound fields but the accuracy of the predictions is greatest for such a sound field, at least for G.

Not many proposals for a minimum total sound level (at an individual seat) exist, G ≥ 0dB at mid-frequencies (mean of 500, 1000 and 2000Hz octaves) is often mentioned (p.66 of ref. 4). Barron[16] has argued that the evidence of sound in a hall appearing to be equally loud irrespective of seat position, what is known as **loudness constancy**, requires that G values are higher close to the source. With the recommended maximum stage to seat distance of 40m, this leads to the curve in Figure 3 for V = 30,000m^3 representing the lower limit of acceptable Strength, G. A volume of 30,000m^3 is a general upper limit for concert halls; all halls with smaller volumes conform to this criterion. Likewise smaller halls with shorter reverberation times conform.

For the clarity measure, C_{80}, an acceptable range of -2 to +2 dB at mid-frequencies has been proposed[4] with slightly higher values also tolerated. Beranek (p.527 of ref. 17) suggests slightly lower values for mean C_{80} averaged over seat positions. In Figures 3 and 4, all values are within this range except for positions close to the source with V = 30,000m^3 and RT = 2s.

One can therefore conclude that the total sound level and objective clarity are acceptable for diffuse spaces of traditional size and reverberation times close to 2s.

4 DIFFUSE SOUND FIELDS IN PRACTICE

Two historical concert halls[4] stand out as examples of design intended to offer diffuse conditions, achieved through inclusion of large areas of scattering surfaces. Scattering wall and ceiling surfaces were, of course, an incidental feature of 19th century halls, such as the Musikvereinssaal, Vienna. The first of the halls specifically designed with scattering surfaces for acoustic reasons is the **Beethovenhalle** in **Bonn**, built in 1959, with 1420 seats and an occupied RT of 1.7s. Acoustic consultants were Meyer and Kuttruff[18] from Göttingen University. The distinctive features of the hall are the highly scattering ceiling and splay walls in front of the stage. Its reputation may be tarnished by its short RT.

The second hall is the **De Doelen Hall** in **Rotterdam** from1966, with an RT of 2.1s and 2230 seats. There are scattering surfaces around the stage and surrounding the lower stalls seating, with profiled side walls and ceiling. The hall has a good acoustic reputation. Nevertheless this approach to concert hall design with a high proportion of scattering surfaces has not often been copied subsequently.

Though profiled surfaces are not obviously evident, terraced surround halls, such as the **Berlin Philharmonie** of 1963, are likely to have diffuse fields due to the reflective surfaces among audience seating. The recent **Walt Disney Concert Hall, Los Angeles** of 2003 has convex vertical divisions between seating areas and horizontal convex ceiling surfaces, both of which can be expected to promote diffusion. The **Sala Minas Concert Hall, Belo Horizonte, Brazil**, which opened this year, also has the same feature[19].

5 AN EXAMPLE OF A HALL WITH A DIFFUSE SOUND FIELD

It is suggested above that two criteria could be applied to establish a diffuse sound field, the NSDRT and NSELL. A hall which satisfies both criteria is the **Anvil Concert, Basingstoke, England**, with an NSDRT of 0.73 and NSELL of 0.19dB. Figure 5 shows the Temporal Energy Analysis[20] in this hall averaged over the three octaves 500 – 2000Hz. The individual plots compare measured values at 14 audience locations with revised theory predictions, in the cases of the early, late, total sound and early-to-late ratio, C_{80}. The hall does not have obvious (bumpy) scattering surfaces, but there are two rows of convex panels running down both sides of the hall. The hall has a good reputation for its acoustics.

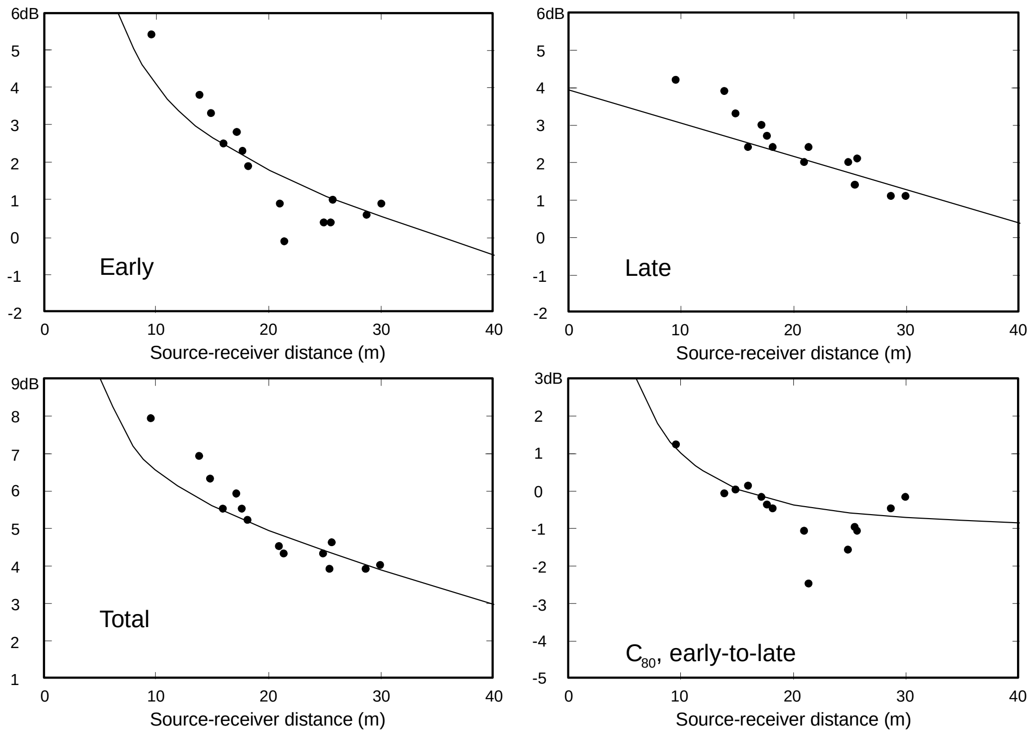

Figure 5. Measured values of the early, late and total and C_{80} levels in the unoccupied Anvil Concert Hall, Basingstoke, as measured in 2006. Lines represent values according to revised theory.

In fact, there is evidence of two deviations from revised theory in this hall. The three closest positions to the source have elevated early and late levels, caused presumably by the geometry of the hall providing extra reflections in this region. Secondly there is position at 21m from the source with a low early sound level, which also shows up on the early-to-late plot.

(The plot of late sound in Figure 5 indicates a further issue relevant to a diffuse sound field. It is not uncommon in concert halls to have a steeper drop-off with distance for the late level. In this case, the slope of the best fit line is steeper than predicted by revised theory by 0.06dB/m. For example, a lined duct would behave as a highly non-diffuse space with a steep slope for late sound vs. distance. At some point, an excess slope of late sound should indicate a sound field no longer diffuse. Steeper slopes do not influence the NSELL.)

6 ADVANTAGES OF A DIFFUSE SOUND FIELD

One can therefore summarise the advantages of a diffuse sound field:

Prediction formulae for RT likely to be accurate
Strength (G) and Objective clarity (C_{80}) predictable from volume and RT
Subjectively diffuse reverberant sound
Variable absorption offers maximum possible change

Overall the diffuse sound field with a suitable RT is likely to offer good acoustics. It can probably be considered as a safe solution for concert hall design for small and medium size halls. This represents a possible solution but not an essential one. Subjective diffusion (feeling surrounded by sound) and satisfactory values for Strength and clarity can be achieved in other ways, without the need for a physically highly diffuse space.

No mention has been made above about source broadening/spatial impression, which depends on early lateral reflections. The impression depends on the geometry of the space, rather than numerical temporal quantities.

In a diffuse sound field, Strength and objective clarity are linked. This link can be broken in a non-diffuse field.

In a large concert hall the requirements for a diffuse space may be more restricting on design and, as already mentioned, other means can be used to achieve subjective diffusion and satisfactory values for Strength and clarity. This paper proposes that it is worthwhile assessing the state of diffusion of concert hall designs, using the diffuse field as a reference point.

7 REFERENCES

1. T.J. Schultz, ‘Diffusion in reverberation rooms’, J. Sound Vib. **16**, 17-28. (1971).
2. P. Damaske, ‘Subjektive Untersuchungen von Schallfeldern’, Acustica **19**,199-213. (1967).
3. M. Barron, ‘Interpretation of early decay times in concert auditoria’, Acustica **81**, 320-331. (1995).
4. M. Barron. Auditorium acoustics and architectural design, 2nd ed. Spon Press, London. (2009).
5. J.L. Davy, I.P. Dunn and P. Dubout, ‘The variance of decay rates in reverberation rooms’, Acustica **43**, 12-25. (1979).
6. J.L. Davy, ‘The variance of impulse decays’, Acustica **44**, 51-56. (1980).
7. J.L. Davy and I.P. Dunn, ‘The statistical bandwidth of Butterworth filters’, J. Sound Vib. **115**, 539-549 (1987).
8. I. Witew (Personal communication).
9. S. Chiles and M. Barron, ‘Sound level distribution and scatter in proportionate spaces’, J. Acoust. Soc. Am. **116**, 1585 – 1595. (2004).
10. M. Barron, ‘Thoughts on the room acoustic enigma: the state of diffusion’, Proc. Institute of Acoustics, **27**, Part 2, 9-19. (2005).
11. E. Green, ‘Scale model analysis of a rectangular concert hall with variable diffusion’, M.Sc. dissertation, University of Southampton, England (2011).
12. M.R. Schroeder, ‘Effect of frequency and space averaging on the transmission responses of multimode media’, J. Acoust. Soc. Am. **46**, 277-283 (1969).

13. D. Lubman, 'Fluctuations of sound with position in a reverberant room', J. Acoust. Soc. Am. **44**, 1491-1502 (1968).
14. M. Barron and L-J. Lee, 'Energy relations in concert auditoriums, I', J. Acoust. Soc. Am. **84**, 619-628. (1988).
15. M. Barron, 'Theory and measurement of early, late and total sound levels in rooms'. J. Acoust. Soc. Am. **137**, 3087-3098. (2015).
16. M. Barron, 'Taking account of loudness constancy for the loudness criterion for concert halls', Applied Acoustics **73**, 1195-1199. (2012).
17. L.L. Beranek. Concert Halls and Opera Houses: Music, Acoustics and Architecture, 2nd ed. Springer, New York. (2004).
18. E. Meyer and H. Kuttruff, 'Zur akustischen Gestaltung der neuerbauten Beethovenhalle in Bonn', Acustica **9**, 465-468. (1959).
19. J. Nepomuceno, C, Blair and M. Barron, 'Design of the Sala Minas Concert Hall, Belo Horizonte, Brazil', Proc. Institute of Acoustics **37**, Pt.3. (This meeting - 2015).
20. M. Barron, 'Objective assessment of concert hall acoustics using Temporal Energy Analysis', Applied Acoustics **74**, 936-944. (2013).

APPENDIX

Davy's theory for the standard deviation of RT[5,6,7] results in the following. If f is the centre frequency and octave bands are used, the expressions for the standard deviation of T_{20} and T_{30} are:

$$\sigma(T_{20}) = 1.08\sqrt{\frac{T_{20}}{f}} \qquad \text{and} \quad \sigma(T_{30}) = 0.666\sqrt{\frac{T_{30}}{f}} \qquad (1)$$

The Lubman/Schroeder formula[12,13] for the standard deviation of level in a diffuse reverberation chamber is as follows. For a noise source, the standard deviation, σ, of the sound pressure level of the reflected component within a room, L, is a function of bandwidth, B, and reverberation time, T:

$$\sigma(L) = \frac{4.34}{\sqrt{\left(1+\left(\frac{BT}{6.9}\right)\right)}} \text{ dB} \qquad (2)$$

(Note: equations (1) and (2) assume normal acoustic waves and are not applicable to results of current computer simulation models.)

Revised theory can be most easily presented in terms of three energy terms (p.465 of ref. 4, refs. 14 and 15). The direct component, $d = 100/r^2$, where r is the source-receiver distance. If T and V are the reverberation time and volume of the auditorium, the early reflected (e_r) and late (l) sound energies are:

$$e_r = \frac{31200\,T}{V}\, e^{-\frac{0.04\,r}{T}}\,.\left(1-e^{-\frac{1.11}{T}}\right) \quad \text{and} \quad l = \frac{31200\,T}{V}\, e^{-\frac{0.04\,r}{T}}\, e^{-\frac{1.11}{T}} \qquad (3)$$

Hence, the early-to-late index, $C_{80} = 10 \log [(d + e_r)/l]$ and Strength, $G = 10 \log (d + e_r + l)$ dB. The total reflected level = 10 log(31200 T/V) – 0.174r/T dB (4). All levels here are expressed relative to the direct sound level at 10m from an omni-directional source.