Institute of Acoustics

'ALTERNATIVE' MEASUREMENTS IN SMALL ROOMS

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1. REVERBERATION TIME, RT.

The reverberation time is the oldest of the objective measures of room acoustics. It correlates well with the overall acoustic impression of a room and inappropriate values are undoubtably responsible for some acoustic defects. For example, large-scale 19th Century romantic music demands the temporal blending and sound level reinforcement provided by a long reverberation time, liturgical music even more so. Excessive reverberation can render other music or speech unintelligible.

The reverberation time is defined as the average time taken for a sound level to decay naturally to −60 dB relative to its initial, steady value. It is, in fact, the reciprocal of an exponential rate of decay. It has been measured as a time-period for historical reasons [1].

The simple room theories which were expounded by Sabine, and which have been the basis of room acoustics ever since, made the assumption that the exponential decay was uniform, both as a function of time and of space. As such, there is no further need to consider alternative measurements – this uniformity is all there could be. (The results may, of course, still be a function of frequency.) Thus, room acoustics would be simply a choice of the proper reverberation time, perhaps different at different frequencies, for the intended purpose. It is still true that an appropriate reverberation time is a necessary first-step in obtaining satisfactory room acoustics, although the range of acceptable values may now be wider than it was once thought to be.

In real rooms the exponential rate of decay is not independent of time or of the position in the room or even the direction from which the sound arrives at a point within the room. These departures from the idealised model have given rise to a range of alternative measurements, some focussing on certain deviations and others on different ones. However, it must be said that all of these alternatives are in effect measures of the departure from the ideal and are therefore fairly small effects, at least in most reasonable rooms. This also makes them not so much **alternative** measurements as **additional** measurements.

Many of these additional measurements have been proposed, mostly in the field of auditorium acoustics. The theoretical acoustic parameter of "diffusion", which is a direct measurement of the lack of uniformity of the exponential decay, has been investigated by the BBC in the past in small rooms [2,3,4,5] and some measurable parameters evaluated, without any lasting success. The most useful of these was a measure of the departures from straight lines of the decay curves [4,5], but even this has been found to be poorly correlated with room quality. Its derivation for routine measurements was abandoned after a period of use of about 10–15 years for that reason. For the remaining proposals [6,7,...,20], no known attempt has been made to assess them in the context of broadcasting studios, except for those large music studios which are like small Concert Halls. This paper is an attempt at an objective evaluation of the applicability of these measurements to broadcasting studios. It has drawn heavily from Ref. 6.

2. RISE-TIME (TR), STEEPNESS (σ) AND INVERSION INDEX (II)

The Rise-Time (TR) is defined as the time taken for a sound level at the measuring position to rise from zero to 50% of its final energy level, excluding the direct propagation delay time. The theoretical value can be derived assuming an exponential build–up of sound level corresponding to the readily–observed (usually) exponential decay which is the reverberation time. It is a reasonable assumption, but no more than that, that the build–up of the sound follows the complementary pattern. It is easy to show that the 'theoretical' value for TR is approximately 0.05RT.

The Steepness (σ) is defined as the slope of the 'line' representing the build–up of the sound level at a level –5 dB relative to the final level. It is, theoretically, approximately equal to 0.13/RT and also to $0.0094c\alpha_m/p$, where c is the velocity of sound, α_m is the mean absorption coefficient of the room and p is the mean free path length.

Both of these lead to definitions of the Inversion Index (II) as their ratios in the audience area and the 'stage' area of the room respectively:

$$II = TR_{(Audience\ Area)}/TR_{(Stage\ Area)} = \sigma_{(Stage\ Area)}/\sigma_{(Audience\ Area)}$$

The Inversion Index, II, is plainly of no interest in the majority of Radio Studios nor in Television Studios either (which are simply required to be acoustically 'dead'). Even in dedicated BBC music studios there is never sufficient room to identify the audience area as being acoustically separate. In any case, in a studio, the microphone sound is the important aspect; conditions for the local audience are strictly secondary. Because of this lack of application, II is not worth further consideration as an additional general acoustic measurement.

For the majority of Radio Studios there may well be problems in measuring the Rise Time. In a Talks studio the TR will be about 10 ms and in a Drama studio about 25 ms. Times of this order could not be measured, even theoretically, in relatively narrow frequency bands. In practice, the lowest bandwidth which could be considered would be about 250 Hz, that is, the three lowest octave bands simultaneously. At higher frequencies single octave–band analysis could probably be carried out from 1 kHz upwards. The frequency resolution would therefore not be very good.

(This raises a conceptual problem – why can we presently measure RT? One difference is that the RT measurement occurs over a longer time–scale, corresponding usually to about 30 dB range of sound level (equivalent to 100 ms even in a 'modern' Talks studio). It is also true that RT measurements are themselves limited by filter bandwidths at low frequencies – to the equivalent of 300 ms at 50 Hz, with perfect filters.)

A second, different problem arises with TR measurements in small rooms with short RTs. That is, the sparsity of reflections in the first few milliseconds. Even in a small room there would be only 2 or 3 discrete reflections (floor and ceiling and perhaps a nearby wall) in the first 10 ms. The resulting measurement would be very erratic, depending greatly on the exact nature of these reflections. The question arises "Why do these measurements appear to be possible in concert halls?" One answer is that such rooms have much smaller α and much larger mean free path. The reflection structure is therefore much denser in the region measured by the TR.

Similar considerations apply to Steepness. Would it be sensible to derive a function for the slope of a line when that line is, essentially, discontinuous? The line could be smoothed (and would inevitably be at low frequencies or with an excessively narrow filter bandwidth) but then the measurement would be of the filter or smoothing network.

In both of these measurements there is also the problem of accuracy. What is considered to be important is the relatively small **difference** between the result and that predicted from a measurement of the mean RT. It is difficult enough measuring the RT repeatably – to then look for the differences between the results of the TR or the σ measurement and the value calculated (from a measurement of the RT) would probably give 100% error margin at best !

3. DECAY PROCESS AND EARLY DECAY TIME, EDT.

The simple, theoretical exponential decay gives a constant value for the gradient of the logarithm of the sound level as a function of time. One of the deviations from the theoretical which is often observed in measurements in real rooms is the variability of this slope. It is especially variable at low frequencies, in small rooms and when the rooms are acoustically heavily damped.

Reverberation time, which is proportional to the reciprocal of this gradient, is, strictly, defined over a fixed range of 60 dB but is usually measured over a smaller range and extrapolated. When measured in this way and in a situation where the decay is not constant, the value obtained depends on the part of the decay which is used for the measurement. This variability has been formalised by defining an 'early' range of levels, –5 dB to –15 dB, over which the 'Early Decay Time' (EDT) is measured. The EDT is the reverberation time as measured over this range and extrapolated to a 60 dB range. In other words, it is six times the time interval required for the sound level to fall from –5 dB to –15 dB relative to its steady–state value.

Its supposed subjective significance is that the time taken for this part of the decay, in a concert hall with a mean reverberation time of 2 s, is similar to the time interval during which the quality of the perceived sound is established, about 200 ms. In fact, M.R. Schroeder who first suggested EDT used a fixed period of 160 ms for the measurement, rather than any particular range of sound levels [21]

The curvature of the decay process is normally such that the sound level falls more quickly initially, giving a 'reverberation time' which is shorter if it is measured over the earlier (higher level) part of the decay. It usually arises in this way because the decay is made up of many contributions from room eigenmodes with different damping factors. Simple logic shows that if there is any observed non–linearity then it will be because the longer decay times will dominate the later part of the decay process, thus leading to a progressively lengthening 'reverberation time'. It is not unknown for the curvature to be in the opposite direction, but this will rarely occur in the moderate–shaped rooms with relatively even distributions of acoustic treatment which are typical of broadcasting studios.

It is this curvature which EDT attempts to quantify. There are, however, several obvious defects in the principle. The first is "Why –5 to –15 dB ?". The –5 dB is mostly because it is not possible, practically, to measure from any higher level. The inevitable variation in the reference 'steady–state level' makes it impossible to determine where the decay starts until it is at least 5 dB down. Thus, the start of the 'EDT interval' is not because of any subjective consideration but is a purely practical one. The end of the interval is equally arbitrary. It obviously must be long enough to make a reasonably accurate assessment of the first part of the decay. However, if it is too long there is a danger of its not being distinct from the 'ordinary' RT. For the practical reasons of maximum reasonable sound power and lowest workable signal/noise ratio, this is often measured over a range of only 30 to 40 dB, especially at low frequencies. To make it different, the EDT range is constrained to be rather less than this. The 10 dB range is a compromise. In fact, as stated above, the main justification for the range was a time–domain consideration. The formalisation of the amplitude range followed.

Subjectively, EDT has some justification in that it might represent a perception threshold for clarity such that repetitive sounds, such as music or speech, rising to about 10 dB above the general reverberance would be heard differently if the EDT was different to the RT. This would suggest that a room with a short EDT would have the double benefits of clarity and reverberance.

Unfortunately, some of the literature [6, p. 212] suggests that the opposite has been the case: "it has been usual to consider values *above* RT values and values *equal* to RT values as satisfactory, but values *below* RT values (especially if more than 15–20% lower) as unsatisfactory.". He does, however go on to say that more recent research indicates that acceptable values are "within a certain definite interval".

A second problem with the EDT is that the time interval of the measurement may or may not encompass a number of factors. One of these is the ratio of the direct to the reverberant sound. It is often the case that, when the excitation source is stopped, there is an immediate fall in the level of the received sound because the direct path is no longer contributing. This fall is not usually of 10–15 dB, except close to the source or in very unusual conditions not encountered in broadcasting studios, but it can be quite significant. Such an instantaneous fall in level will significantly affect the measured EDT, giving justification to the question "What is the subjective significance of a measurement which can be so influenced by such erratic events?".

A second factor which may or may not be included in the measurement of EDT is the occurrence of decays with two distinct portions, both of which are fairly straight but which have quite different gradients. They are generally caused by two separate reverberation processes occurring simultaneously in the same space – for example on the stage of a Concert Hall or, more particularly, in the pit of a Theatre or Opera House. In these cases, the much longer–duration but rather lower–level (when heard on the stage or in the pit) response of the auditorium is observed separately, after the the contributions of the stage area have diminished because of absorption or diffusion into the main body of the hall.

Thus the EDT would appear to be unreliable, even if it could be shown that it had a worthwhile subjective importance. Like the other **additional** acoustic measurements, it is also subject to very severe accuracy limitations because its significance is the difference between the value predicted from the RT measurement and the measured value of EDT.

In broadcasting studios or control rooms most of the characteristics purported to be measured by the EDT do not occur, except for the inevitable problems in small rooms at low frequencies. There is also the significant discrepancy in the time intervals. For most studios and control rooms, the EDT time would be of the order of 30 ms, plainly not what Schroeder *et al* had in mind when the measurement was proposed.

Double decays rarely arise because different areas are acoustically distinct but they can sometimes arise if a room has a particular mode or group of modes which have anomalously low damping factors. A similar process can arise (and has been observed many times) from the mechanical vibration of elements within the room. If they are at a significant level these are acoustic faults which must be avoided. In such cases, the results of an EDT measurement in such a room would generally be the 'normal' RT value which would have occurred in the absence of the fault. Thus, the EDT might have a useful application in the detection of such faults and in the specification of corresponding criteria, but the problems of accuracy would remain.

The parameter derived by the BBC [4] as a measure of diffusion is the ratio of the RT for the initial part of the decay to that for the later part of the decay, the decay curves being somewhat arbitrarily divided at about the –25 dB level. This was ultimately found to be poorly correlated with room quality.

4. ENERGY–TIME CRITERIA: CLARITY (C), INDEX OF ROOM IMPRESSION (R), ROOM RESPONSE (RR), LATERAL EFFICIENCY (LE), INTERAURAL COHERENCE (IC) AND 'RAUMLICHKEIT'

Clarity, Index of Room Impression, Room Response, Lateral Efficiency, Interaural Coherence and 'Raumlichkeit' are a group of criteria which measure, in some way, the temporal distribution of the sound energy received at a point in a room. All of them except for Clarity also incorporate a measure of the directional distribution of the sound energy at the receiving position.

The origin of these criteria was, essentially, in the criterion 'Deutlichkeit' (definition) introduced by R. Thiele in 1953 [8]. It was defined as the ratio of the energy arriving in the first 50 ms to the total energy, expressed in decibels. The basis of the criterion was that, in the perception of sound, the quality was fully established in the first 50 ms. It was originally proposed as a criterion for speech articulation. Similar criteria for music were proposed by Beranek and Schultz ('Hallmass') [13] and by Reichardt ('Hallabstand') [14] using 50 ms (again) and 5 ms respectively with slightly different expressions. Clarity (C) was introduced by Reichardt *et all* [16] as a modification of his Hallabstand, using 80 ms as the boundary between the two regions. Clarity is defined as the ratio of the energy in the first 80 ms to the remaining energy, expressed in decibels.

At about this time it was becoming clear that the sound energy arriving from the direction of the sides of a room was important for giving an impression of spaciousness, particularly if it arrived at the listener between 25 and 80 ms after the direct sound. It has also been found [17] that the total energy arriving in the interval 80 to 160 ms is also important for the spatial impression. Accordingly, a complex criterion was derived called the Index of Room Impression (R) [18]. In principle, this is the ratio of all energy contributing to the 'spatial sound' to all energy components contributing to the 'direct sound', again expressed in decibels. This is a very complex criterion which has been somewhat simplified into a rather contrived criterion, called the Room Response (RR) [6. p161] which is the ratio of the 25–80 ms lateral energy plus the 80–160 ms total energy to the 0–80ms total energy, again expressed in decibels.

The fourth of this group of criteria is the Lateral Efficiency [6. p179]. It is defined as the ratio of the 25–80 ms lateral energy and the 0–80 ms total energy. It is not measured in decibels but is simply expressed as a coefficient. The Interaural Coherence has been shown [22,23,24,25], under some circumstances, to be approximately equal to 1–LE and need not be considered separately.

The criterion 'Raumlichkeit' [26] is another measure of the early lateral energy which is said to be well–correlated with the level of the direct sound and the amount of lateral reflection. It is defined as the ratio of the lateral energy in the interval 10 – 80 ms to the direct energy (say, 0 – 5 ms) and is again expressed in decibels. Attempts to distinguish subjectively between 'reverberance' and 'Raumlichkeit' have shown that it may not be possible [27]. It is therefore not worthwhile to pursue this criterion further.

All of these criteria were derived for use in concert halls with reverberation times of the order of 2 s. As such, the distinction between the 'early energy' and the rest of the energy is reasonably clear. Even by the end of the longest of the periods involved (160 ms) the reverberant sound energy would be only about 5 dB down in level. Thus the remainder of the decay would carry a significant fraction of the total energy. It therefore might be meaningful to make such distinctions. In a typical broadcasting studio (excluding the few cases of large music studios) the reverberant sound energy would be at least 15 dB down even after only 50 ms and would therefore contribute much less to the total overall sound energy. Thus, it is not meaningful to separate the 'early energy' in such places. Alternatively, it would be necessary to choose a proportionally shorter time window.

Unfortunately, psychoacoustics does essentially control the time–scale in respect of the perception of sound quality. It is beyond reasonable dispute that sound arriving within a period extending from the arrival of the direct sound to about 50–80 ms later is integrated with the direct sound to produce a sensation of quality. Shorter periods of measurement could be specified but they would have no meaningful basis in the perception of sound. They would also limit the frequency resolution of the measurement to something less than the reciprocal of the time–window.

Even in Concert Halls there are problems with the frequency resolution of these types of measurements. Jordan himself [6; pp 162,165 and 176] admits that the reproducibility of the measurements is poor, the results obtained being greatly affected by small variations in the microphone positions. To reduce the variability he suggests using "bandwidths of two or even three octaves instead of one". To extend the criteria to the shorter time–scales appropriate for the majority of broadcasting studios would limit the frequency resolution to very wide bands indeed, even without the other problems of very short time intervals.

(There is another aspect to the time–domain considerations, that is the so–called 'Haas effect' which occurs with very short delay reflections, of the order of up to 5 ms. These reflections can alter the perceived direction of the sound source but are neither perceptible as discrete echoes nor do much to influence the perceived sound quality. They are of great importance in the design of control rooms for stereophonic monitoring but are not relevant to the present subject.)

In the definitions which involve the distinction of the direction from which the energy is incident it is somewhat unclear what is meant by the 'direction'. It is implicitly assumed by most of their proponents that sufficient spatial resolution is obtained by the use of 'figure of eight' microphones. No justifications are given for this assumption other than that which is implicit in the fact that it is all which could reasonably be done. There is no practicable alternative which could give very much better spatial resolution, especially over an extended frequency range. A pure velocity microphone does at least have the advantage of reasonably uniform directivity over a range of frequencies.

Again in small rooms, it would be difficult to distinguish the 'lateral energy'. By 50 ms the reflection structure is so dense that the sound field could be considered to be effectively totally diffuse. This is unlike the case of a large room where the sound field structure is such that only a few discrete reflections occur, even in the first 160 ms.

For all of these measurements, accuracy is also again a problem because the significant factors are differences between the values obtained and those idealised values obtained from measurements of the reverberation time. In fact, the 'acceptable' limits for EDT, C and RR are given as $\pm$ a small range relative to the 'ideal' [6; p191,25,28,29,30].

5. SUBJECTIVE JUDGEMENTS, 'FACTOR ANALYSIS' AND SPECTRAL DENSITY

Other groups of workers beside those at Dresden (on whose work most of the preceding sections have been based) have tried different approaches to the subjective evaluation of Concert Halls. The Gottingen group attempted to establish how many independent factors were involved [31]. Ultimately they concluded that a criterion related to LE and one which actually formed the basis of RR contained most of the variations [21,22,23,24,25,32,33].

The Berlin group attempted to form judgements along 19 different axes [30,34] (for example, 'hallig–trocken', 'gross–klein', etc.). They found that the three most important factors were, in order: 1) level of sound, 2) definition, 3) tonal balance.

some extent, it is suggested (by no less a person than one of their proponents [2; p.191]) that the frequency range of the measurement should be extended to perhaps three octaves. Two conclusions which reasonably may be drawn from this are (a) that the measurements are not satisfactorily assessing the subjective 'quality' of the room because that **does not** generally change so drastically with source/receiver position and (b) that a measure which has a frequency resolution of no better than three octaves is not much use for the routine specification of room characteristics or for identifying room defects.

The above criticisms apply even in the field of application for which the criteria were derived. In smaller rooms the time-scales are such that the intended distinction between the early sound and the later sound are not made by the criteria as defined. If the time-scales were to be altered in an attempt to make such a distinction then the psychoacoustic justifications for the measures would be lost. There would also be further losses of frequency resolution as a result of the even shorter time-scale.

The one new criterion which might have some merit in smaller rooms is that of the variation of Reverberation Time with frequency (not EDT as originally proposed by Lehmann, because it has already been argued that it cannot be measured adequately in a small room). It may be that irregularities of RT have a more quantifiable effect on the subjective quality of a room than has hitherto been supposed. In fact, there is a BBC tolerance specification for the permissible variations in RT. This was originally arrived at by a mixture of judgement and experience, tempered with realism, by a group of BBC 'experts' with many years' experience in the acoustic design and acceptability of rooms of all sorts. It is the author's opinion that had there been any more quantifiable effects they would have become evident many years ago.

Many of the above comments relate to the application of these 'new' criteria to rooms for which they were not intended. In their intended environment there is substantial evidence that some are soundly based. Many modern Concert Halls have been completed for which such criteria were an important part of the design process. It appears to be the consensus of opinion that most of these halls, especially the smaller ones, are more satisfactory than ones built without such aids. In fact, the main principle seems to have been a less rigorous approach, simply using the idea of maximising the early lateral reflections. In terms of broadcasting studios, it is likely that such methods could be applied to the design of a large music studio, especially if it had to accomodate an audience. In these days of multiple, close-microphone techniques, the 'studio' aspect could be assigned rather less importance than it has been and the 'audience' aspect rather more. This would probably benefit the subjective aspects of the room without causing any serious difficulties with the broadcast sound. These criteria also have the great benefit of being realistically measurable in a scale model, including the development of reflectors if necessary. However, large music studios are not built very often so that this would not constitute a frequent use of these criteria.

8. REFERENCES.

In the interests of saving space and to indicate the particular point of reference some of the following differ from the usual form of presentation in that the subject is given rather than the full formal title. This is indicated by single quote marks ('...').

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Leaving aside for the moment that these subjective criteria were specifically derived for use in large Concert Halls and with large–scale musical performances, the results of the Berlin group are interesting for two main reasons. The first is that they alone considered the absolute level of the sound – most others had ignored it or thought it to be self–evident. However, subsequent tests in 25 Concert Halls [6; p189] showed 19 of them to give levels within a range of 3 dB when excited by the same stimulus. It was also found that the preferences of the subjects in the tests fell into two separate groups. These two factors make such a criterion essentially worthless. Their criterion for definition was similar in principle to that of other workers, for example Clarity or Room Response.

The criterion for tonal balance [35] was different to the other new proposals, although something like it had appeared before [36]. Spectral balance in terms of the frequency dependence of the RT characteristic has been considered in the past [6;Chap.1,37,38], but the basic premise of all of this more recent work on room acoustic criteria is that of the "utter insufficiency of the RT as an acoustic criterion for *large* halls" [6;p.189]. Thus, logically, the RT could not be used and a much more complicated criterion was developed called the **spectral density (S)** [33]. Unfortunately, when subjective tests were carried out with this criterion the results were not unanimous and were also influenced by the absolute level of the test material.

A much simpler criterion for tonal balance was proposed by Lehmann which is simply the gradient of the EDT *v* frequency characteristic for the five octaves 125 – 2000 Hz [35]. Attempts have been made to correlate this slope with the subjective impression of 'brightness'. It seems that "differences of individual taste" present formidable obstacles to its general acceptance as a criterion.

Returning to the subject of small rooms for broadcasting, these criteria as they stand are of no use whatsoever. They are purely subjective assessments which have been carried out in relation to large rooms and large–scale music. To evaluate their relevance to smaller rooms, for other music or for speech, the same kind of (very extensive) assessments would need to be carried out. There is, in any case, the difficulty in measuring the EDT in small rooms as already discussed.

There may however be some relevance in the gradient of, or at least variations in, the RT *v* frequency characteristic. On the gross scale of the Spectral Density criterion there can be little doubt that 'experts' within the BBC are already competent to judge whether a room is generally 'bright' or not and do not need a measure of that. More subtle variations may not be so self–evident but may (as an outside chance) be affecting the subjective performances of rooms.

6. CONCLUSIONS.

Many of the recent (relative to the Reverberation Time) proposals for acoustic criteria for the subjective evaluation of rooms have been described and discussed.

In all but the cases of sound level and spectral balance these criteria are in fact measures of the departure from the theoretical response of the room with a perfectly diffuse sound field. In other words, all rooms have some value which would be obtained from each type of measurement, even with an ideal sound field. They are, in effect, measures of the diffusion of the sound field. This leads to practical difficulties of measurement accuracy because each criterion is a difference between two not very easy or particularly repeatable measurements. This is not to say that the measurements cannot be carried out, but to do so with reasonable accuracy would take a great deal of time.

The measurements which involve short time–domain responses are also prone to large differences caused by small variations in source or receiver positions. In order to overcome this deficiency to

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