NRC Publications Archive Archives des publications du CNRC

Auditorium acoustics measures from pistol shots

Bradley, J. S.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version
acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

Journal of the Acoustical Society of America, 80, 1, pp. 199-205, 1986-07

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=4685b394-ba03-48e0-b838-a71778b6db2>,
<https://publications-cnrc.canada.ca/fra/voir/objet/?id=4685b394-ba03-48e0-b838-a71778b6db2e>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research
Council Canada

Conseil national de
recherches Canada

Canada

Ser
TH1
N21d
no. 1395
c. 2
BLDG

**National Research
Council Canada**

**Institute for
Research in
Construction**

**Conseil national
de recherches Canada**

**Institut de
recherche en
construction**

Auditorium Acoustics Measures from Pistol Shots

by J.S. Bradley

Reprinted from
Journal of the Acoustical Society of America
Vol. 80, No. 1, July 1986
p. 199-205
(IRC Paper No. 1395)

ANALYZED

Price \$2.00

NRCC 26200

NRC - CISTI
BLDG. RES.
LIBRARY

86- 11- 2 4

BIBLIOTHÈQUE
Rech. Bâtim.
CNRC - ICIST

RÉSUMÉ

Ce document décrit en détail une méthode de calcul précise de diverses mesures acoustiques de tir au pistolet dans des auditoriums. Les rapports du son initial/final, les durées d'amortissement, le temps central, et les fonctions de transfert de modulation sont calculés par octaves. Les mesures relevées dans des conditions acoustiques très diverses sont comparées aux simples prédictions et l'on constate que certaines valeurs trouvées sont fortement liées les unes aux autres.

CISTI / ICIST

3 1809 00210 5887

Auditorium acoustics measures from pistol shots

J. S. Bradley

Division of Building Research, National Research Council of Canada, Ottawa, Canada K1A 0R6

(Received 8 April 1985; accepted for publication 21 February 1986)

Details of a procedure for efficiently and accurately calculating various auditorium acoustics measures from pistol shots are described. Early/late sound ratios, decay times, center time, and modulation transfer functions are calculated in octave bands. Measurements for a wide range of acoustical conditions are compared with simple predictions, and various quantities are found to be strongly intercorrelated.

PACS numbers: 43.55.Br, 43.55.Gx, 43.85.Gn

INTRODUCTION

A number of auditorium acoustical measures not yet in common use are known to relate to the acoustical quality of speech or music in rooms. There is now a need to establish practical and efficient procedures that will permit these quantities to be measured in a larger number of auditoria. This paper describes procedures to obtain a wide range of monophonic quantities from pistol shot recordings in rooms. The first part describes the reasoning behind the experimental procedures that were developed, while the second part considers the results of a set of measurements in five rooms chosen specifically for their quite varied acoustical conditions.

Reverberation time (RT) has long been the major objective parameter relating to acoustical conditions in large rooms. It is still a useful descriptor of the mean properties of a room and is easily estimated from knowledge of the room materials and geometry. The early part of the decay is now known to relate more closely to subjective evaluations,¹ and so it too should be considered. Early decay time (EDT), measured over the first 10 dB of decay and extrapolated to 60 dB, is thus a useful measure that relates to subjective judgments. Early/late sound ratios have been shown to relate to the degree of clarity or definition for music² and also to speech intelligibility scores.³ C_{80} (or Klarheitsmass) is the ratio of the early arriving sound energy in the first 0.08 s after the direct sound to the late sound energy arriving after 0.08 s. C_{80} is calculated as follows:

$$C_{80} = 10 \log \left(\frac{\int_0^{0.08} p^2(t) dt}{\int_{0.08}^{\infty} p^2(t) dt} \right), \quad (1)$$

where $p^2(t)$ is the squared response to the pulse source.

Other early/late ratios have been suggested with differing early sound limits. Center time TS (or Schwerpunktzeit) has been proposed as an alternative to early/late ratios that would avoid the abrupt cutoff between early and late sound:⁴

$$TS = \frac{\int_0^{\infty} t p^2(t) dt}{\int_0^{\infty} p^2(t) dt}. \quad (2)$$

The sound transmission index (STI), derived from modulation transfer functions, has recently been demonstrated to relate to speech intelligibility test scores in rooms.^{5,6} When the RT becomes increasingly large in relation to the

period of the modulation, the depth of the modulation is increasingly reduced by the acoustical properties of the room. With dominant speech modulation frequencies in the range of 3 to 4 Hz, there would be some reduction in the modulation depth in almost all real rooms. The reductions of the amplitude modulation of test signals at various acoustical frequencies as a function of speech modulation rate are combined to produce this one index STI.

All of these measures, except to a much lesser extent RT, vary throughout a room when either the source or receiver positions are changed. Thus, to evaluate a hall with respect to one or more of these quantities, measurements must be made at a large number of source-receiver combinations. Practical considerations suggest that to make large numbers of measurements in a number of auditoria, a computerized system of data processing is almost essential. It is also important that all equipment used in the field be compact, portable, and function in a manner that will minimize the time required for measurements in each hall. Without complete consideration of these practical problems as well as other factors affecting the precision of the measurements, results will be limited in both quantity and quality.

I. PROCEDURES

It is well known that the impulse response between two points of a linear system fully describes the properties of the system between the points. All of the acoustical quantities of interest can be calculated from such impulse responses. Normally, one would want a source that produces an approximation to an infinitely short duration ideal impulse. When results are to be analyzed in octave bands, this leads to there being much more energy in the higher frequency bands than in the lower ones. As background noises are typically greater at lower frequencies, signal-to-noise problems can easily occur at these frequencies when complete decays are required. A better optimization is to use an impulse that has acoustical energy more evenly distributed over all of the octave bands of interest, usually from 125 to 8000 Hz. It is also necessary that an impulse source be quite omnidirectional over all of these octave bands because it is impossible to correct for a directional source after impulses have been recorded.

After testing a number of sources, a 0.38 caliber blank pistol firing black powder blanks was found to best approxi-

mate the ideal requirements.⁷ Figure 1 shows an octave band spectrum of the gun in an anechoic room and the range of values measured over all angles tested. Directional variations of this source were no more than ± 2.5 dB. Other guns were found to be more directional, and smaller-caliber guns lacked adequate low-frequency energy. Small details of apparently similar guns were found to influence the directional properties. Spark sources, although adequately omnidirectional, tend to be lacking in low-frequency energy (see Fig. 5 of Ref. 8). Loudspeakers are frequently used as impulse sources in rooms, but they have serious disadvantages. Although various techniques have been used to correct the on-axis frequency response of the loudspeaker,⁹ it is not possible to correct it for all angles of radiation. Generally, when the loudspeaker is large enough to radiate enough power, it is at the point of becoming too directional. Satisfactory results can only be obtained by using loudspeakers for quite limited frequency ranges.¹⁰ They have the added disadvantage that they and the associated power amplifiers are quite bulky and hence much less convenient.

The accurate and reliable recording of impulses in rooms requires a high-quality tape recorder with a very large dynamic range. The new digital domestic stereo tape recorders, such as the Technics SVP-100 that was used in this study, typically provide up to 86 dB of dynamic range with a nearly perfectly flat response from 2 to 20 kHz. With such instruments, the tape recorder is no longer a practical limit to the accuracy of the measurements.

The first step in processing the data requires filtering the pulse responses into octave bands. This could be done using conventional analog filters or in software using digital filters. The use of seven parallel analog octave filters followed by rms circuits with time constants of a few milliseconds would require the digitizing of only a relatively small number of samples. The calculation of energy ratios and decay times could then be performed on a quite small computer.¹¹ The original unfiltered pulse responses, however, would not then be available for other processing and visual display. For greater flexibility in this study, the recorded impulse re-

FIG. 1. Octave band spectrum of 0.38 caliber gun in an anechoic room for 0° incidence and range of values for other angles.

sponses were digitized and the octave filtering performed in software.

To reproduce the very short pulses of the recorded pistol shots precisely, a very high sampling rate is required. As results in the 8-kHz octave band were desired, it was necessary to sample the recorded impulses at a rate such that there were at least two points per cycle at all frequencies up to the upper limit of this band. A sampling frequency of 22 627 Hz was used since it is double the upper corner frequency of the 8-kHz band. Sampling at such a high rate restricts the number of data points that can be efficiently stored and processed. As this procedure was initially developed on a small minicomputer, each digitized pulse was limited to 24 000 samples corresponding to just over 1 s of data and a small pre-trigger portion to allow detection of background noise problems.

The digital filtering of the recorded signal into octave bands was performed using a combination of high- and low-pass filters,¹² as shown in the flow chart of Fig. 2. By decimation of the signal (reducing the number of points by a factor of 2) after each octave, the same sets of filter coefficients for the high- and low-pass filters can be used over again for each successive octave band. The program stores two different time records, labeled A and B on the flow chart. A contains all frequencies up to and including the current octave band; B contains only the frequencies of the current octave band. On digitizing, the analog low-pass antialiasing filters serves to limit the upper end of the 8-kHz band. After processing

- A TIME RECORD CONTAINING FREQUENCIES UP TO AND INCLUDING THE CURRENT BAND
- B TIME RECORD CONTAINING FREQUENCIES OF ONLY THE CURRENT BAND

FIG. 2. Computer processing flow chart.

with the high-pass filter routine, the B time record corresponding to the pulse response in the 8-kHz octave band is created. From this B time record, the acoustical measures for the octave band are calculated. Subsequently, time record A is low-pass filtered to remove information at frequencies in the current octave band. This record is then decimated so that there are half as many data-points, and then the same high-pass filter effectively functions 1 oct lower in frequency than in the previous pass. A new record B is created and the next lower octave band results are calculated. The program continues to loop around until the results in all seven octave bands have been calculated.

Calculation of various early/late ratios is a straightforward matter involving summing pressure squared values over various time periods. As each quantity is a ratio of energy sums from different parts of the same decay, there is no need to calibrate the records in terms of absolute sound pressures. Early/late ratios with 0.035, 0.050, and 0.080 s early sound interval limits were calculated and are referred to as C_{35} , C_{50} , and C_{80} , respectively. TS or center time was also calculated.

The Schroeder integrated impulse method¹³ was used to obtain decay curves from which RT and EDT values could be calculated. Using a least-squares best fit, RT values were calculated from the first 30 dB of decay and EDT values from the first 10 dB of decay. By the Schroeder method, the impulse response is integrated in reverse time to produce a smooth decay curve equivalent to the ensemble average decay curve. Because of the fixed approximately 1 s time window of data, this procedure presents some programming problems. If the decay is much shorter than 1 s and there is a moderate amount of background noise, then the accumulated effect of integrating the background noise seriously decreases the available useful decay range by artificially increasing the levels in the later parts of the decays. If the reverberation time is much longer than the 1 s time window of data, the integrated impulse decay curve will curve downward towards the end of the 30 dB interval used to calculate RT values. To minimize such problems, a two-pass technique was used where the first approximation of the EDT value was used only to choose an appropriate shorter time window for the data. Limiting the time window to about two-thirds of the reverberation time seemed to produce optimum results.

Schroeder¹⁴ has shown that the complex modulation transfer function can be calculated from an impulse response by the following equation:

$$m(\omega) = \frac{\int_0^\infty h^2(t)e^{-i\omega t} dt}{\int_0^\infty h^2(t) dt}, \quad (3)$$

where the first integral is the Fourier transform of the squared impulse response $h^2(t)$. In performing the calculations, the gun source is assumed to approximate an ideal impulse and $h^2(t)$ is replaced by $p^2(t)$, the squared pressure response to the gun pulses. If one takes the magnitude of each complex pair, one obtains modulation transfer function values ranging from 0 to 1.0 at each modulation frequency f (where $f = \omega/2\pi$) that are comparable to values obtained from steady-state methods. For each of the seven acoustical

octave bands, modulation transfer function values were calculated in 14 speech modulation 1/3 octave bands from 0.63 to 12.5 Hz. To convert the modulation transfer function values at discrete ω into 1/3-octave values, the frequency resolution of the discrete modulation frequencies must be small enough that there are several values in each of the 1/3 octave bands. The frequency resolution of a Fourier transform spectrum is given by

$$\Delta f = f_s/n. \quad (4)$$

In the present case, the sampling frequency f_s is fixed at 22 627 Hz. Only the number of points n can be increased by adding zeroes to the pulse record. It is necessary, however, to increase the record length by a considerable amount to even approach an adequately small frequency resolution. For example, if the record is padded to a length of 128 k points (128×1024 points), then the resulting frequency resolution would be 0.173 Hz. Performing a 128-k transform requires a large computer and considerable computer time if large numbers of pulses are to be processed. A much more efficient approach is possible by using a technique demonstrated by Chu¹⁵ in which long transforms are performed in parts. With this method the first part yields the lowest frequency components. For the present problem, only the lowest frequency components are required. As a final compromise, this method was used to obtain only the first 2-k point part of a 64-k point transform. A result equivalent to a 128-k transform was then obtained by interpolating between each pair of successive frequency components without requiring the creation and storage of a 128-k point array. Even this approach incorporated into the same program with the octave band digital filters required a quite powerful 32-bit minicomputer. Alternatively, one could first modify the time record to preserve only the low-frequency information. For example, one could low-pass filter the record to 177 Hz ($11\ 313/64$) and effectively reduce the sampling rate by taking only each 64th point. If the resulting 375 points were padded with zeros to 2-k points, a frequency resolution of 0.173 Hz would again be achieved.

To verify the success of the calculation method, comparisons were made with published theoretical modulation transfer functions for ideal exponential decays. Figure 3 compares the results obtained from processing synthesized exponential decays with theoretical results (from Fig. 5 of Ref. 5) for RT values of 0.5, 1.0, 2.0, and 4.0 s plotted as the modulation reduction versus modulation frequency. (Houtgast *et al.*⁵ used modulation reduction to describe the reduction in the amplitude modulation of a test signal. A value of 1.0 corresponds to no reduction; a value of 0.0 corresponding to complete reduction, so that there is no modulation left.) The agreement is excellent for all but the longest reverberation time. For a 4.0-s RT, the 1 s of actual data (before padding with zeros) is not long enough for accurate determination of modulation reductions at modulation frequencies of 1 Hz and lower. Modulations in speech are strongest at frequencies of 3 to 4 Hz. Therefore, the calculation procedure works very well in all typical situations. It is only for combinations of unusually long reverberation times and much lower than average modulation frequencies that the

FIG. 3. Comparison of measured (dashed lines) and theoretical (solid lines) modulation transfer functions for RT values of 0.5, 1.0, 2.0, and 4.0 s (going from top to bottom).

method begins to fail and overpredicts by up to 23%. As the final STI values are based on the combined results of all modulation frequencies, these errors would change the overall STI values by only a very small amount. Third-octave modulation reductions were obtained by taking the lowest modulation reduction within each 1/3 octave band to represent the band, since it represents the most severe effect that would obscure lesser effects in the same band.

Following the procedures of Houtgast *et al.*,⁵ the 1/3 oct modulation reductions were converted to equivalent signal-to-noise ratios, limited to ± 15 dB, and averaged over all the modulation frequency bands. Finally, these mean limited signal-to-noise ratios were transformed to STI values ranging from 0 to 1.0, and the individual results of each of the octave bands from 125 to 8 kHz were weighted and assumed to an overall single STI value in a manner similar to the calculation of articulation index (AI) values.

II. COMPARISONS OF MEASURES

To ensure that the results of the comparisons of measures are generally applicable, pulse measurements were made in five rooms chosen to cover a wide range of room sizes and reverberation times. Room volumes ranged from

FIG. 4. Measured + + +; calculated— (from exponential decay theory); C_{80} values vs RT.

362 to 20 000 m^3 , and 1 kHz RT values varied from 0.8 to 3.8 s. A total of 40 different source-receiver combinations were recorded in these rooms, with at least six source-receiver combinations in each room. For each source-receiver combination, four pistol shots were recorded and all results are an average of the results from sets of four shots.

A. Comparisons of measured and predicted values

Simple procedures for predicting the measured quantities have been put forward, usually based on the assumption of ideal exponential decays.¹⁶ In practice, real decays are not ideal exponential decays. The initial part of real decays is usually made up of a small number of discrete pulses; the full decay may or may not closely follow an exponential curve. It is therefore useful to examine how closely such simple prediction methods agree with the present measured values. One can derive analytical expressions for early/late arriving sound ratios by the integration of an exponential decay of the form

$$p^2(t) = Ae^{-t/\tau}, \quad (5)$$

where the time constant $\tau = RT/13.815$. Then for an early time limit t_e by substituting Eq. (5) in Eq. (1), the corresponding early/late arriving sound ratio is given by

TABLE I. Mean and rms differences between measured values and predictions based on ideal exponential decays.

Measure	125 Hz	250 Hz	500 Hz	Mean differences			
				1 kHz	2 kHz	4 kHz	8 kHz
C ₃₅	− 2.61	2.04	1.68	0.64	0.26	0.78	1.68
C ₅₀	− 1.45	2.18	1.76	0.90	0.43	1.09	2.04
C ₈₀	− 0.46	2.13	1.96	1.28	0.44	0.98	2.16
TS	0.0012	− 0.0160	− 0.0178	− 0.0094	− 0.0030	− 0.0084	− 0.0150
				rms differences			
C ₃₅	5.15	3.68	3.42	2.69	2.27	2.28	2.64
C ₅₀	4.23	3.26	2.91	2.47	2.09	2.24	2.91
C ₈₀	2.47	3.07	2.74	2.21	1.88	2.03	2.80
TS	0.0208	0.0282	0.0289	0.0233	0.0192	0.0160	0.0174

FIG. 5. Measured + + +; calculated --- (from exponential decay theory); and the best fit regression line to the measured values, —, of TS vs RT.

$$C_{te} = 10 \log[\exp(13.815 \cdot t_e / RT) - 1.0]. \quad (6)$$

Similarly, one can derive an analytical expression for TS, assuming an ideal exponential decay of infinite duration and time constant τ by substituting Eq. (5) in Eq. (2)

$$TS = RT/13.815. \quad (7)$$

Figure 4 compares calculated and measured C_{80} values as a function of RT. It may be seen that there is a tendency for the measured values to be above the curve of calculated values, particularly for smaller RT values. Similar results were obtained for C_{35} and C_{50} values, with increasing scatter in the early/late ratios as the early time limit became shorter; Table I summarizes these comparisons for all octave bands. Both the mean and differences between measured and calculated values are given. The mean difference at 1 kHz for C_{80} values was 1.28 dB, indicating that measured values tended to be greater than calculated values as observed for the same data in Fig. 4. Thus the mean differences indicate whether the calculated curves tend to under- or overpredict measured values. The smallest mean differences occurred at 2 kHz for all three ratios. The mean differences became nega-

FIG. 7. Predicted vs measured C_{80} values with Barron's equation. Measured values + + +; best fit regression line —; and line of equality between measured and predicted ---.

tive in the 125-Hz octave band due to the seat dip effect^{17,18} in at least some of the rooms. By this phenomenon, sound passing over the audience at near-grazing incidence is selectively attenuated at lower frequencies. This reduction in the early sound energy in the 125-Hz octave band causes the early/late ratios to tend to be lower than predicted by the simple ideal exponential decay predictions.

The rms differences in Table I are also smallest for the 2-kHz octave band, increasing in magnitude for higher and lower frequency bands. The rms differences also increase as the early time limit decreases. If these rms differences are considered as prediction errors, then at 1 kHz one would expect to predict the three early/late ratios with an error of ± 2 to 3 dB.

Figure 5 compares measured and calculated TS values as a function of RT. Here the best fit regression line, the solid line, agrees quite closely with the calculated relation shown by the dashed line. Table I indicates a tendency for the calculated values to underpredict the measured values, since the mean differences are negative. Although for TS there is again a minimum in the mean difference at 2 kHz, the 125-Hz values had a smaller mean difference. The rms differences were smallest at 4 kHz for TS values and, at 1 kHz, measured values could be predicted with a prediction accuracy of ± 0.023 s. As the mean TS value at 1 kHz was 0.124, this corresponds to an error of $\pm 18.5\%$.

FIG. 6. Measured + + +; calculated —; STI vs RT.

TABLE II. Correlation coefficients for correlations between 1-kHz measures $N = 40$.

	C_{35}	C_{50}	C_{80}	TS	EDT	RT	STI
C_{35}							
C_{50}		0.967					
C_{80}		0.928	0.974				
TS		-0.912	-0.946	0.983			
EDT		-0.866	-0.913	-0.952	0.986		
RT		-0.871	-0.908	-0.943	0.983	0.992	
STI		0.902	0.941	0.960	-0.909	-0.936	-0.938

TABLE III. Linear regression results for measured data.

Dependent variable	Independent variable	Slope	Intercept	Correlation coefficient	Standard deviation
TS	C_{80}	-0.0186	0.1459	-0.968	0.0194
log (TS)	C_{80}	-0.0620	-0.9053	-0.987	0.0411
C_{50}	C_{80}	1.049	-3.107	0.974	0.978
C_{35}	C_{80}	1.026	-5.167	0.928	1.646
C_{80}	log (RT)	-17.79	5.314	-0.934	1.429
C_{50}	log (RT)	-18.44	2.415	-0.899	1.893
C_{35}	log (RT)	-18.12	0.253	-0.861	2.253
log (TS)	STI	-20.87	0.834	-0.947	0.782
C_{80}	STI	34.68	-16.44	0.960	1.12

Houtgast *et al.*⁵ calculated STI as a function of reverberation time, assuming ideal exponential decays. Figure 6 compares measured and calculated STI values. The calculated curve is from the no-noise case of Fig. 8 of Ref. 5. Of course, the calculations would assume identical RT values in all octave bands, which is not true for the measured values. Nevertheless, Fig. 6 indicates that STI values can be predicted approximately as well as the other measures and indicates that there is a tendency to underpredict the measured values. This would correspond to underpredicting the C_{80} values in Fig. 4. The rms differences indicate that one could predict STI values with an accuracy of ± 0.075 using the measured RT at 1 kHz.

Since these newer acoustical measures are expected to vary from seat to seat in an auditorium, it is clear that predictions based only on RT values and an assumed ideal exponential decay cannot be completely satisfactory. In a recent paper, Barron¹⁶ has proposed a method for predicting C_{80} values which requires the room volume, the source-receiver distance, and the RT as input. Figure 7 plots measured C_{80} values versus predicted values using Barron's method [Eq. (7), Ref. 16]. Both the least-squares regression line (the solid line) and the line representing equality between measured and calculated values (the dashed line) are shown. The rms error between measured and predicted was ± 1.48

dB, which is slightly larger than the 1.4-dB rms error that Barron reported, but smaller than the 2.21 dB given in Table I for the simple exponential decay theory. Thus Barron's procedure is an improvement, but the results of Fig. 7 suggest that there still may be a small systematic error between measured and predicted values that might yet be included in some future prediction scheme.

In an attempt to achieve a more accurate prediction of C_{80} values using the same parameters as Barron, a multiple linear regression analysis was performed regressing C_{80} values on RT, room volume, and source-receiver distance. The following regression coefficients were obtained:

$$C_{80} = -3.499 \cdot RT + 0.0001411 \cdot V - 0.08204 \cdot D, \quad (8)$$

where V is the room volume in m^3 and D is the source-receiver distances in m.

The rms prediction error was reduced to 1.05 dB using this equation.

B. Interrelations between measures

As was expected, many of the newer measures were quite highly correlated with each other. Table II gives the correlation coefficients between all the measures reported in this study. All correlations are for the 1-kHz octave band except STI, which is a multiband measure. All correlations

FIG. 8. Logarithm of TS vs C_{80} ; measured values + + +; best fit regression line —; and exponential decay predictions ---.

FIG. 9. Early/late ratio values vs the logarithm of RT; solid lines from exponential decay predictions; dashed lines from best fit regression lines to measured values. Curves are for C_{35} , C_{50} , and C_{80} from bottom to top.

are highly significant. It is seen that STI is most highly correlated with C_{80} , and TS is most strongly correlated with C_{80} , EDT, and RT. Although TS, EDT, and STI are each derived by quite different calculation procedures, they are all strongly correlated with the more established C_{80} (correlation coefficients ≥ 0.95). The various early/late ratios are most strongly correlated when the early time limits are most similar.

With such strongly correlated measures, knowledge of one quantity suggests that one could approximately predict one of the other quantities. Table III give the results of fitting regression lines to a number of approximately linear relationships. The slopes and intercepts of the regression lines are given along with the corresponding correlation coefficients and the standard deviations of the results about the regression lines. As an example, Fig. 8 shows the approximately linear relationship between C_{80} values and the logarithm of the TS values at 1 kHz. The solid line is the best fit regression line while the dashed line is the relationship derived from ideal exponential decays. If the exponential decay predictions are based on integration to 1.0 s rather than to ∞ , there is improved agreement with measurements at the lowest C_{80} values.

For the relationships between early/late ratios and the logarithm of the reverberation time, the best fit regression lines (dashed lines in Fig. 9) and the curves derived from ideal exponential decays (solid lines) do not agree as closely. For shorter RT values, the exponential decay predictions tend to underpredict and the dashed lines are all several dB above the solid lines for an RT of 0.5 s. Very approximately, one can estimate C_{50} and C_{35} values for C_{80} values by subtracting 3 and 5 dB, respectively.

III. CONCLUSIONS

A method that allows the accurate and efficient calculation of various newer auditorium acoustics measures has been demonstrated. As the source was approximately omnidirectional over the octave bands from 125 to 8 kHz, results were obtained simultaneously in seven octave bands, and can be compared to predictions that assume an omnidirectional source or to other measurements made with an approximately omnidirectional source. The efficiency of the data gathering and the resulting computer processing make it possible to obtain results for a number of different source-receiver positions in each auditorium. By completely processing the results with software, the original pulse response is always available for other types of calculation. In this study it was possible to calculate decay times and early/late ratios, as well as modulation transfer functions from the same digitized pulses.

Comparisons between measured values and calculated values based on ideal exponential decays showed that such predictions are not particularly accurate but give a rough

indication of the mean trends. A newer method by Barron was found to predict C_{80} values a little more accurately. All of the measures calculated were strongly correlated with each other. Thus measures with quite different derivations such as C_{80} , TS, EDT, and STI all measure similar aspects of the same physical properties of a room. It is necessary to consider how well each measure is related to subjective evaluations or to speech intelligibility test scores to determine which is most appropriate in a particular situation.

ACKNOWLEDGMENTS

This paper is a contribution from the Division of Building Research, National Research Council of Canada and is published with the approval of the Director of the Division.

The author would like to thank Reina Lamothe for her considerable assistance with programming and processing of the data, and the National Arts Centre, in Ottawa, Canada for its cooperation and assistance.

- ¹B. S. Atal, M. R. Schroeder, and G. M. Sessler, "Subjective reverberation time and its relation to sound decay," Proceedings of the 5th ICA, Liege, Paper G32 (1965).
- ²W. Reichardt and U. Lehman, "Optimierung von Raumeindruck und durchsichtigkeit von musikdarbietungen durch auswertung von impuls-shalltests," *Acustica* **48**, 174-185 (1981).
- ³J. P. S. Lochner and J. F. Burger, "The influence of reflections on auditorium acoustics," *J. Sound Vib.* **1**(4), 426-454 (1964).
- ⁴S. Ström, "Concert Hall Acoustics," University of Trondheim, Norway, ELAB Report STF44, A82006 (1982).
- ⁵T. Houtgast, H. J. M. Steeneken, and R. Plomp, "Predicting speech intelligibility in rooms from the modulation transfer function. I. General room acoustics," *Acustica* **46**, 60-72 (1980).
- ⁶H. J. M. Steeneken and T. Houtgast, "A physical method for measuring speech transmission quality," *J. Acoust. Soc. Am.* **67**, 318-326 (1980).
- ⁷M. J. R. Lamothe and J. S. Bradley, "Acoustical characteristics of guns as impulse sources," *Can. Acoust.* **13**(2), 16-24 (1985).
- ⁸H. G. Latham, "The signal-to-noise ratio for speech intelligibility—An auditorium acoustics design index," *Appl. Acoust.* **12**(4), 253-320 (1979).
- ⁹J. C. Davies, J. McIntosh, and K. A. Mulholland, "The generation of short duration acoustic signals," *J. Sound Vib.* **76**(1), 77-82 (1981).
- ¹⁰M. Barron, "Impulse testing techniques for auditoria," *Appl. Acoust.* **17**, 165-181 (1984).
- ¹¹J. S. Bradley, "Experience with new auditorium acoustic measurements," *J. Acoust. Soc. Am.* **73**, 2051-2058 (1983).
- ¹²R. K. Otnes and L. Enochsen, *Applied Time Series Analysis* (Wiley, New York, 1978).
- ¹³M. R. Schroeder, "New method of measuring reverberation time," *J. Acoust. Soc. Am.* **37**, 409-412 (1965).
- ¹⁴M. R. Schroeder, "Modulation transfer functions: Definition and measurement," *Acustica* **49**(3), 179-182 (1981).
- ¹⁵W. T. Chu, "A technique for zoom transform and long-time signal analysis," *Can. Acoust.* **11**(3), 45-50 (1983).
- ¹⁶M. Barron and L.-J. Lee, "Energy relations in concert auditoria. I," *J. Acoust. Soc. Am.* (submitted).
- ¹⁷T. J. Schultz and B. G. Watters, "Propagation of sound across audience seating," *J. Acoust. Soc. Am.* **36**, 885-896 (1964).
- ¹⁸G. M. Sessler and J. E. West, "Sound transmission over theater seats," *J. Acoust. Soc. Am.* **36**, 1725-1732 (1964).

This paper is being distributed in reprint form by the Institute for Research in Construction. A list of building practice and research publications available from the Institute may be obtained by writing to the Publications Section, Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario, K1A 0R6.

Ce document est distribué sous forme de tiré-à-part par l'Institut de recherche en construction. On peut obtenir une liste des publications de l'Institut portant sur les techniques ou les recherches en matière de bâtiment en écrivant à la Section des publications, Institut de recherche en construction, Conseil national de recherches du Canada, Ottawa (Ontario), K1A 0R6.