Acoust. Sci. & Tech. **26**, 2 (2005)

PAPER

Supplemental data of dependence of objective room acoustical parameters on source and receiver positions at field measurement

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(*Received 3 July 2004, Accepted for publication 7 December 2004*)

Abstract: Representative values of acoustical parameters in rooms for music performance are obtained from measurements in many halls. Discussed are the effects of source locations and positions of receivers on the results. The parameters studied are reverberation time *RT*, early decay time *EDT*, strength *G*, clarity C_{80}, and interaural-cross-correlation coefficient *IACC*, which were measured using identical procedures, and where possible, according to international standard ISO 3382. Separate ranges and positions are suggested for symphony halls, chamber music halls and opera houses. It is indicated that the minimum number of positions given in ISO 3382 should be exceeded when measuring some parameters.

Keywords: Objective acoustical parameter, ISO3382, Concert hall, Opera house

PACS number: 43.55Gx, 43.55Fw [DOI: 10.1250/ast.26.128]

1. INTRODUCTION

Guideline numbers of source and receiver positions for the measurement of room acoustical parameters are indicated in international standard ISO 3382 (1997) (see Table 1). That standard is directed toward many kinds of performing spaces and, thus, does not give adequate guidance for measurements in performance halls, i.e., how to determine representative values of the parameters necessary for inter-hall comparisons. For example, the standard states, "Choose the number and location of source positions so as to include *all areas* likely to be occupied by performers. . .."

The purpose of this study is to investigate the proper locations of sound source and number of receivers, based on acoustical measurements in 15 symphony halls, 7 chamber halls, and 4 opera houses. In Table 2, four statistically independent parameters are listed [1–3], namely: RT_{M}, RT_{L} (pertinent to Bass Ratio, *BR*), G_{M}, and $IACC_{\mathrm{E3}}$. Also listed are highly correlated parameters: EDT_{M}, $C_{80,3}$ and G_{L}. The subscript "L," "M," and "3" mean, respectively, that the octave-band average is for 125/250, 500/1 k, 500/1 k/2 k Hz. These parameters are then compared and estimated.

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Table 1 Minimum recommended number of receiver positions as a function of hall size shown in ISO 3382, Table A.2.

Number of seats	Minimum number of microphone positions
500	6
1,000	8
2,000	10

2. CRITERIA OF JUDGMENT

Necessary at the outset are criteria for judging whether the averaged values of the acoustical parameters (corresponding to various combinations of sources and receivers) are significant or not. The criteria chosen here were either taken from psychological difference limens (*DL*'s) of the parameters, or measurement errors, or equipment limitations, or simply the statistical significance of the numerical numbers. The values chosen with reference to the sources, are presented in Table 3 [4–8]. These values also become the permissible measurement errors.

3. LOCATIONS OF THE SOUND SOURCE

The numbers and placements of the sound source on the stage of a typical concert hall are shown in Fig. 1(a). Twelve source positions in the Tokyo Opera City (TOC)

Table 2 Correlation coefficients among physical quantities from the results of measurements in 39 Symphony Halls (upper), 23 Opera Houses (middle), and 18 Chamber Music Halls (lower). ITDG, V, and N are initial-time-delay-gap, room volume, and seating number, respectively. Other parameters are defined in the text. The subscript "L," "M," and "3" mean, respectively, that the octave band average is for 125 and 250 Hz, 500 and 1 k Hz, and 500, 1 k, and 2 k Hz. The coefficients with significance level $p = 1\%$ are with "*".

(a) Symphony Halls (39 halls)

	RTM	$EDTM$	$C_{80,3}$	GM	$IACC_{E3}$	BR	$ITDG$	V	N
RT_M	—								
EDT_M	0.99*	—							
$C_{80,3}$	−0.84*	−0.87*	—						
G_M	0.31	0.31	−0.34	—					
$IACC_{E3}$	−0.17	−0.20	0.37	−0.46	—				
BR	0.08	0.04	0.04	0.04	0.16	—			
$ITDG$	−0.48	−0.50	0.57	−0.43	0.13	−0.04	—		
V	0.27	0.23	−0.03	−0.55	0.51	0.21	0.25	—	
N	0.11	0.09	0.05	−0.53	0.55	0.29	0.18	0.84*	—

"*": significant level $p = 1\%$

(b) Opera Houses (23 halls)

	RT_M	EDT_M	$C_{80,3}$	G_M	$IACC_{E3}$	BR	$ITDG$	V	N
RT_M	—								
EDT_M	0.98*	—							
$C_{80,3}$	−0.86*	−0.88*	—						
G_M	−0.11	−0.12	0.14	—					
$IACC_{E3}$	−0.05	0.04	0.06	−0.34	—				
BR	0.13	0.05	−0.09	0.08	0.07	—			
$ITDG$	0.18	0.17	−0.35	−0.20	0.42	0.19	—		
V	0.63*	0.58	−0.46	−0.21	0.05	−0.12	0.23	—	
N	0.42	0.35	−0.24	−0.30	0.22	−0.06	0.25	0.92*	—

(c) Chamber Music Halls (18 halls)

	RT_M	EDT_M	$C_{80,3}$	G_M	$IACC_{E3}$	BR	$ITDG$	V	N
RT_M	—								
EDT_M	0.98*	—							
$C_{80,3}$	−0.96*	−0.98*	—						
G_M	0.21	0.31	−0.26	—					
$IACC_{E3}$	−0.30	−0.26	0.25	−0.35	—				
BR	0.24	0.26	−0.17	0.55	−0.04	—			
$ITDG$	0.12	−0.02	0.02	−0.49	0.18	−0.11	—		
V	0.39	0.26	−0.29	−0.67*	−0.06	−0.30	0.72*	—	
N	0.40	0.28	−0.29	−0.46	0.09	0.02	0.65	0.75*	—

Table 3 Criterion of judgment whether the averaged values of the acoustical measurements are significant or not. Theses numbers become the permissible measurement errors.

Parameter	Difference limen, DL	Reference	Physical measurement limit
RT_L	6.5%	Tahara (1990)	0.05 s
RT_M	4%	Seraphin (1958)	
EDT_M	5%	Tahara (1990)	
C_{80}	0.5 dB	Cox *et al.* (1993)	0.5 dB
G_L	0.5 dB	Zwiker/Fastle (1990)	
G_M			
$IACC_{E3}$	0.09	Cox *et al.* (1993), Hidaka *et al.* (1995)	0.05

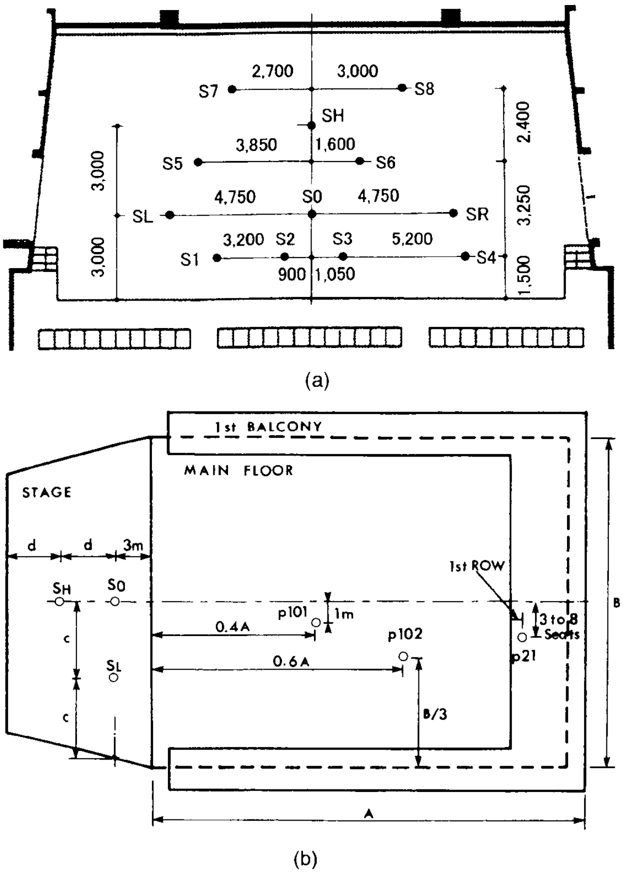

Fig. 1 (a) Twelve source positions set on the stage of TOC concert hall. (b) Measuring positions for symmetrical halls.

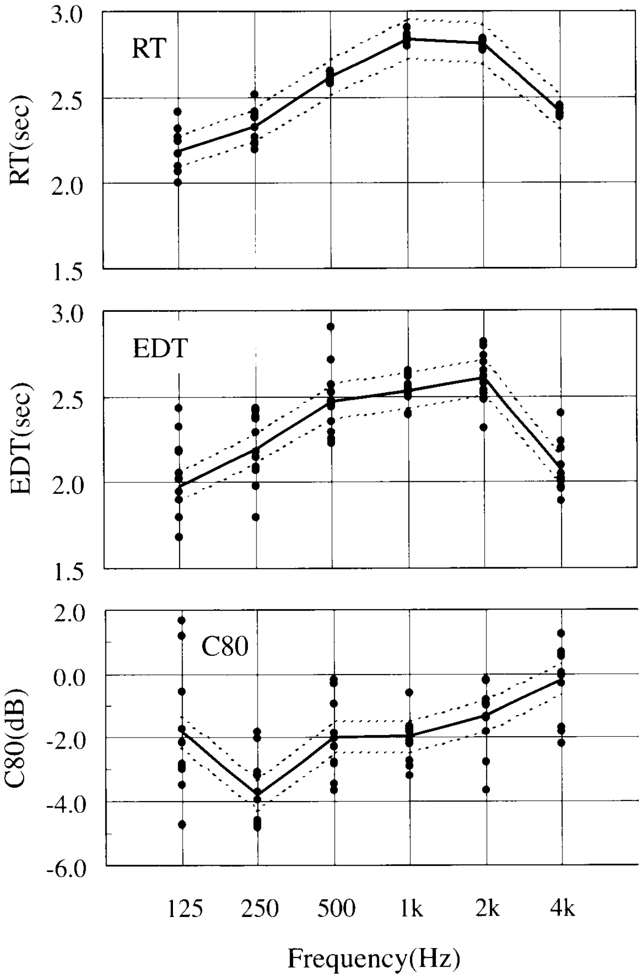

Fig. 2 *RT*, *EDT*, and C_{80} measured from 12 different source positions on the stage, received at center main floor in TOC concert hall. Solid and dotted lines are the average and the $\pm DL$ values, respectively.

Concert Hall were used for this experiment [1]. A calibrated dodecahedral loudspeaker at a height above the stage of 1.5 m served as the sound source. The reference point S0 is on the center-line and 3 m from the front edge of the stage. This point was used in all halls measured [1–3]. However, for small chamber music halls, the 3 m-distance from the front edge was reduced to 1.5 m. The positions SL, SR and SH, arranged at the left, right and back side of S0, are located at an intermediate point between S0 and the appropriate stage sidewall. The area surrounded by these 4 points is here called "the main performance area" and is reasonably near the conductor's and soloists' positions. Positions S1 to S8 are located near the microphone positions used in typical multi-channel recordings of orchestral music. Further details about the measurement on room acoustical parameters are given in [9].

For the 12 source locations, the frequency characteristics of *RT*, *EDT*, and C_{80} measured at a position near the center of the main floor (Position 101, Fig. 1(b)) are shown in Fig. 2. The solid line and the dotted lines are the average and the $\pm DL$ values in Table 3, respectively. The measured reverberation time *RT* is nearly independent of the source position for the 500 to 4 k Hz bands, but in the 125 and 250 Hz bands it exceeds the *DL*. Significantly different, the values of *EDT* and C_{80} spread over a range that is 5 to 6 times the *DL* for all frequency bands. Obviously, the change in source location causes large variations in the early reflection patterns, especially within the first 80 ms after arrival of the direct sound (see Fig. 3).

Measurements of G_L (which is highly correlated with G_M), $C_{80,3}$, EDT_M and $IACC_{E3}$ were made in TOC at three receiver positions, front, rear and center of the main floor, with the source at the 12 stage positions, and are plotted in Fig. 4 as a function of distance between source and receiver. It is seen that G_L decreases with distance nearly at the rate of 3 dB per doubling of distance. However, even in the TOC hall, which possesses good physical sound diffusivity, the values for G_L fluctuate $\pm 1.0 \sim 1.5$ dB, which is two to three times larger than the *DL* in Table 3. Also for each receiving position, *G* at S0 does not always take on the median value in each set, and can be at an upper value. Without the front seat position, C_{80} is not a function

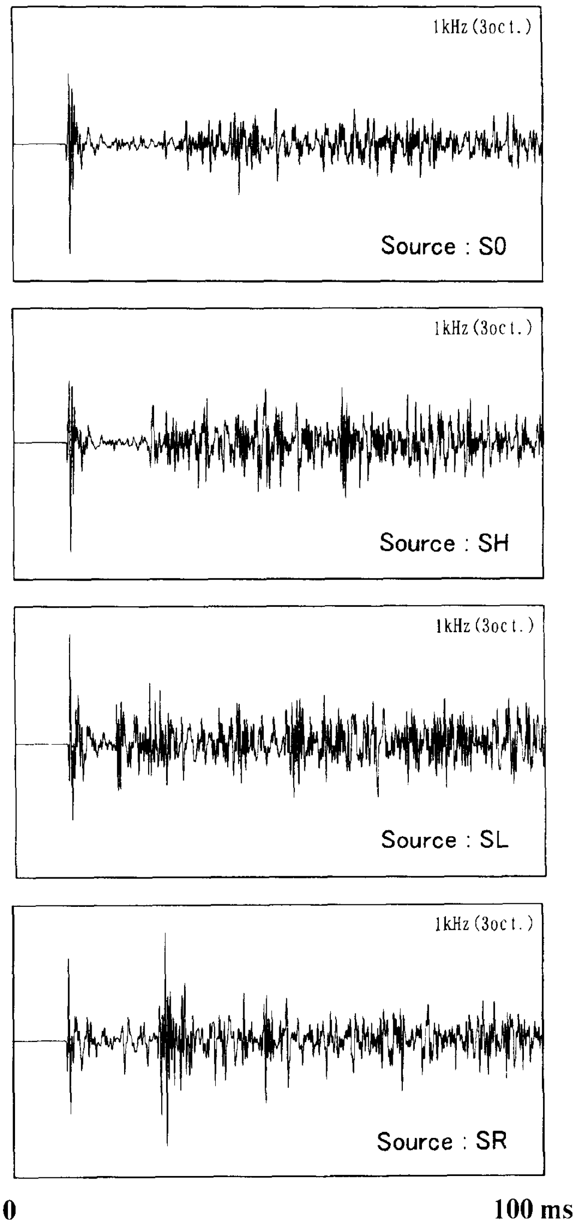

Fig. 3 Reflectograms from 4 source positions in the main performance area at TOC hall ($N = 1{,}600$), received at center of the main floor, in which a 3-octave-wide band-pass filter with a mid-frequency of 1 kHz ($f_L = 335$ Hz and $f_H = 2.8$ kHz) was applied, which is consistent with the 3-bands concept for the $IACC_{E3}$ definition [11].

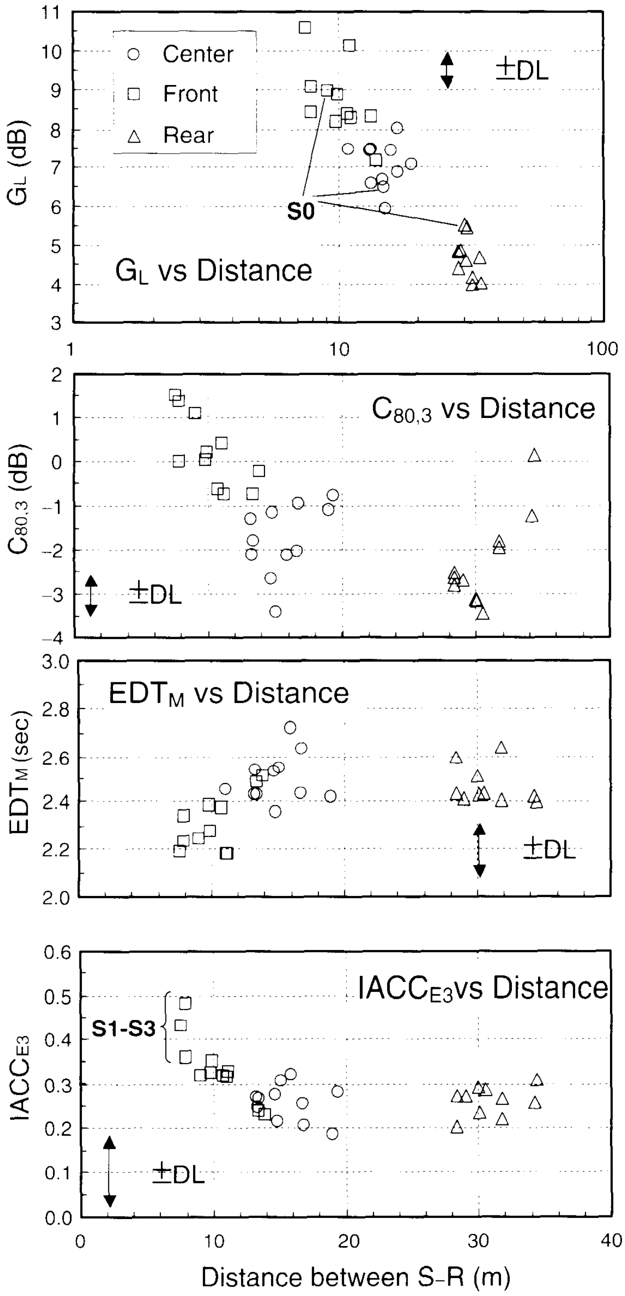

Fig. 4 G_L, $C_{80,3}$, EDT_M, and $IACC_{E3}$ values measured at three receiver positions with the source at the 12 stage positions in TOC hall plotted as a function of distance between the sources and receivers.

of the distance and spreads $\pm 1.5 \sim 1.8$ dB around the median value. Also, C_{80} varies randomly when the source location is shifted, so that no one source position is selectively better. In addition, EDT_M has reverse characteristics, i.e., the shorter the distance from the source, the smaller the EDT_M. At distances beyond 10 m, it randomly fluctuates around its median value. On the other hand, if the front positions of the source, S1, S2 and S3, are disregarded, $IACC_{E3}$ is constant within DL as a function of distance.

Table 4 summarizes the comparison of acoustical parameters measured with the source at S0 to that measured with source at SL, SR and SH (Fig. 1) for symphony halls, chamber halls and opera houses. The source location is listed only if the averaged parameter value at that location compared to that at S0 exceeds the criterion in Table 3. When a statistically significant difference also occurs (significance level of 1% by the Welch test) between these two averages, Italic type is used. It is seen that (1) RT_L, RT_M and $IACC_{E3}$ do not exceed each

Table 4 Acoustical parameters with the source at S0 compared to source positions at SL, SR, and SH. Source locations are only listed beneath the acoustical parameters, if the averaged value exceeds the criterion. Italic means that a statistical difference occurs ($p = 1\%$).

	Halls	N	RT_L	RT_M	EDT_M	$C_{80,3}$	G_L	G_M	$IACC_{E3}$
Symphony Hall	Tokyo, Suntory Hall	2,006				SL			
	Tokyo, Bunka-Kaikan	2,327				*SL*	*SH*		
	Tokyo, Met Art Center	2,017				*SH*,SL	SH		
	Tokyo, TOC Concert Hall	1,632				SL			
	Sapporo, Symphony Hall	2,008							
	Boston Symp. Hall	2,625							
	SF, Davies Symp. Hall*	2,743				SR			
	Orange County, Segerstrom	2,903					SL		
	Baltimore, Meyerhoff Symp Hall	2,467				SR	SL		
	Salt Lake City, Symp. Hall	2,812							
	Zulich, Tonhalle Gross	1,546							
	Berlin Konzerthaus	1,575				SH	SH	SH	
	Amsterdam, Concertgebouw	2,037				SH			
	Vienna, Musukvereinssaal	1,680							
	Vienna Konzerthaus*	1,740				SR		SL	
Chamber Hall	Tokyo, Daiichi Seimei	767				SH,SL	SH,SL	SL	
	Zulich, Kleinersaal	610				SR	SL		
	Vienna, Brahmssaal	604							
	Vienna, Schubertsaal*	336				SL,SR	SL,SR		
	Vienna, Mozartsaal*	716							
	Salzburg, Mozareteum	844				SL			
	Salzburg, Wienersaal	209							
Opera House	Tokyo, NNT Opera House	1,810				*SH*	*SH*	*SH*	
	Tokyo, NNT Mideum Theater	1,038					*SH*	*SH*	
	Berlin, Komischeoper	1,222			*SH*	SH	*SH*	*SH*	—
	Dresden, Semperoper	1,300			*SH*	SH	*SH*	*SH*	—

*: Before recent renovation.

criterion for all the halls, (2) EDT_M exceeds the criterion at SH only for two opera houses, (3) C_{80} and G_L often take different values even with sources in the main performance area, and (4) when the source is moved backward on the stage in many opera houses, C_{80}, G_L and G_M undergo significant differences. This observation coincides with intrinsic subjective issue of opera houses so that the stage set is designed reflective [2]. But for symphony halls, G values are within a tolerable range, if the number of receiving positions is increased enough, as will be explained later. It is noted that two chamber halls, Tokyo Daiichi (TD) and Vienna Schubertsaal (VS), have distinguishing features [3], i.e., TD is an oval hall, and diffusing elements were necessary to avoid sound focusing, and VS has a concave ceiling that causes bending in RT decay curves. If these two halls are excluded, we may say that chamber halls have similar tendencies to symphony halls.

4. NUMBER OF RECEIVING POSITIONS

Averaged values of the acoustical parameters based on different sets of receiving points are plotted as a function of N/N_r in Fig. 5, where N and N_r are the number of total seats and the number of receiving positions, respectively. As an example, this comparison was shown for five halls: The Segerstrom Hall in Orange County California and, in Tokyo the TOC Concert Hall, the New National Theater (NNT) Opera House, the NNT Medium (Drama) Theater, and the Hamarikyu (Music) Hall [10,11], which have

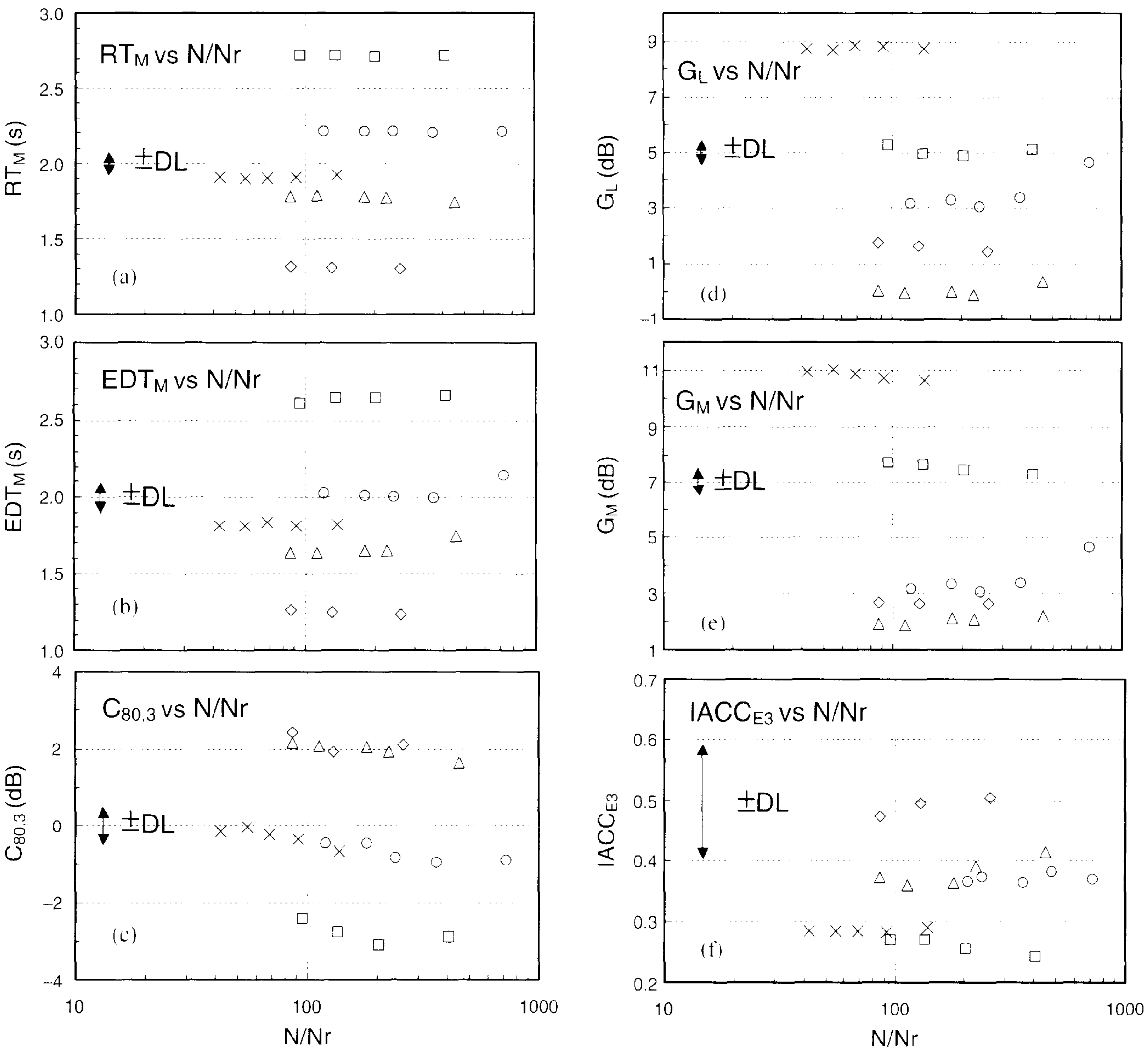

Fig. 5 Averaged values of the acoustical parameters for five halls as a function of the total seating count N divided by the numbers of receivers N_r. DL values in (a) and (b) are that for $RT = 2$ s. (: Orange County, : TOC, △: NNT Opera, ◇: NNT Drama, ×: Hamarikyu).

different shapes, sizes and sound diffusivities. On the whole, the influence of the change in values with number of receiving points is less than that with source location, and it can be considered that each plot converges tolerable value within $\pm DL/2$ in Table 3 with the increase of N_r, excepting C_{80}. RT_M and RT_L (not shown) approach constant values around $N/N_r = 300$ to 400, and EDT_M and $IACC_{E3}$ require a larger number of locations, i.e., $N/N_r = 150$ to 250 to satisfy the tolerable values. However, the spread of $C_{80,3}$, G_L and G_M is so large that adequate N/N_r for them should be less than 100. The guideline in ISO 3382, which specifies $N_r = 6$ to 10, may lead to unsatisfactory results with the measurements of $C_{80,3}$, G_L and G_M.

Another important finding from these observations is that the proper N_r value dose not depend on the room shape significantly. In other words, one may assume that N_r is a function of only the total seating count N, and the influence of the room shape on N_r is relatively weak. As a simple explanation of this result, rectangle hall (TOC) and a model-fan shaped hall with the same seating number, 1,600 were compared. The provability density of the source-to-receiver distance for all the seats to source S0 was calculated. Obviously, the fan shaped hall has more compact distribution, i.e., its spread in the source-to-receiver distance is much smaller than that of the rectangle hall as shown in Fig. 6, where the average and standard deviation for each hall are (13 m, 4 m) for fan-shape and (20 m, 8 m) for rectangle, respectively. That means the variation of acoustical parameters in the fan-shaped hall will be less, if the sound diffusivity in the two halls would be the same order. However, it is indisputably known that the higher density of early reflections in a rectangle hall

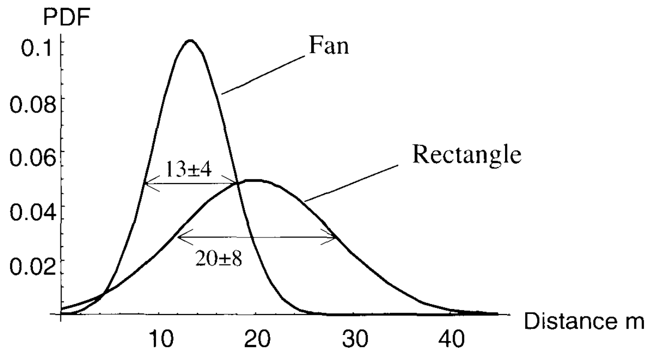

Fig. 6 Probability density of the source-to-receiver distance for all the seats to source S0 in rectangle hall (TOC) and a fan-shaped hall with the same seating number, 1,600. The latter hall has sidewalls splayed 45-degree to outer direction. The numerical numbers shown mean the average ± the standard deviation.

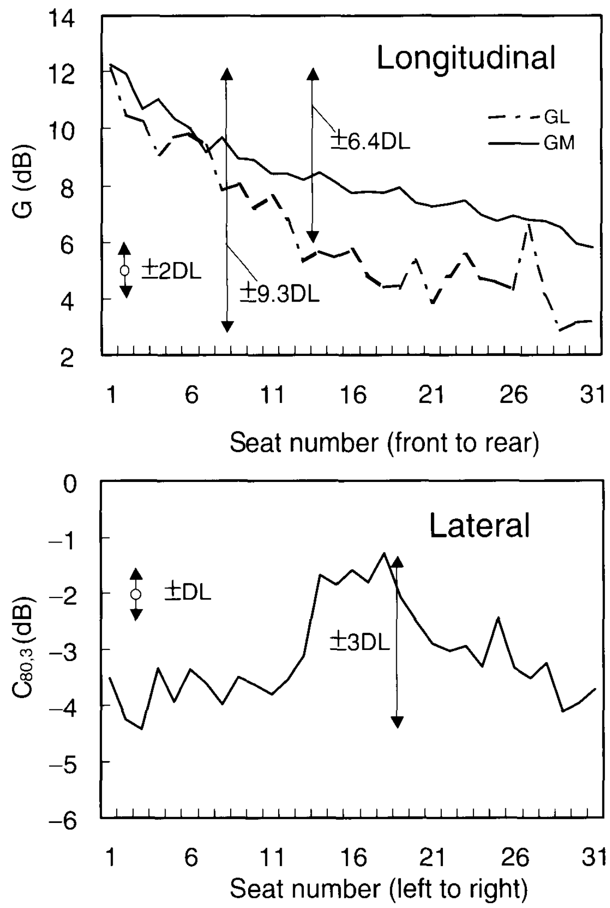

Fig. 7 G values measured at every seat along a longitudinal line (upper) and C_{80} values at every seat along a lateral row in the TOC hall. Both measuring lines intersect at the P-101 position that was located near the center of the hall. The sound source was located at S0.

compared to that in a fan-shaped hall leads to superior acoustics. Consequently, these two factors cancel out each other so that one may expect the similar numbers of N/N_r can be applied for both shapes, although adequate measurements are not yet available.

Further measurements of each acoustical parameter at every seat along longitudinal line and lateral row were executed in the TOC hall. Figure 7 shows some of the typical results. As is known, G is a function of the distance from source to receiver. Thus, one can observe G_L and G_M vary ±9.3 and ±6.4 times the DL around the median value, respectively. On the other hand, C_{80} significantly varies along not only longitudinal but lateral direction like lower figure. In this case, ±3 times the DL around the median value.

Table 5 shows the summary of such measurement along with the data at one another hall. Now, C_{80}, G, and including EDT, they vary strongly along the longitudinal direction, but RT_L, RT_M and $IACC_{E3}$'s variations are small, within ±1.5 times the DL at maximum. For lateral direction, it looks like sound diffusivity or local reflections affect on the variation. However, C_{80} and G are also sensitive to the lateral direction than other parameters. Presumably this kind of analysis backs up the conclusion that C_{80} and G are tough parameters to obtain average or representative value in each hall.

Table 5 Variation range, [Max value]–[Min value], around median value of each acoustical parameter normalized by its difference limen, DL, measured at TOC Concert Hall with high diffusion and a Multipurpose Hall with less diffusion. Asterisk means that the variation range exceeds ±3 times the DL.

Parameter	TOC		A Hall (N = 1,800, Fan Shape)	
	Lateral Row	Longitudinal Row	Lateral Row	Longitudinal Row
RT_L	±0.8	±0.9	±1.2	±1.0
RT_M	±0.7	±0.5	±1.2	±0.6
EDT_M	±1.6	±3.3*	±2.9	±4.3*
$C_{80,3}$	±3.0*	±5.1*	±3.0*	±5.2*
G_L	±5.0*	±9.3*	±2.8	±8.0*
G_M	±4.2*	±6.4*	±1.7	±6.2*
$IACC_{E3}$	±0.9	±1.5	±2.4	±1.2

Table 6 Summarized result of measurement condition for symphony halls. If multiple source positions are used, values in the third column are adjusted.

Parameter	Source position	Receiver's number (N/N_r)
$RT_L(BR)$	S0	300–400
RT_M		
EDT_M	S0	150–250
$C_{80,3}$	(need more investigation.)	
G_L	S0	<100
G_M		
$IACC_{E3}$	S0	150–250

5. CONCLUSIONS

In order to inter-compare halls, the same source location should be defined, and the main performance area seems to be appropriate for this purpose. When the measurement conditions shown in Table 6 are applied, one obtains reasonable values of RT_M, RT_L, EDT_M, and $IACC_{E3}$ for the each N/N_r unless the sound field in the hall is greatly non-diffuse. For G, the adequate value of N/N_r is probably less than 100, and depends on hall shape and sound diffusivity. There were few useful findings relating to C_{80} in this study. In opera houses, every parameter except for RT_M may vary significantly with source location. Further research in opera houses is required to better recommend numbers and locations. Finally, it is suggested that one should take into account both guidelines by Table 6 and ISO 3382 when executing the practical measurement at the present situation.

ACKNOWLEDGEMENT

The author wishes to thank Dr. Leo L. Beranek for his kind editorial assistance.

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