A comparison between shoebox and non-shoebox halls based on objective measurements in actual halls

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This paper examines objectively-measured differences in the sound fields in shoebox, non-shoebox and surround types of concert halls. Many concert-goers report that the average subjective sound quality in these three types of halls differs appreciably and that there are substantial differences from one seating location to another. Special attention is given to the temporal and amplitude structure in the early part (before 200 ms) of the impulse responses measured at various seat positions in six well-known concert halls (three shoebox and three surround). In particular, reflective energy cumulative curves RECC and sound strengths G are plotted. A method for visually assessing Texture is also presented. For 19 concert halls of the three types, the hall-averaged values of RECC, Binaural Quality Index BQI and Listener Envelopment LEV are tabulated.

1. Preface

This paper examines objective acoustical differences among shoebox, non-shoebox, and surround concert halls. The impetus behind this study was remarks by listeners that sound quality at different seat locations is greater in non-shoebox halls than in shoebox halls. Here, shoebox halls are defined as rectangular with the audience seating so configured that large areas of upper sidewalls are available for around-the-hall high-up reverberation. Parenthetically, in these halls the orchestra is always located at one end. Non-shoebox halls are those so configured that at least one sidewall (or rear wall) is mostly covered by audience seating, thus eliminating the possibility of high-up around-the-hall reverberation. Surround halls are those in which the audience seating clearly surrounds the orchestra. Also, in most surround halls, around-the-hall high-up reverberation is limited.

2. Recent findings by others

Loudness in halls: Zahorik and Wightman [1] determined in a concert hall that blindfolded listeners judged that the loudness of music from loudspeakers on the stage was essentially constant as the distance between the listeners and the loudspeakers was increased, even though the sound levels fell off appreciably. They opined that the listeners must make their loudness judgments based on the reverberant sound whose levels were relatively constant over the separation distance. Barron [2] reported a similar study except that the judgments of loudness were made with the listeners looking at the stage while moving back in the auditorium. Here also the loudnesses were judged to be almost independent of distance from the stage. He attributed this fact to the possibility that the listeners had established in their minds a definite sound strength for the orchestra and seeing that this is the same orchestra, they perceived the loudness to be unchanged. As to the fall-off in levels, Barron and Lee [3] show that in a typical concert hall ($V = 20{,}000\ m^3$ and $T = 2$ s) the overall sound strength G falls off about 5 dB for source-receiver distances between 10 m and 40 m, while the reverberant field falls off about 2 dB for these separations. Whether the above judgments were made by listeners paying attention to the reverberant field or to the visual effect needs further investigation.

Perception of bass: Bradley and Soulodre [4] investigated whether the perception of bass in a concert hall can be predicted from the ratio of the reverberation time at mid-frequencies to that at low frequencies (the so-called bass ratio) or from the sound strength alone at low frequencies, particularly at 125 Hz. They found, holding the strength constant, that changes in the ratio of reverberation times made almost no difference in the subjective perception of bass. Beranek [5] came to the same conclusion after plotting the bass ratio for halls of varying acoustical quality. Bradley and Soulodre then varied the strength of the sound in the low frequency octaves (for different reverberation times) and found that strength G correlated highly with subjective perception of bass. This result might even be more evident at 75 Hz, but no data exist. Beranek [5] found that the overall perceived quality of the acoustics in concert halls was judged better in halls with 3 to 4 dB more strength of the measured value of sound strength G at 125 Hz (halls unoccupied).

Listener Envelopment LEV: Soulodre, Lavoie and Norcross [6] derived a formula for calculation of listener envelopment LEV based on extensive laboratory subjective measurements. Beranek [7] modified their formula, without changing its validity, by adapting it for use with acoustical data on concert halls available in the literature. The revised formula is,

$$LEV = 0.5\, G_{Late,mid} + 10 \log [1 - IACC_{Late,mid}]\ \text{dB} \qquad (1)$$

were IACC is the interaural cross-correlation coefficient, Late means after 80 ms, and mid means average for 500/1000 Hz bands and where $G_{Late,mid}$ is determined from

$$G_{Late} = G - 10 \log (1 + C_{80}/10) \qquad (2)$$

where G is the overall sound strength in dB and C_{80} is the clarity factor.

Measurements in Boston Symphony Hall: Boston Symphony Hall is used in two ways: For Pops concerts, the main floor seats are removed and tables and chairs are substituted. For regular symphonic concerts the floor is raked from front to rear. The seats are fastened to a 1.9 cm thick base of plywood which in turn is supported on steel stanchions that vary in height. The seats are lightly holstered (2 cm thick felt beneath an impervious leather covering) and would be expected to have a sound absorption at 125 Hz, unoccupied, of about 0.3 if mounted on a solid floor. However, measurements made before and after the Boston seats on their plywood base were brought into the hall revealed that the absorption at 125 Hz is about 0.46 [8]. By contrast, measurements made with the seats occupied, show that the audience absorption is almost the same as that measured in other shoebox halls, namely, Berlin Konzerthaus, Vienna Musikvereinssaal, Lenox Seiji Ozawa, Seattle and Lucerne. Thus it is unfair to compare the measurements of the strength of sound at 125 Hz in the unoccupied Boston hall with that in other unoccupied halls, although comparisons at mid frequencies in the unoccupied hall are valid.

3. Strength of sound in the seats in conventional shoebox halls compared to that in surround halls.

G versus distance: The sound strengths G averaged at 125/250 Hz versus the distance between source and receiver (unoccupied) for two shoebox halls and three surround halls are shown in Fig. 1(a). For the two configurations, the levels are about 3.5 dB different for short distances and 5 dB for distances in excess of 25 m. At 500/1000 Hz, as shown in Fig. 1(b), the differences are about 2 dB for short distances and 3 dB for large distances. Why is the strength G greater in shoebox halls? The orchestra in a shoebox hall is located at one end with the side walls directing the sound toward the audience. Thus the radiated sound is confined to a lateral angle of less than 90 degrees. In a surround hall, the sound must radiate into a full 360 degrees, which predicts a difference in radiated levels of about 6 dB.

In both **Figs. 1(a) and (b)** it is apparent that the levels drop off faster with distance in the surround halls than in shoebox halls. This is probably due to the fact that the overhead reverberation can not develop as thoroughly in the surround halls so that the levels are less constant over distance.

4. RECC Curves

Toyota *et al.,* [9] introduced "reflected energy cumulative curve," which determines the rise in strength of the early sound [7]. It is defined by,

$$\mathrm{RECC}(t) = 10\log\left(\int_{5\mathrm{ms}}^{t} p^2(t)dt / K\right) \quad (3)$$

$$K = \int_0^\infty p_0^2(t)dt \quad (4)$$

where, $p(t)$ is a room impulse response measured between source and receiver, and $p_0(t)$ is that measured at 10 m from the same sound source in a free space. For the measurements, an omni-directional source S0 (height 1.5 m) was placed 3 m from the stage lip at the center of the stage. Note that in the next figures the steady-state strength G is given at the right end of the x-axis.

5. Measured RECC curves

Surround and shoebox halls: The Tokyo Suntory Hall was selected for illustration of a surround hall because it has been a successful venue for symphonic concerts. The Vienna Musikvereinssaal was chosen because it is the best known of its type. The different positions of the receiving omni-directional microphone are shown in Fig. 2. These positions are nearly the same in shoebox halls where the side balconies have numbers that are equivalent although they do not extend to the sides and rear of the stage.

The variation in the levels from one seat to another before 160 Hz is about 12 decibels as shown in Fig. 3 for the surround hall and is about 6 dB for the shoebox hall. Similar ranges are found at middle frequencies and for other halls. How serious are the variations in level within the halls must be judged in light of the findings in Section 2 above.

The surround hall: If one overlays the bottom 10 curves in Fig. 3 on the assemblage of the curves in Fig. 4 for shoebox halls, the observable difference is mainly a 7 dB shift in level. This means at those seats the energy growth is continuous and is typical of uniform arrival of many early reflections. Quite different are the curves for seats 12, 16, 26, 27 and 29. For seats 26 and 27, there is a large growth in level at 20 ms (after arrival of the direct sound) and slow growth between 20 and 60 ms, indicating arrival of few early reflections. This is followed by a sudden growth between 60 and 80 ms, indicating the arrival of a number of early reflections. For seat 29, there is a steep growth between 20 and 60 ms, then, the same as for 12, 26 and 27, there is little growth afterwards, indicating that the bunching between 20 and 60 ms entails unusually strong early reflections followed by weak early reflections, if any. In the balcony (dotted curves and 21) early reflections do not arrive until 80 to 100 ms after the direct sound arrival. The reason is that there is no stage enclosure and the panels over the orchestra do not effectively reflect the low frequencies. Certainly, the differences between the lower well-ordered and the upper odd shaped curves can be hear by listeners.

For those seats behind the stage, it must be realized that orchestral music sounds different than for seats in front—French horns radiate backwards and trumpets radiate forward. The most striking difference occurs for a piano performance. The reflecting board on the piano sends all of the high frequency sound forward—only the lowest notes diffract around it. Such a result is also obtained for a soprano voice which is highly directive forward.

The shoebox hall: The spread in the RECC curves at 125 Hz is smaller in Fig. 4 than for the surround hall of Fig. 3, 6 dB vs. 12 dB. For all except two upper curves of Fig. 4, the energy growth is continuous, which indicates uniform arrival of many early reflections. In fact, these RECC curves approach the growth derived from ideal diffuse sound field theory. The center side first balcony curve at the top indicates nearness to the stage which means arrival of strong direct sound, followed by a bunch of early reflections. The other strong curve from the back of the main floor indicates the simultaneous arrival of many early reflections between 40 and 60 ms.

Five contrasting halls: In Fig. 5, two of the halls are shoebox and three are surround. The difference in level at 125 Hz between the shoebox (top two curves) and surround (lower two curves) is about 6 db. The curve for the Berlin Philharmonie hall is very similar to that for the upper two halls, which may explain why the Berlin hall has been so successful, particularly for those sitting on the main floor.

Measurements with source at different positions on stage: RECC levels are plotted in Fig. 6 for typical position of the source on stage during measurements. S0 is the usual position of the omni-directional source (height 1.5 m) placed 3 m from the stage lip, and at stage center. Source positions SL, SR and SH are respectively at 4m left, 4 m right and 4m back from S0. The receiver is at position 101 just off center on the main floor. For the shoebox hall (Boston) RECC approaches stationary value (G minus 3 dB) at 80 to 100 ms for all four source positions. In the surround hall, the stationary value occurs at about twice the time length (more than 160 ms). This indicates that the stage enclosure in Boston is picking up the sound from all parts of the stage uniformly.

It was stated in Section 2 that data at 125 Hz for Boston are not typical for shoebox halls because of the plywood mounting for the chairs on the main floor. An overlay of Fig. 6 on Fig. 4 indicates a 4 decibel lower level in Boston, certainly owing to the greater sound absorption by the plywood.

RECC_E vs. RECC_L : It is interesting to determine how early RECC correlates with late RECC. It is usually taken that before about 100 ms (after arrival of the direct sound), the listener can make accurate localizations (lateral angles) and that the source is widened [7]. After about 100 ms, localization is no longer possible and the listener speaks of being enveloped by the reverberant sound field. Soulodre *et al.*,[10] determined that the separation time between ASW (apparent source width) and LEV (listener envelopment) is longer at low frequencies than at high frequencies. For the sake of simplicity, using their values as guidance, we shall assume 160 ms for the 125/250 Hz bands and 80 ms for the 500/1k bands. RECC_E is for integration up to the separation time and RECC_L is integration from the separation time to infinity. Plots of these two functions are shown in Fig. 7. We see that correlation between RECC_E and RECC_L is very high in both frequency regions. Hence, RECC is a useful measure in both the ASW and LEV regions.

6. Sound texture

Sound texture is the objective impression the listeners derive from the patterns in which the sequence of early sound reflections arrive at their ears. Good texture requires a large number of early reflections, uniformly but not precisely spaced apart, and with no single reflection dominating the others [11]. In a previous study [12] it was concluded that for opera houses in the first 80 ms after arrival of the direct sound there should be 15 at most and 12 at least early reflections. In concert halls the reflection patters are usually more complex and there is uncertainty about choosing the threshold between countable and non-countable reflections. To help get around this uncertainty, RC processing is applied to the impulse response. The result is shown in Figs. 8 and 9. In Fig. 8, the lower curves are the impulse response and the upper curves are RC processing of the IR using a non-directional microphone. It is seen that for the source on stage at S0 and the microphone at position 102 in the audience the RC curve is smoother for the shoebox hall (Berlin Konzerthaus) than for the surround hall (Berlin Philharmonie). The RC processing may be better illustrated by using a figure-eight microphone in the audience with the null response pointed at the stage. Using the figure-8 microphone, two Tokyo halls are compared in Fig. 9, TOC which is shoebox shaped and Suntory which is surround shaped. Here, the RC curve is smoother in the shoebox hall. The RC texture function appears to be a useful objective measure. The issue remaining is how to quantify the RC curve.

7. Tabulated measurements for 19 concert halls

Measurements of $RECC_{E,\,Low}$ (Low indicating average of 125/250 Hz bands), $RECC_{E,\,3B}$ (3B indicating average of 500/1k/2k bands), $RECC_{L,\,3B}$, Binaural Quality Index (1 – $IACC_{E3B}$), and LEV, are tabulated in Table I for 19 halls. Each item is the average for that function throughout the seating areas. From the group averages it is seen that all the values are greater for the shoebox halls than for the surround and non-shoebox halls.

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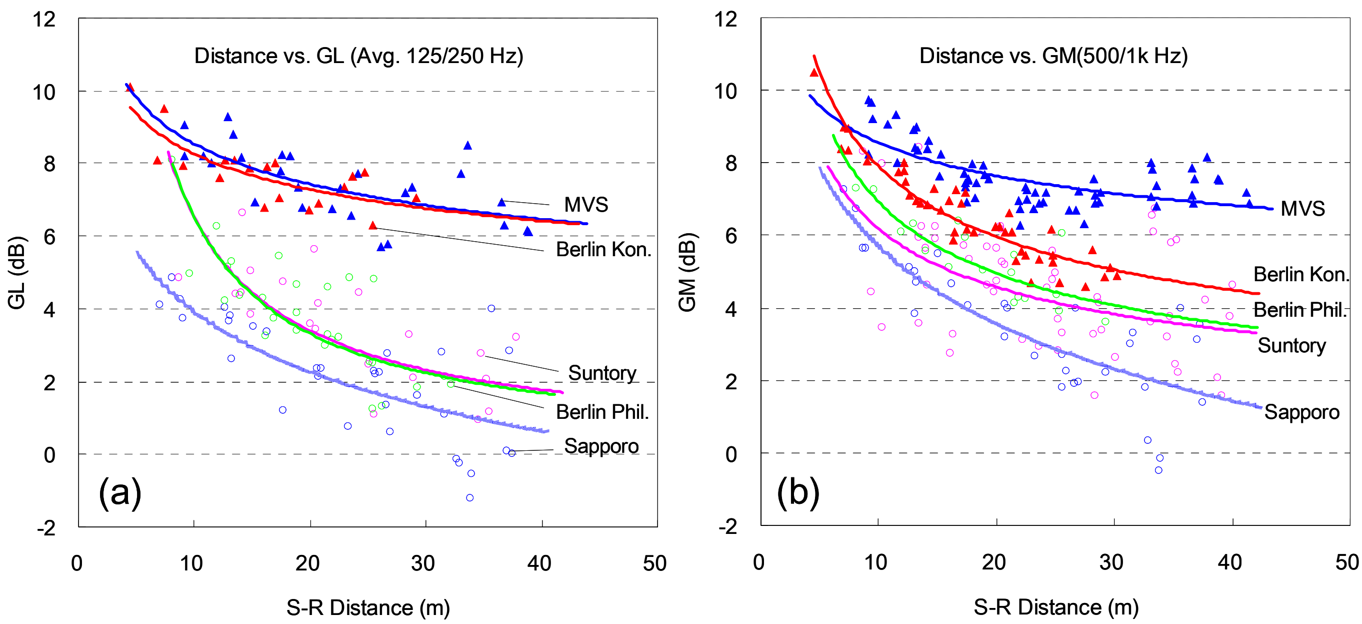

Fig. 1. Plot of strengths G vs. source-receiver distances measured in 5 halls: Berlin Konzerthaus, Vienna Musikvereinssaal, Berlin Philharmonie, Tokyo Suntory Hall, and Sapporo 'Kitara' Symp. Hall. The regression lines for each plot are shown. Left: Avg. of 125/250 Hz, Right: 500/1k Hz.

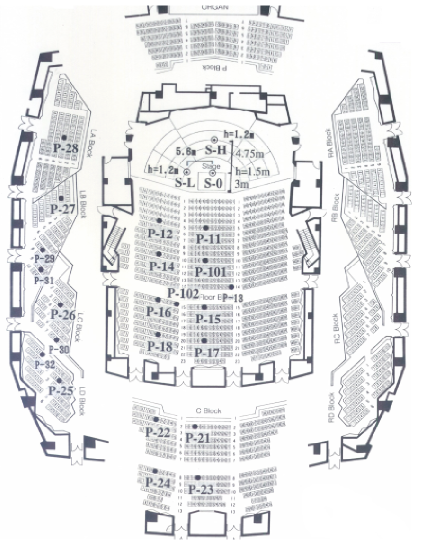

Fig. 2. Source and receiver positions measured in Tokyo, Suntory Hall.

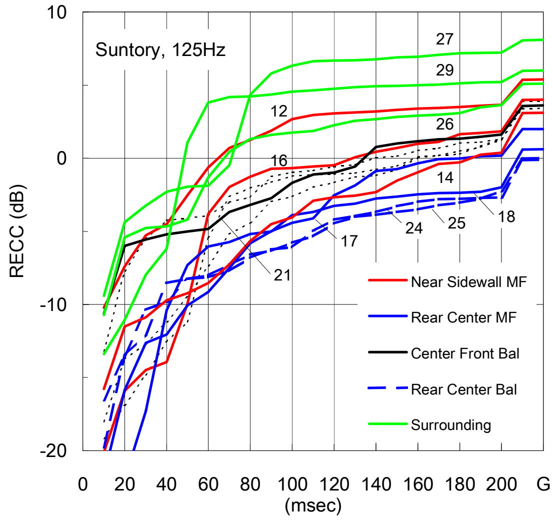

Fig. 3. RECC (125 Hz band) for initial 200 msec measured in Suntory Hall. Each number corresponds to the receiver position in Fig. 1. Two plots next to 200 msec and right end mean RECC (3 sec) and strength G.

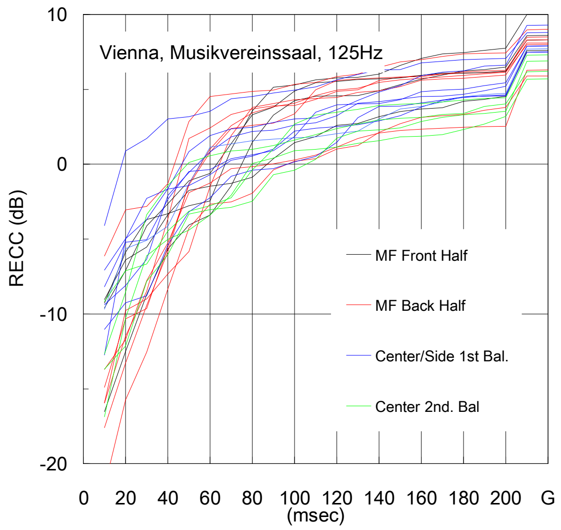

Fig. 4. Key as in Fig. 3, except for measured in Vienna Musikvereinssaal.

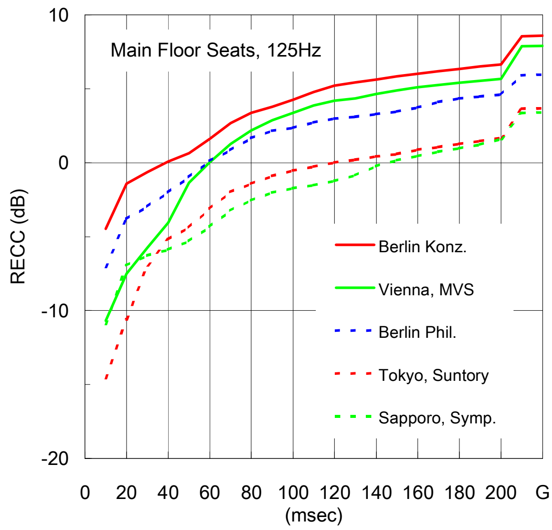

Fig. 5. REC curves for two SB hall and three SR halls. Each curve is an averaged value at all receiver positions on main floor.

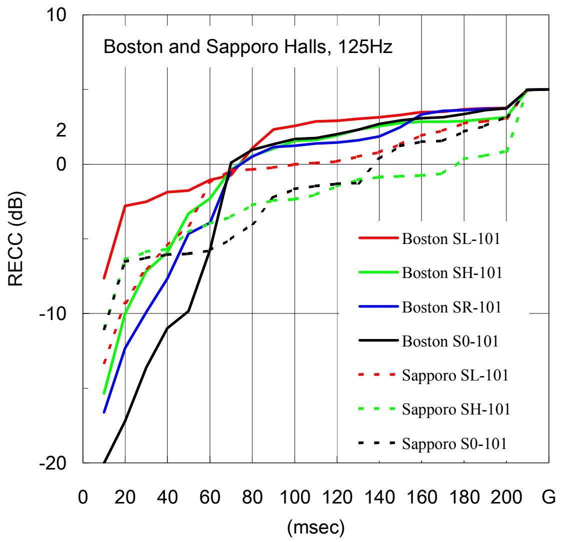

Fig. 6. REC curves at receiver position 101 (1m off center on main floor) and various source locations S0, SL, SR and SR measured in Boston Symphony Hall and Sapporo 'Kitara' Hall. The G value (at right edge) was adjusted to (equal) averaged value, 5 dB, for each measurement.

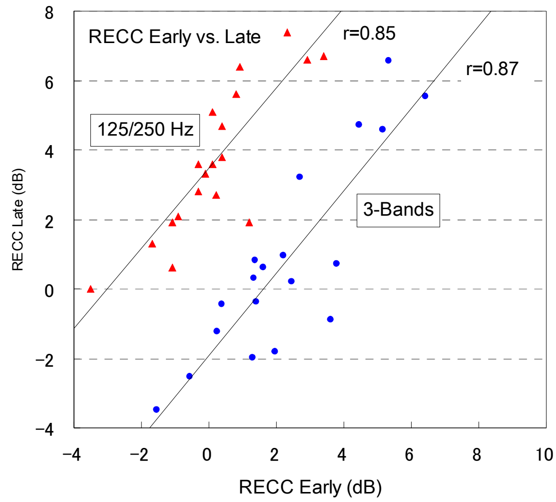

Fig. 7. Plot of $RECC_E$ vs. $RECC_L$ for 19 concert halls. Left: Avg. of 125/250 Hz; Right: 500/1k/2k Hz.

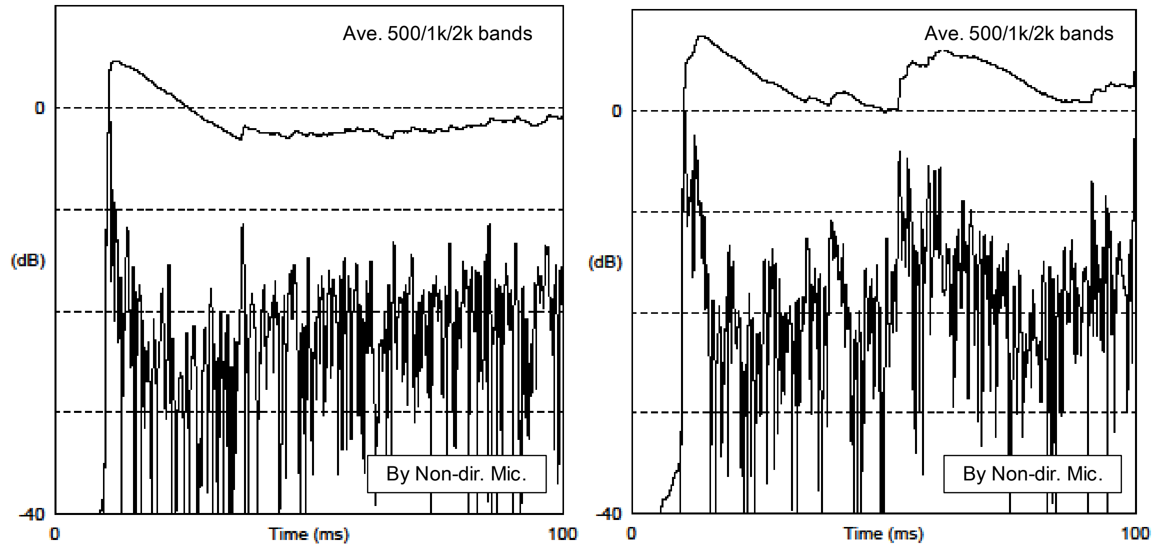

Fig. 8. Amplitude (lower) and RC processing (upper) of the IR measured at off center on main floor and source S0. Non-directional microphone was used, and a 3-octave-wide BP filter (500/1k/2k Hz) was connected in series. Left: Berlin Konzerthaus; Right: Berlin Philharmonie.

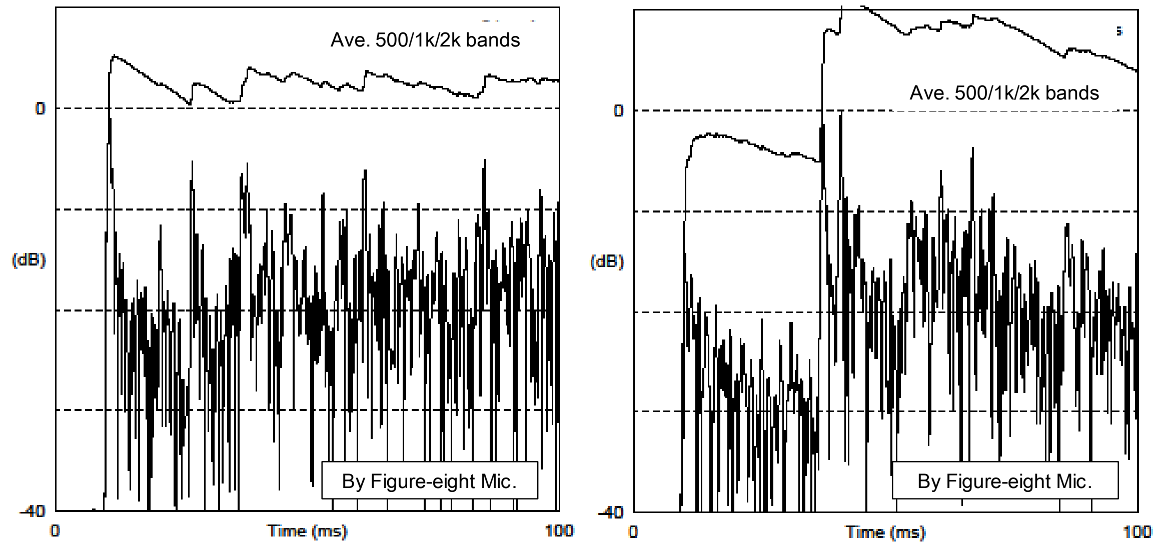

Fig. 9. Key as Fig. 8, except for figure-8 microphone. Left: Tokyo TOC Hall; Right: Tokyo Suntory

Table I Measured values of $RECC_{E, Low}$, $RECC_{E, 3B}$, $RECC_{L, 3B}$, BQI=[1-$IACC_{E,3}$] and LEV in 19 halls, which are averaged value at all receivers throughout seating area and source at S0. Low and 3B indicate avg. of 125/250 Hz bands and 500/1k/2k Hz bands, respectively.

		$RECC_{E, Low}$	$RECC_{E, 3B}$	$RECC_{L, 3B}$	BQI	LEV
Shoebox	Zurich, Tonhale	5.3	2.3	7.4	0.64	2.5
	Tokyo, TOC Hall	3.8	3.4	6.7	0.72	1.0
	Basel, Stadt-casino	6.4	2.9	6.6	0.62	2.0
	Vienna, Musikvereinssaal	4.5	0.9	6.4	0.64	2.0
	Berlin, Konzerthaus	5.1	0.8	5.6	0.64	1.2
	Amsterdam, Concertgebouw	2.7	0.1	5.1	0.54	1.4
	Boston, Symphony Hall	1.4	0.4	4.7	0.65	0.3
	Munich, Herculessaal	1.4	-0.1	3.3	0.63	0.0
	Average	3.8	1.3	5.7	0.64	1.3
Surround	Tokyo, Suntory Hall	1.4	0.4	3.8	0.53	-0.1
	Berlin, Philharmonie	2.5	0.1	3.6	0.46	-0.2
	Sapporo,"Kitara" Concert Hall	0.2	-0.9	2.1	0.47	-1.5
	San Francisco, Davies Hall (BR)	0.4	-1.1	1.9	0.44	-1.3
	Average	1.1	-0.4	2.9	0.48	-0.8
Non Shoebox	Baltimore, Symphony Hall	1.6	-0.3	3.6	0.54	0.0
	Tokyo, Bunka Kaikan	2.0	-0.3	2.8	0.60	-0.4
	Tokyo, Met. Art Center	2.2	0.2	2.7	0.59	-0.3
	Buffalo, Kleinhans	3.6	1.2	1.9	0.47	-2.2
	Salt Lake City, Symphony Hall	-0.6	-1.7	1.3	0.59	-1.1
	Rochester, Eastman	1.3	-1.1	0.6	0.54	-1.1
	Munich, Gasteig	-1.6	-3.5	0.0	0.57	-1.5
	Average	1.2	-0.8	1.8	0.56	-0.9