The effect of scattering surfaces in rectangular concert halls: A scale model analysis

by Evan Green, M Barron, D Thompson

ABSTRACT

The presence of sound scattering surfaces has long been identified as an essential ingredient in the acoustical quality of acoustically successful auditoria. Nevertheless, the influence of scattering surfaces and the related topic of sound field diffusion in auditoria has been the focus of little research. A high proportion of scattering surfaces is not without risks however. In his assessment of 17 British concert halls, Barron found three halls with significantly lower early sound levels, all of which have highly scattering ceilings.

In general, very little research has been carried out into a standardized way of measuring the effectiveness and influence of scattering elements in auditoria. Barron has presented results, based on measurements made by Chiles, investigating the effect of varying the scattering nature of different surfaces in a scale model rectangular concert hall. A major result from this study was that a scattering ceiling had little influence on the degree of diffusion (given audience seating on the floor). Barron postulates that with plane vertical walls, a horizontal sound field is established above the audience seating and that the scattering nature of the ceiling with audience seating in place has little influence on the state of diffusion.

The research presented here continues the work of Chiles and Barron and investigates further the degree of diffusion in the same scale model rectangular concert hall as well as the influence which scattering surfaces and their location have on the sound field in general.

Related paper: Diffusivity and its significance to effective seat absorption in concert halls by M Skålevik

THE EFFECT OF SCATTERING SURFACES IN RECTANGULAR CONCERT HALLS: A SCALE MODEL ANALYSIS

E Green Institute of Sound and Vibration Research (see below) now at Sound Space Design, London, UK
M Barron Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY
D Thompson Institute of Sound and Vibration Research, University of Southampton, Southampton, UK

1 INTRODUCTION

The presence of sound scattering surfaces has long been identified as an essential ingredient in the acoustical quality of acoustically successful auditoria. The acoustical failure of some venues, notably the ill-fated New York Philharmonic Hall[1], as well as the success of acoustical gems such as the Vienna Grosser Musikvereinsaal and Amsterdam Concertgebouw have been at least partly attributed to the effects of scattering elements such as coffered ceilings, niches, statuettes and ornamentally molded surfaces[2,3,4]. On the topic of scattering surfaces, Beranek states[4]:

> "I have listened to music in only one hall that had no irregularities on any surface. That was the ill fated Philharmonic Hall in New York City. (...) The sound in that hall was "glassy", "hard" and very disturbing. (...) [T]he lack of irregularities was more responsible for the unsatisfactory sound in Philharmonic Hall than any other factor."

Nevertheless, the influence of scattering surfaces and the related topic of sound field diffusion in auditoria has been the focus of little research. Haan and Fricke[5] have investigated whether a relationship exists between the perceived quality of a concert hall's acoustics and the degree of scattering attributable to the interior surfaces. 16 conductors, 16 solo musicians and 3 music critics were asked to rate 53 international venues for their acoustical quality. Haan and Fricke state that[5]:

> "the diffuseness of the reverberant sound field in an auditorium is related to the irregularity of the hall surfaces"

and go on to base their measure of the degree of diffusion (the Surface Diffusivity Index, SDI) on a visual inspection of wall and ceiling profiles. Qualitative descriptors such as "heavy ornamental design" or "large flat surface" were used to place the walls and ceilings of each hall into 'high', 'medium' and 'low' diffusivity classes. The SDI was given by taking the mean of the ceiling and wall diffusivity class. A strong correlation between acoustical quality and SDI was found, indicating that diffuse scattering surfaces may be linked to good subjective acoustics. However, the research does not establish a link between the presence of scattering elements and sound field diffusion – the most liked concert halls may contain many scattering elements but this does not necessarily mean that the sound field is diffuse.

A high proportion of scattering surfaces is not without risks however. In his assessment of 17 British concert halls, Barron found three halls with significantly lower early sound levels, all of which have highly scattering ceilings[6]. Barron states that the probable reason is that scattering surfaces direct most energy normal to the ceiling, irrespective of the angle of incidence, rather than specularly. Ryu and Jeon[7] report an average reduction in the level of first reflections due to the presence of scattering surfaces of 5dB. Objective measures such as the EDT, C-80 and G (along with their subjective counterparts, reverberance, clarity and strength) are highly influenced by the early energy so on this basis these measures would be affected by scattering elements applied to surfaces which provide early reflections.

Ryu[7] and Torres[8] have independently conducted listening tests on sound fields created in a 1:10 scale model opera house and a ray-tracing computer simulation, respectively, with and without scattering surface treatments. They found that, in general, scattering is preferred up to the point where it begins to impair the reverberance and loudness. Torres[8] also discovered that if scatterers only act in a particular frequency range, weakening of the specular component for only those frequencies can also lead to tone colouration.

In general, very little research has been carried out into a standardised way of measuring the effectiveness and influence of scattering elements in auditoria[4]. Barron[9] has presented results, based on measurements made by Chiles[10], investigating the effect of varying the scattering nature of different surfaces in a scale model rectangular concert hall. A major result from this study was that a scattering ceiling had little influence on the degree of diffusion (given audience seating on the floor). Barron postulates that with plane vertical walls, a horizontal sound field is established above the audience seating and that the scattering nature of the ceiling with audience seating in place has little influence on the state of diffusion[9].

The research presented here continues the work of Chiles and Barron and investigates further the degree of diffusion in the same scale model rectangular concert hall as well as the influence which scattering surfaces and their location have on the sound field in general. The experimental work was conducted at the Department of Architecture and Civil Engineering, University of Bath.

2 DIFFUSION IN AUDITORIA

2.1 Definition of Diffusion

While there is no universally agreed definition of sound field diffusion, all commonly used definitions incorporate some requirement for *homogeneity* and *isotropy* of the sound field. However, measuring homogeneity and isotropy of energy density at multiple points in a room directly is very difficult and time consuming, therefore indirect methods of assessing diffusion are employed. In the indirect case a measurable quantity, such as the room average reverberation time, is compared with the predicted value based on diffuse field theory, for instance the reverberation time calculated according to the Sabine or Eyring equations.

2.2 Normalised Standard Deviation of Reverberation Time

Davy and colleagues[11,12,13] have developed theoretical predictions for the ensemble and spatial variance of reverberation time (RT) in a diffuse space for measurements made using the interrupted noise and integrated impulse response methods. These predictions are included in the latest revision of ISO 3382[14]. When using the interrupted noise method to measure RT, ensemble variance occurs due to the statistical nature of the noise source. In the case of the integrated impulse response method (so-called Schroeder method), since the resultant decay curve is the theoretical average of an infinite number of noise decays (for that source and receiver position), the ensemble standard deviation is zero. With both methods, spatial variance occurs due to the unique decay curve found at each point in a room and the regression over a limited decay section used to determine the decay rate and from this the RT. For octave bands and 20dB decays the predicted spatial standard deviation of RT is given by:

$$\sigma_s(T_{20}) = 0.882\sqrt{T_{20}/B} = 0.995\sqrt{T_{20}/f_c} \tag{1}$$

where B is the frequency bandwidth and f_c is the octave band centre frequency. Here, on Davy's advice, the bandwidth has been replaced with the statistical bandwidth which for the 5th order Butterworth filters used in this research is approximately 11% greater.

Barron[9] has proposed using Davy's predictions of the standard deviation of RT as the reference for an indirect assessment of the degree of diffusion. The ratio of the measured standard deviation of RT to the predicted value is termed the Normalised Standard Deviation of RT (NSDRT):

$$\text{NSDRT} = \frac{\text{Measured standard deviation of RT}}{\text{Theoretical standard deviation of RT}} \qquad (2)$$

An NSDRT close to unity results when the measured standard deviation of RT is close to the theoretical prediction and implies that the sound field is diffuse. For non-diffuse spaces, an NSDRT significantly in excess of unity would be expected.

2.3 Scale Model Rectangular Concert Hall

As in previous work by Barron[9] and Chiles and Barron[15], a 1:25 scale model, modular, rectangular concert hall was used to study the effects of scattering surfaces and their placement. The model has full-size dimensions of length 45m, width 22m and height 18.2m which gives an enclosed volume of approximately 18,000m^3 (throughout the paper dimensions and frequencies apply to full size). The model includes modeled audience seating, stage, balcony and variable wall and ceiling panels. The 24 wall and ceiling panels can be interchanged to provide either specular or scattered reflections. Each panel has a full-size area of 72m^2. For this research 20mm hemispherical scatterers with 50% coverage were chosen. According to Jeon et al.[16] scatterers of this size and form should provide a scattering coefficient of 0.7 above a full-size frequency of 250Hz. The dimensions of the scale model are shown in Figure 1. For this study the model orchestra was not used and the balcony was omitted. Although removable, all measurements discussed here included model seating. The absorption coefficients of all surfaces in the model auditorium have been measured previously.

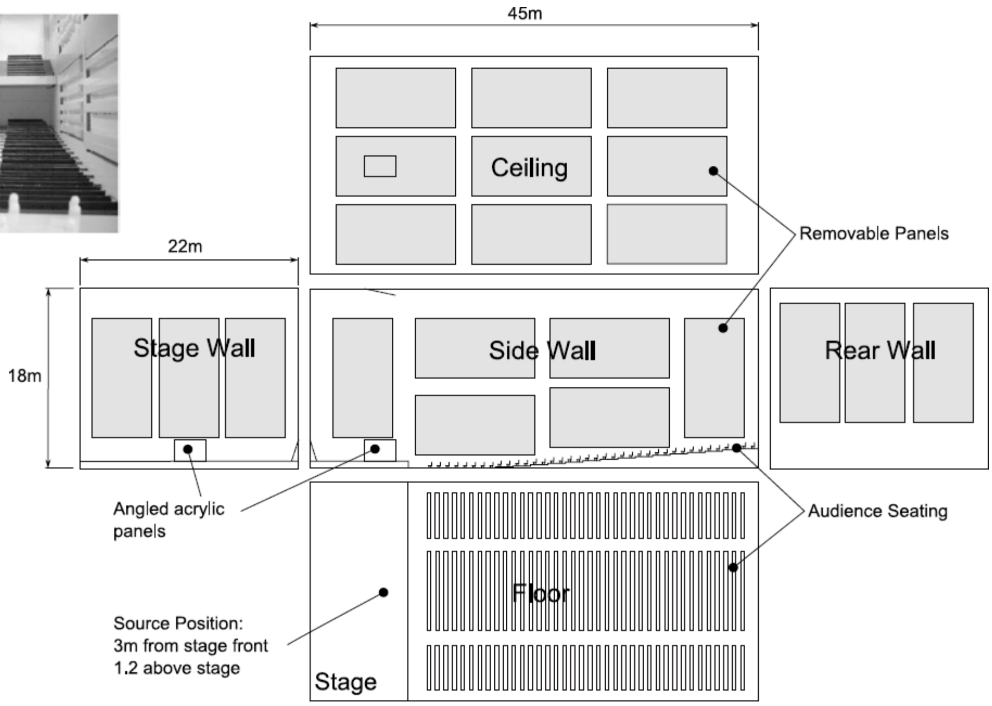

Figure 1. Internal elevations of the model auditorium Inset: Photograph of the interior of the auditorium model with a mixture of plane and scattering removable panels and the balcony in place. The model musicians in the foreground were not used in this research.

A spark source located on stage (see Figure 1) was used to generate an impulsive sound which was recorded digitally via 1/8" microphones. For each room configuration tested, impulse responses were recorded at 19 receiver positions. Measurements were made in atmospheric conditions with computer corrections for air absorption and noise. The high proportion of air absorption at frequencies of 2kHz and above together the inaccuracy of the theoretical corrections for air absorption at these frequencies resulted in a maximum frequency band of 1 kHz. Decay curves were generated from the recorded impulse responses by reverse integration and the RT was determined over a 20dB decay (T20).

3 RESULTS

3.1 NSDRT as an Indicator of Degree of Diffusion: Plane vs. Scattering

The maximum (24 x 72m^2 = 1728m^2) and minimum (0m^2) areas of scattering surfaces were installed and tested in the concert hall to give insight into the response of the NSDRT to changes in sound field diffusion. For this model it was assumed that installing scattering panels on all vertical surfaces and the ceiling would maximise sound field diffusion. These configurations have been labelled as *Pl* (all plane) and *Sc* (all scattering). Figure 2 shows the NSDRT for these configurations. Significantly, the NSDRT reduces at all frequencies when adding scattering surfaces which, based on the general assumption that scattering surfaces increase sound field diffusion, confirms that the NSDRT responds in the expected way to changes in diffusion. Furthermore, in configuration *Sc* the NSDRT is close to unity for all frequencies indicating that, according to Davy's theory, the degree of diffusion is close to maximum in this configuration.

Interesting corroborating evidence that the NSDRT functions well as an indicator of the degree of diffusion is also shown in Figure 2. Here the ratio of the average measured T20 to the Sabine RT based on measured absorption coefficients is shown for the same configurations. The result of this traditional and common indicator of the degree of diffusion is very similar to the NSDRT in both form and the conclusions that can be drawn. The NSDRT however holds the major advantage that it can be calculated solely from measured impulse responses whereas the RT comparison requires estimations of the room absorption to calculate the Sabine RT.

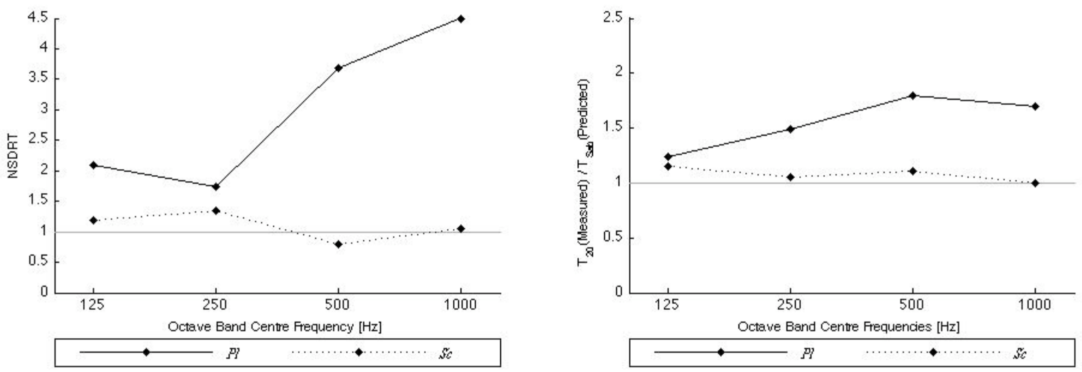

Figure 2. NSDRT (left) and Ratio of mean measured T20 to predicted Sabine RT (right) for concert hall model configurations with the minimum (*Pl*) and maximum (*Sc*) areas of scattering surfaces. Configuration Sc contains 1728m^2 of scattering panels on all vertical surfaces and the ceiling.

Decays recorded in these configurations (Figure 3) also demonstrate the lack of diffusion in configuration *Pl*. For this configuration with all surfaces plane and audience seating present, non-linear decays are evident – the straight red lines superimposed over the black decay curve show that two distinct decay rates are present. The reason for this is believed to be that a horizontal sound field becomes established which is remote from the only absorbing surface (seating). Sound in this horizontal field interacts only with surfaces of low absorption which leads to a reduction in decay rate for later times.

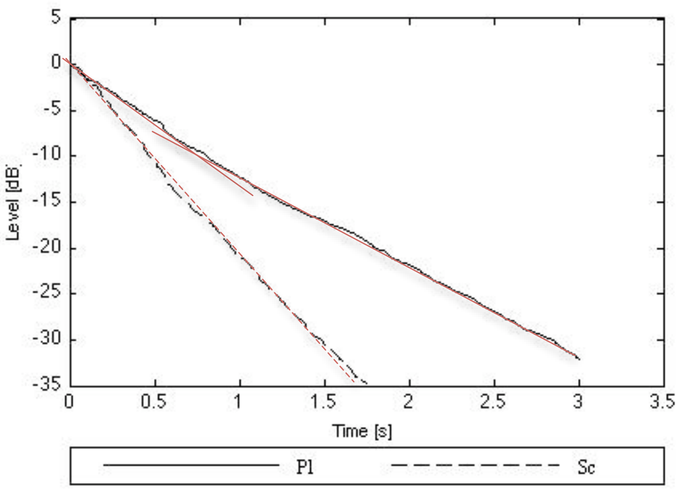

Figure 3. Example decays in concert hall model configurations with the minimum (*Pl*) and maximum (*Sc*) areas of scattering surfaces. Red lines indicate linear portions of each decay.

3.2 Variations with Height

To establish whether a horizontal sound field was being established at high level within the concert hall model, measurements were made in a configuration with scattering panels on the lower side walls (two panels on each side, 288m^2 overall) with all other surfaces plane. Measurements were made at the same 19 receiver positions 1.2m above the floor (configuration Lf) while a second set of measurements were made at 1.2m below the ceiling (configuration Lc). Marked differences were found in the sound fields at these two levels.

Figure 4 shows that the mean T20 for measurements close to the ceiling was on average 12% longer. This indicates that the sound field at this height interacts with a smaller absorption area than sound propagating near the floor.

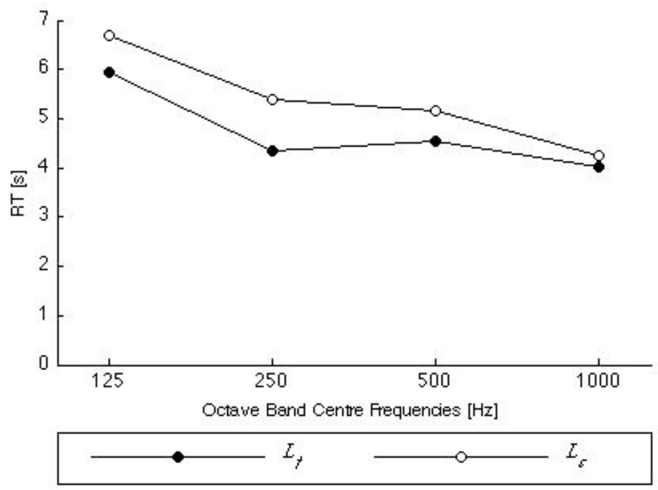

Figure 4. Reverberation time (T20) for configurations containing seating and scattering near floor level only. Measurements Lf and Lc were made 1.2m above the floor and below the ceiling, respectively.

The NSDRT data for these measurements, shown in Figure 5, indicates another significant difference. The NSDRT for measurements close to the ceiling is smaller at all frequencies and at

500Hz this difference has a statistical significance of 65% (based on an F-test of measured T20). This indicates that the measured RT is more consistent in a plane at high level and implies that the sound field here is more diffuse. Inspection of decay curves (Figure 6) shows that at high level an initial faster decay is followed by a terminal decay with lower decay rate. Near the ceiling, the change from initial to terminal decay occurs above a level of -5dB and therefore the portion used to evaluate the T20 is linear. There is therefore less uncertainty in the regression analysis and consistent estimates of the T20 are generated. For decays near the floor, the decay rate is inconsistent. This introduces uncertainty and a higher variance into the regression analysis which leads to a wider spread of RT estimates and a higher NSDRT.

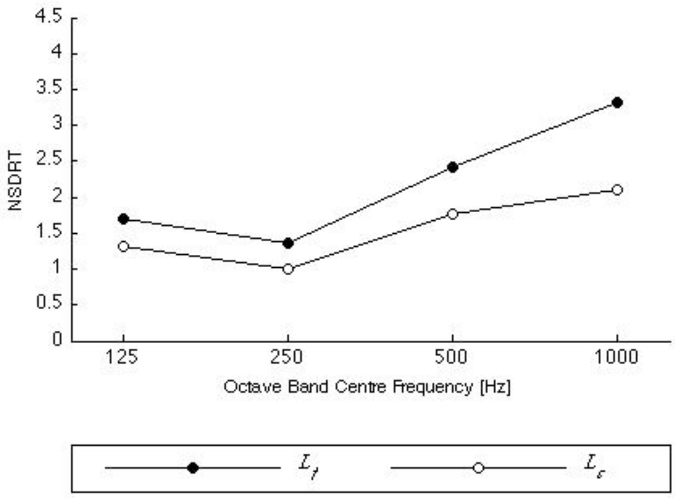

Figure 5. NSDRT for configurations containing seating and scattering near floor level only. Measurements Lf and Lc were made 1.2m above the floor and below the ceiling, respectively.

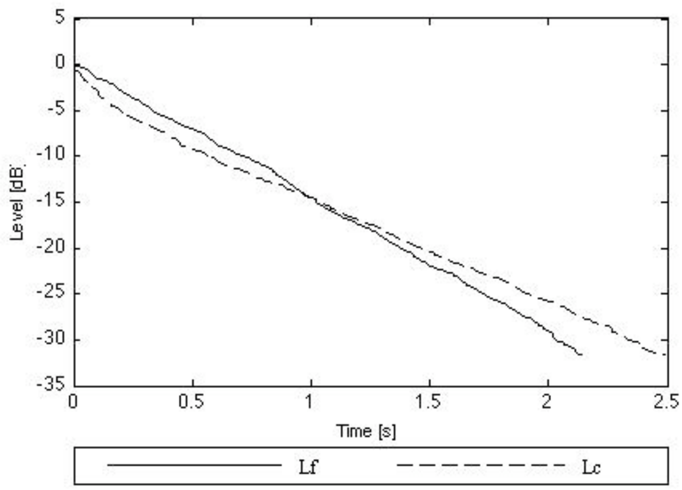

Figure 6. Example 500Hz decays for configurations containing seating and scattering near floor level only. Measurements Lf and Lc were made 1.2m above the floor and below the ceiling, respectively.

Overall, these results imply that sound with a significant vertical component is absorbed early on in the decay by the audience seating. At high level the lack of scattering and absorbing surfaces means that the remaining sound (now with a predominantly horizontal vector) continues to propagate horizontally and exhibit a low decay rate. Sound at low level, on reflection from the scattering wall surfaces, is given a vertical vector component and can continue to interact with the absorbent seating leading to a higher decay rate. Eventually however, the energy density near the ceiling will be significantly greater than that near the floor and sound energy will diffuse down to low level, arriving at floor receivers at near grazing incidence. Kuttruff and Straßen[17] observed this phenomenon in Monte Carlo simulations of rooms with plane vertical walls and an absorbing surface on the floor. This accounts for the changes between decay rates for receivers near the floor – their late sound arrives from regions of the room where it has previously encountered little absorption, in this case the ceiling.

3.3 Location of Scattering Surfaces

As discussed above, the location of scattering surfaces can have a significant impact on various characteristics of a sound field. In another set of configurations 8 scattering panels (total 576m^2) were installed in various locations:

- The ceiling (*Cl*) – all 8 panels on the ceiling.
- Around the stage enclosure (*St*) - 2 panels on the stage ceiling, 2 on the upstage wall and 1 on each of the side walls.
- Around the rear of the hall (*Rr*) - 2 panels on the rear ceiling, 2 on the rear wall and 2 on the rear area of side walls.
- On the side walls (*Sw*) – 4 panels on each side wall in a central location at high and low level.

All other variable panels were plane and model seating was present in all configurations. Measurements were made at the same 19 receiver positions 1.2 m above the floor.

3.3.1 NSDRT, RT and Decay Curves

Figure 7 shows the NSDRT evaluated for each of the 4 configurations above. The all plane and all scattering configurations from Section 3.1 are included for comparison. An immediate result from this data set is that the NSDRT with the ceiling scattering (configuration *Cl*) is much higher than the other configurations with the same scattering area. Indeed, the NSDRT is very similar to configuration *Pl* with no scattering surfaces. The reason for this can again be linked to a horizontal sound field and non-linear decays (see Figure 8). Such a sound field would interact little with both the seating and scattering ceiling, rendering both the absorption and scattering of these surfaces less effective.

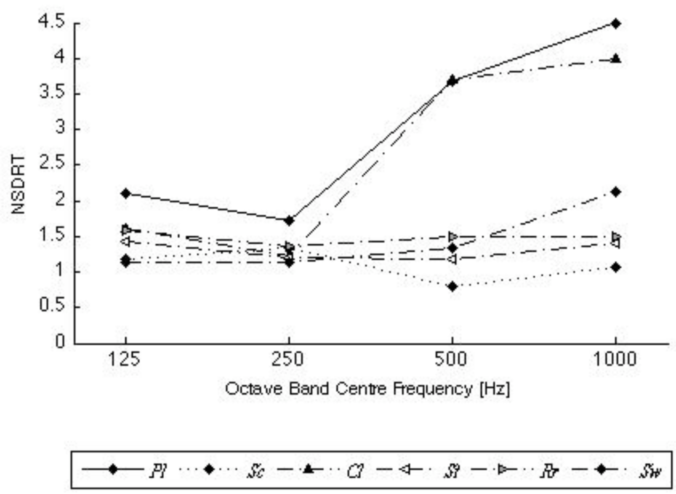

Figure 7. NSDRT for configurations with 8 scattering panels on ceiling (*Cl*), around stage (*St*), around rear (*Rr*) and on side walls. Values for all plane (*Pl*) and all scattering (*Sc*) configurations from Figure 2 included for comparison.

In all other configurations, the scattering surfaces are located on vertical surfaces and this seems adequate to disturb the horizontal sound field, produce linear decays and lead to NSDRT values close to unity.

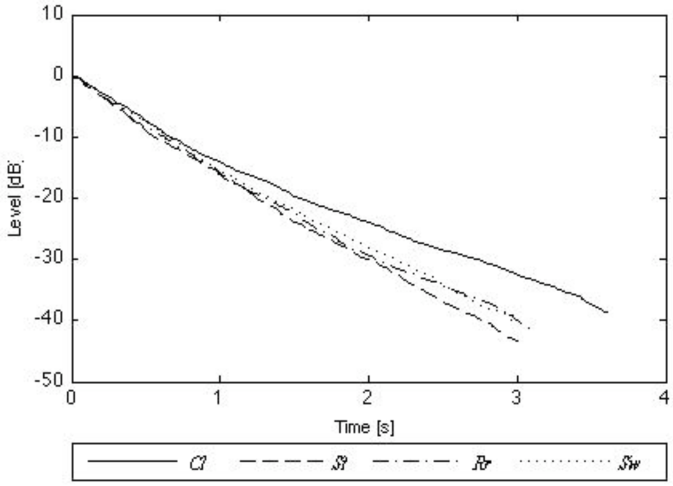

Figure 8. 500Hz decays recorded at the same receiver location in room configurations with 8 scattering panels on ceiling (*Cl*), around stage (*St*), around rear (*Rr*) and on side walls. Values for all plane (*Pl*) and all scattering (*Sc*) configurations from Figure 2 included for comparison.

3.3.2 Effect of scattering surfaces on sound level

Barron[6] has postulated that scattering surfaces on the ceilings and side walls of concert halls can lead to reduced sound levels at distant seats. To test this, the strength (G) was evaluated for the four configurations containing 8 scattering panels. As a reference for the diffuse condition, the predicted strength was also calculated from the measured EDT using Barron and Lee's revised theory of sound level[6]. Figure 9 shows the measured 500Hz strength at each receiver position normalized to the revised theory prediction plotted against source-receiver distance. Consequently, where the sound level varies according to revised theory, values close to 0dB are expected.

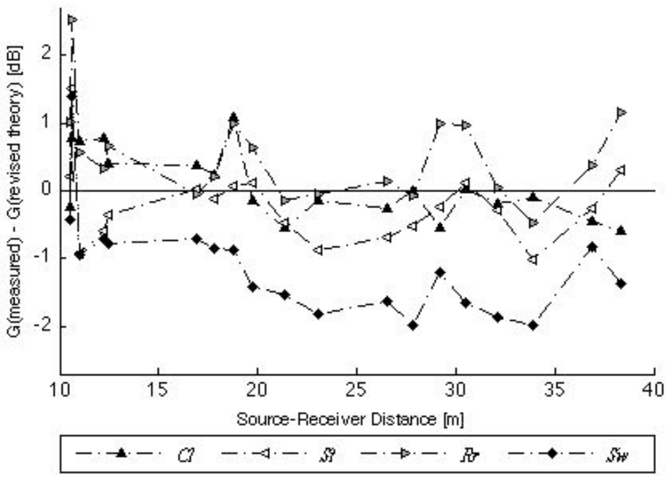

Figure 9. Difference between measured total level G at 500Hz and the expected value calculated from revised theory for scale model configurations containing 8 scattering panels and seating.

For configurations with scattering panels on the ceiling, stage and rear of the concert hall model, sound levels generally vary within ±1dB of the revised theory prediction. For configurations *St* and *Rr* with linear decays and low values of NSDRT, this may be expected. However, configuration *Cl* has highly non-linear decays and therefore the close agreement with revised theory is surprising. Furthermore, configuration *Sw* with scattering side walls has linear decays and low NSDRT values but demonstrates sound levels consistently 1 to 2dB below the revised theory prediction.

These differences can be explained by considering the back-scattering effect of scattering surfaces. In other words, scattering surfaces in concert halls tend to impede the flow of sound energy from the stage to the rear. This is clearly the case with scattering side walls. With a scattering ceiling (configuration *Cl*) it is believed that the specularly reflecting side walls in this model mitigate the back-scattering of the ceiling. Closer inspection of Figure 9 reveals that configuration *Rr* has the highest mean sound level which follows from the preceding argument since few early reflections (which tend to dominate the strength) are influenced by scattering surfaces.

4 CONCLUSION

A 1:25 scale model concert hall has been used to investigate the effect of scattering surfaces in this acoustic environment. Measurements in planes 1.2m above the floor and below the ceiling have demonstrated significantly different acoustic conditions at these heights and point to the presence of a horizontal sound field at high level. Scattering surfaces placed on vertical surfaces have been demonstrated to disturb this horizontal sound field, with surfaces around the stage (source) most effective at generating linear decays. It has also been demonstrated that scattering surfaces placed on surfaces parallel to the horizontal sound field (the ceiling) are ineffective at promoting diffusion. Care must however be taken with the location of scattering surfaces since back-scattering can lead to deficient sound levels at the rear of the hall, especially with scattering treatments on surfaces key for early reflections such as the side walls.

5 REFERENCES

1. L. Beranek, F. R. Johnson, T. J. Schultz and B. G. Watters “Acoustics of Philharmonic Hall, New York, during its first season”, *Journal of the Acoustical Society of America* (1964) 1247-1262.
2. L. Beranek “Subjective rank orderings and acoustical measurements for fifty-eight concert halls”, *ACTA Acustica united with Acustica* **89** (2003) 494-508
3. L. Beranek “Acoustics and the concert hall”, *Journal of the Acoustical Society of America* **57** (1975) 1258-1262.
4. T. Hidaka and L. Beranek “Acoustical design of the Tokyo Opera City (TOC) concert hall, Japan”, *Journal of the Acoustical Society of America* **107** (2000) 340-354.
5. C. Haan and F. Fricke “Surface diffusivity as a measure of the acoustic quality of concert halls”, *Applied Acoustics* **51** (1997) 53-69.
6. M. Barron and L. J. Lee “Energy relations in concert auditoriums”, *Journal of the Acoustical Society of America* **84** (1988) 618-628.
7. J. K. Ryu and J. Y. Jeon “Subjective and objective evaluations of a scattered sound field in a scale model opera house”, *Journal of the Acoustical Society of America* **124** (2008) 1538-1549.
8. R. R. Torres, M. Kleiner and B. I. Dalenbäck “Audibility of 'diffusion' in room acoustics auralization: an initial investigation”, *Acustica* **86** (2000) 919.
9. M. Barron “Thoughts on the room acoustic enigma: the state of diffusion”, *Proceedings of the Institute of Acoustics* **27** (2005).
10. S. Chiles “Sound behaviour in proportionate spaces and auditoria”, Ph.D. thesis, University of Bath, UK (2004).
11. J. L. Davy, I.P. Dunn and P. Dubout “The variance of decay rates in reverberation rooms”, *Acustica* **43** (1979) 12-25.
12. J. L. Davy “The variance of impulse decays”, *Acustica* **44** (1980) 51-56.
13. J. L. Davy “The variance of decay rates at low frequencies”, *Applied Acoustics* **23** (1988) 63-79.

14. International Standards Organisation, ISO3382-2:2008 Measurement of the reverberation time of rooms with reference to other acoustical parameters – Part 1 (2008).
15. S. Chiles and M. Barron "Sound level distribution and scatter in proportionate spaces", *Journal of the Acoustical Society of America* **116** (2004) 1585-1595.
16. J. Jeon, S. C. Lee and M. Vorländer "Development of scattering surfaces for concert halls", *Applied Acoustics* **65** (2004) 341-355.
17. H. Kuttruff and T. Straßen "Zur Abhängigkeit des Raumnachhalls von der Wanddiffusität und der Raumform", *Acustica* **45** (1980) 246-255.