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DEVELOPMENT OF A 3D TOOL TO VISUALISE THE LATERAL ENERGY COMPONENT WITHIN EACH SOUND REFLECTION IN CONCERT HALLS

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ABSTRACT

Early lateral sound reflections create a desirable sense of spaciousness and are an important design feature in concert hall design. Barron and Marshall derived the “early lateral energy fraction” (LF), defined as the linear ratio of the early lateral energy to the total early energy. LF is an acoustic descriptor of spatial impression, which has been shown to correlate highly with subjective listener preferences.
The direction of arrival and level of individual sound reflections can be visually identified in 3D raytracing analysis in computer models or 3D room acoustic measurements tools like IRIS. The results of these measurements are also commonly translated to a single LF figure. However, the late Sir Harold Marshall pointed out that how much each reflection contributes to the lateral sound is not easily identifiable. This paper discusses the implementation of a visualization tool with the objective of showing the contribution to the ‘lateral energy’ of each individual reflection. 3D acoustic measurements in several concert halls have been analysed using this tool to better understand which sound reflections are contributing most to the lateral energy. Furthermore, the use of this tool to enhance the design possibilities of raytracing analysis tools has also been explored.

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1. INTRODUCTION

1.1 Sir Harold Marshall and the importance of lateral sound reflections in concert halls

Sir Harold Marshall is renowned for his groundbreaking discovery of the importance of lateral sound to the concert hall listening experience [1]. Marshall discovered lateral sound reflections are essential to the spatial impression which he quoted as “the difference between feeling ‘inside’ the music or ‘looking at it’, as through a window” [1].
The Christchurch Town Hall was a bold and innovative design that supported his theory. The large suspended lateral reflectors are an architectural masterpiece and the key to its acoustical success and its design is referenced in most auditorium acoustics texts since 1975 [2].
Later research by Mike Barron and Sir Harold Marshall found that the degree of apparent source width (initially referred as spatial responsiveness) was maximised when the sound arrived from the side to the listener and minimised when the sound arrived from the direction of the source. This research confirmed the importance of lateral sound, and these developed an objective measure known as the Early Lateral Energy Fraction (LF) in 1981 [3]. The LF is based on the ratio of the early lateral sound relative to the total sound energy as shown in the Eqn.1.

$$LF = \frac{\int_{0.005}^{0.080} p_L^2(t)dt}{\int_{0}^{0.080} p^2(t)dt} \tag{1}$$

where p_L (t) is the impulse response signal measured with a figure of eight microphone and p(t) the signal measured with an omnidirectional microphone.
Recent research by Pätynen et al. has also established that the perceived dynamic range is enhanced by strong lateral reflections [4].
The theory of the importance of lateral sound has been reinforced by highly successful designs such as the Segerstrom Hall (Orange County), Guangzhou Opera House and the Philharmonie de Paris. The unique nature of each of these rooms cemented Sir Harold's place as one of the most innovative acoustic designers of all time.

1.2 Visualization of sound reflections

Measuring rooms with 3D Room Impulse Responses (3DRIR) provides spatial information about the acoustical characteristics of a space that traditional IRs measured with an omnidirectional microphone cannot.
IRIS [5] is a 3DRIR measurement system developed by Marshall Day Acoustics, which captures the impulse response of a room using an ambisonics microphone. In addition to providing objective room acoustics parameters, this graphically presents the sound arriving to the receiver as a series of vectors with magnitude, direction and time of arrival in a an 'IRIS plot' or hedgehog pattern that allows users to quickly assess and understand some of the acoustic characteristics of the space. Figure 1 shows an example of an IRIS plot.

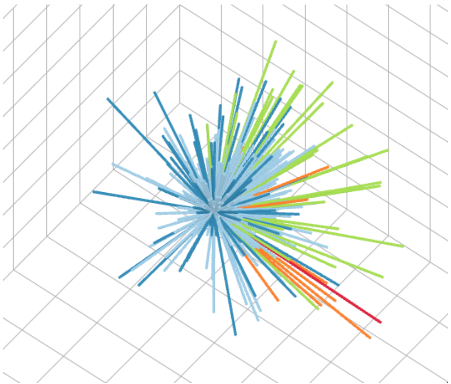

Figure 1. Example of IRIS plot

The use of computer raytracing techniques in modelling software like Grasshopper for Rhinoceros provide a large degree of flexibility and design capacities during the early design stages and enhance the collaboration between architect and acoustician. The raytracing tools developed in Grasshopper allows real time feedback of the changes in the room surfaces and the effects on the sound reflections (see Figure 2). Sound reflections can be easily visualised and typical acoustic parameters like time delay, strength of sound reflection and angle of incidence can be easily calculated and displayed.

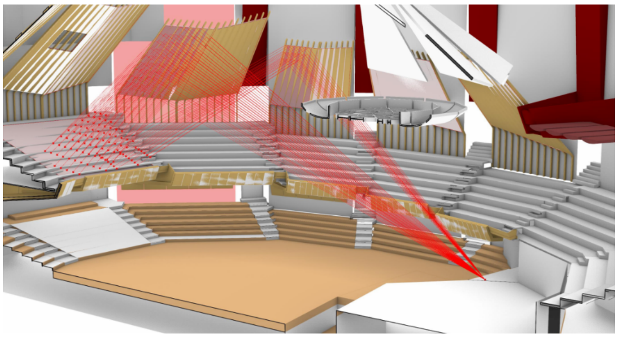

Figure 2. Example of raytracing analysis in Rhino/Grasshopper

While 3DRIRs measurement results (e.g. IRIS plots) and computer raytracing results allow users to identify the level and direction of the sound reflections, the late Marshall pointed out that how much each reflection contributes to the lateral sound was not immediately identifiable in the plot.
This paper describes the implementation of a visualization tool designed to show the contribution of each individual reflection to the 'lateral energy'.

2. VISUALISATION OF LATERAL SOUND CONTRIBUTION

2.1 Lateral sound contribution factor definition

The goal of the authors is to create a 3D-tool that analyses and visually displays the contribution of each sound reflection to the 'lateral energy'.
The tool is based on the lateral sound component of the early lateral fraction (LF) descriptor, in which the lateral sound component is measured with a figure of eight pattern.
A 3D figure of eight can be mathematically represented with Eqn. (2), where the 'φ' is the azimuth angle and 'θ' represents elevation angle and ranges between -90˚ and 90˚.

$$\sin\varphi \times \cos\theta \tag{2}$$

The contribution to the lateral sound of each sound reflection depends on its level and angle of arrival. It can be clearly seen that if a sound reflection arrives frontal (e.g. frontal ceiling reflection) this would barely contribute to the

LF and therefore to the associated subjective impression related of the source widening. In contrast, sound reflection arriving from the side of the listener (φ = 90, θ = 0) should maximise the spatial impression. However, if the level of this sound reflection is low, then the contribution to the lateral sound / spatial impression would be low.
The proposed tool analyses each sound reflection individually and calculates how 'lateral' or in other words how much it contributes to LF. At this stage, it only analyses the effect of each sound reflection analysed in isolation, it does not consider the late energy, or potential masking effects from other sound reflections.
The metric of the contribution factor to the lateral sound proposed (LSC) is defined as indicated in Eqn. (3). The magnitude of all sound reflections is normalised in relation to the direct sound. This normalisation allows the comparison of different measurements.

$$\text{LSC factor} = \left(10^{\frac{\text{SPL}}{20}}\right) \times |\sin\varphi \times \cos\theta| \qquad (3)$$

The contribution factor theoretically ranges between 0 and 1. A factor of 0 is obtained with a frontal sound reflection (coming from the same direction than the direct sound) and a factor of 1 represents a sound reflection arriving at 90˚ to the side with the same strength as the direct sound, which is unlikely to occur in practice. To give context to the numbers calculated with Eqn.1, the lateral sound contribution factor has been calculated for the theoretical case study where a sound reflection with a fixed delay from its direct sound, reaches the receiver at different angles and strengths. Results are summarised in Table 1.

Table 1. Calculation of lateral sound contribution factor for specific sound reflections

SPL (dB)	Azimuth (deg)	Elevation (deg)	LSC	Example
0	0	0	0.00	Direct sound
-1	10	0	0.15	Stage enclosure
-4	0	45	0.00	Forestage
-5	45	15	0.39	Overhead lateral
-5	45	0	0.406	Side wall
-5	90	0	0.574	Perpendicular

2.2 Visualisation of results

At this stage, visualisation of the tool has been implemented in Rhino/Grasshopper as it is a commonly used tool by acousticians for the development of 3D models and the raytracing analysis in the design stages [6] [7]. The spatial information provided by the IRIS plots can also be integrated in this 3D environment too which allows further analysis.
This tool has been used to analyse the acoustical characteristics of multiple existing halls measured with IRIS. This tool is also implemented as part of the raytracing script used during the design process.
By colouring the vectors from IRIS plots and/or sound rays in raytracing analysis tools according to the contribution factor, the tool provides visually a better understanding of the 'usefulness' of each reflection.
Figure 3 shows an example of an IRIS plot imported into Rhinoceros/Grasshopper showing the spatial information provided by an IRIS plot (left-hand side) and the right-hand plot is filtered to show only the early energy (< 80ms). Figure 4 then provides the same measurement showing the lateral sound contribution (LSC) of each 'sound reflection', showing the direct sound as a black vector.

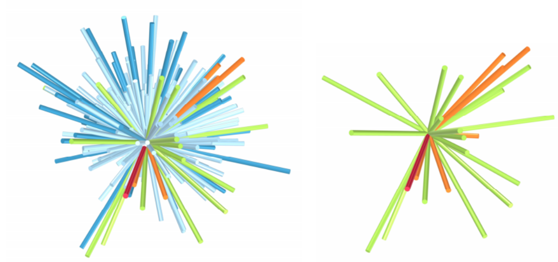

Figure 3. Example of imported IRIS plots (filtered plot on the right)

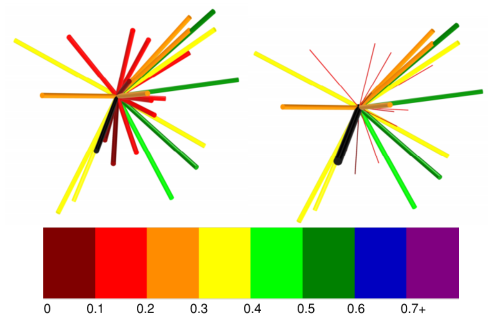

Figure 4. Example of lateral sound contribution factor of IRIS plot with legend

The legend of the lateral sound contribution factor shown in Figure 4 has been devised based on the analysis of 3DRIRs measurements of existing halls, and the results of the analysis of the single sound reflection analysis in Tab. 1. Broadly, the brown and red reflections are not contributing to the lateral (and possibly masking) and the orange to green are significant with the blue and purple being very strong contributors.
To visually help interpreting the lateral reflections in larger drawings, the vector representation of reflections with minimal contribution to the lateral (LFC <0.2) have been thinned in the case studies discussed in this paper.

3. CASE STUDIES OF MEASURED HALLS

Three concert halls, which the design of lateral sound reflections was a key design element have been analysed with this tool to study its acoustic performance and identify the architectural features that contribute to the lateral sound.
The measurements shows were undertaken by Marshall Day Acoustics using an omnidirectional speaker and an ambisonics microphone using IRIS. Measurements have been post-analysed with this tool to visualise the LSC of each sound reflection.
All results shown in this paper have been analysed for the 500 Hz octave band with a window resolution of the IRIS measurements of 2-3ms. This provides an accurate and consistent approach and provides a good resolution to understand the sequence of sound reflections.
The concert halls shown in Figure 5 to Figure 7 have been analysed.

Figure 5. Christchurch Town Hall, New Zealand

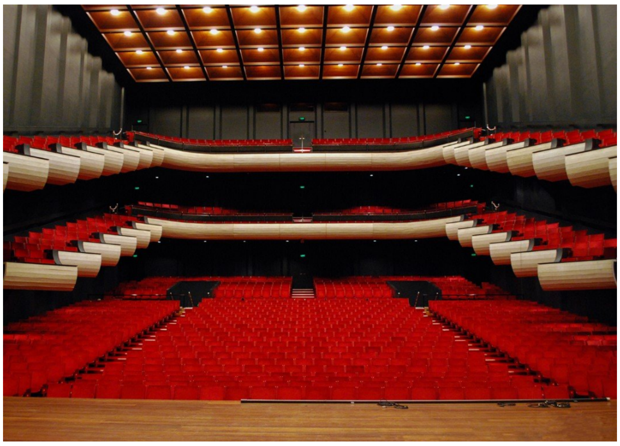

Figure 6. Perth Town Hall, Australia

Figure 7. Philharmonie de Paris, France

3.1 Christchurch Town Hall

The Christchurch Town Hall [2] is well known for its great acoustics and is referenced in many specialised books. The key feature of the Christchurch Town Hall is the large oblique reflectors which provide early lateral sound reflections that in combination with the reverberance from the large volume provide good clarity and envelopment.

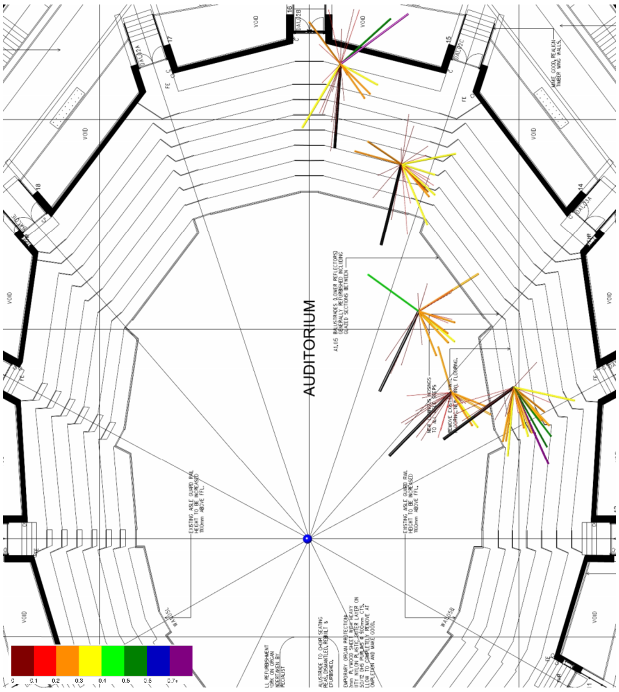

Figure 8. Christchurch Town Hall lateral sound contribution factor

Figure 8 shows abundant number of yellow and orange reflections across all the seats analysed from these large reflectors. Balcony seats receive at least one lateral reflection from the adjacent reflectors, see yellow reflections in the contribution plots in Figure 9, and some locations receive additional lateral reflections from other reflectors located further away. The balcony fronts also supplement lateral sound reflections to the stalls (see the right plots in Figure 11).

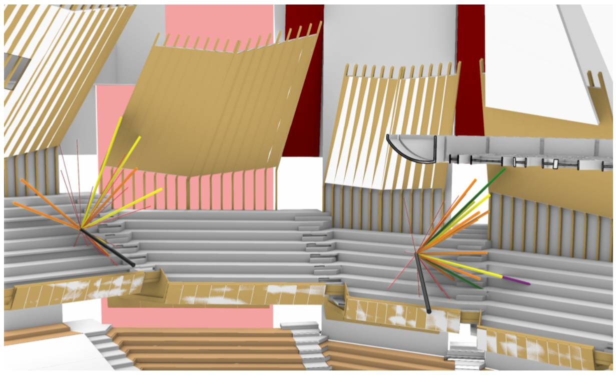

Figure 9. LSC in balcony seats

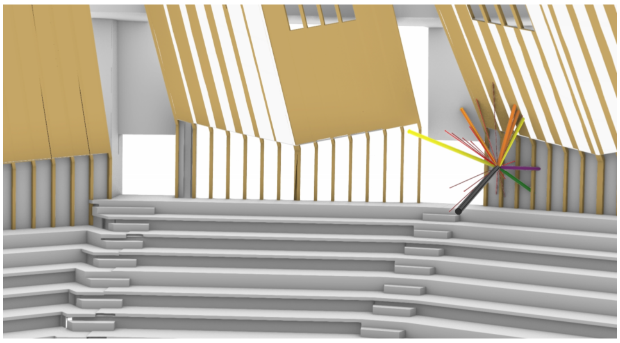

Figure 10. LSC in balcony central seat

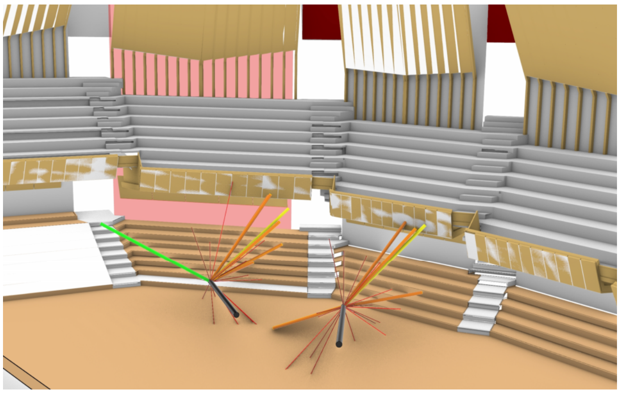

Figure 11. LSC in stalls

3.2 Perth Town Hall

The Perth Town Hall was constructed in a similar era to the Christchurch Town Hall but has a very different design.
The Perth Town Hall has a more traditional shoebox typology with two levels of balconies. The coffered ceiling reduces the strength of the frontal ceiling reflections and audience receive several lateral reflections (see Figure 12).

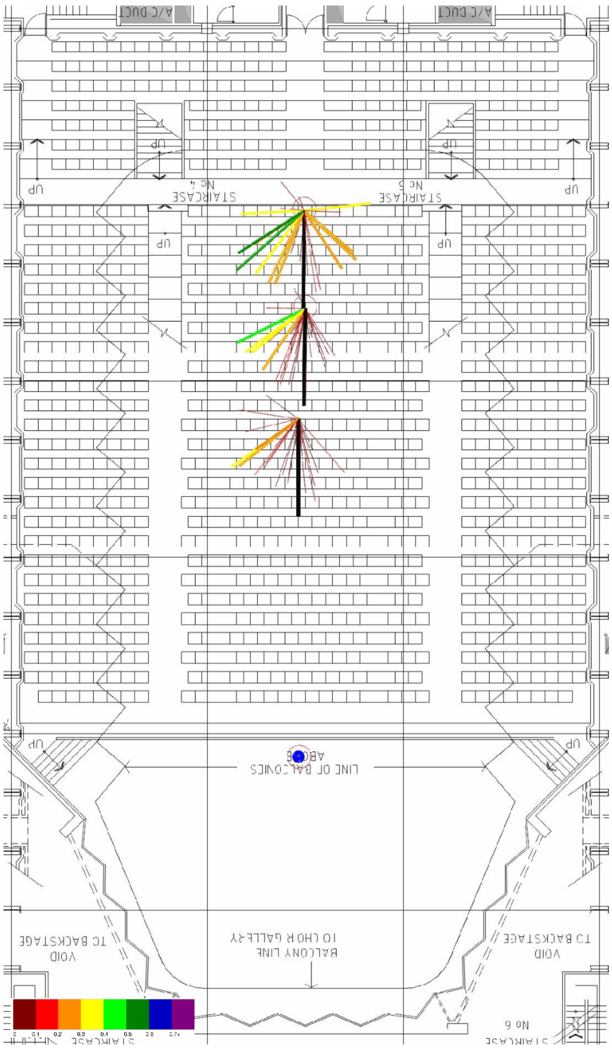

Figure 12. Perth Town Hall - stalls

Figure 13 and 14 shows in a clear way that skeletal lateral sound reflections arrive from the side walls, balcony fronts, and cornice reflections between the side walls and underside of the balconies [8]. The contribution of these sound reflections range between 0.2 (orange) and 0.6 (dark green).

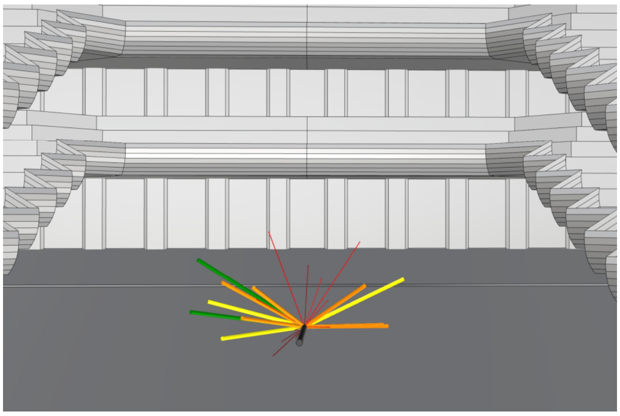

Figure 13. LSC in rear stalls

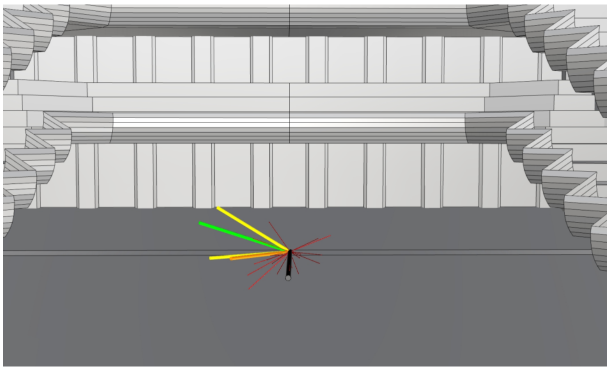

Figure 14. LSC in mid stalls

3.3 Philharmonie de Paris

The design brief for the Philharmonie de Paris competition required for the concert hall to achieve great clarity and high reverberance and a new hall typology [9]. The design of the Philharmonie de Paris has a large acoustic volume with an intimate audience inner chamber. Early lateral reflections are provided by the suspended 'nuages' or clouds along with the wall areas near the seating pods and balcony fronts. Figures 15 and 16 show most of the receivers receive strong lateral reflections, visualised with several yellow and green vectors.

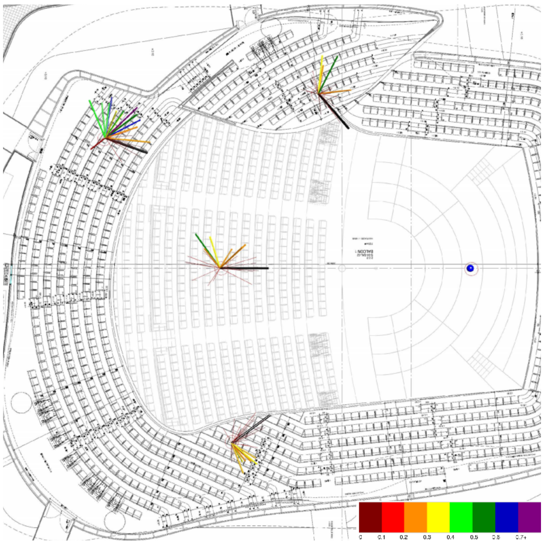

Figure 15. PdP – LSC in stalls and first balcony

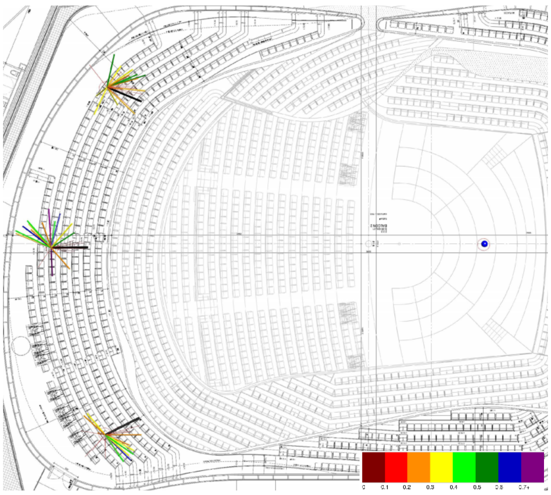

Figure 16. PdP – LSC in second balcony

Figure 17 shows the analysis of the sound reflections at three balcony positions. These show that strong lateral sound reflections from the 'nuages' coming from above and to the side, in some locations from both sides (see top plots) and from the balcony front and curved walls around the seating pods on the right.

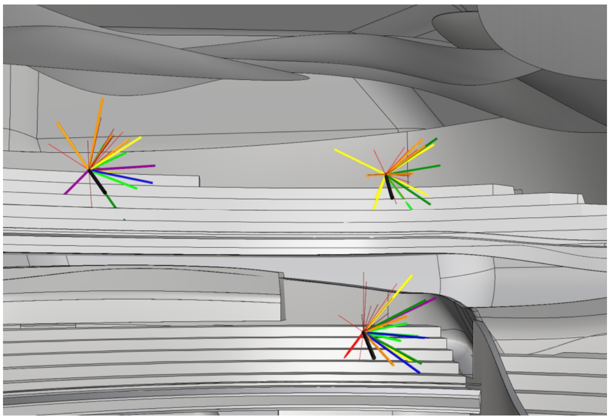

Figure 17. Balconies lateral sound reflections

Figure 18 shows the reflections for a receiver in the stalls. This position still receives some reflections from the suspended 'nuages' but due to the longer distance, the level and contribution of these reflections is lower than in the balconies, but still noticeable. However, additional useful reflections arrive from the balcony fronts and side walls.

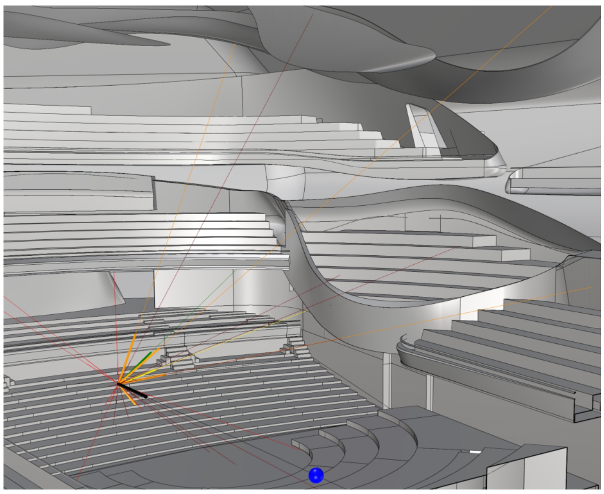

Figure 18. Stalls lateral sound reflections

4. LATERAL SOUND VISULATION TOOL DURING DESIGN STAGES

The use of raytracing analysis in Rhinoceros/Grasshopper is a very flexible and powerful tool during early design phases where the collaboration between architect and acoustician requires assessing continuous changes. The implementation of the lateral sound contribution factor has also been implemented into raytracing analysis tools. This could be used to analyse the LSC of the design or assessing how changes in the architectural design can affect the contribution of the lateral sound contribution.

A simple example is shown in in Figure 19. This shows the frontal sound reflection from the overhang reflector (LSC < 0.1) and lateral sound reflections from the side walls (LSC 0.4-0.5) and cornices (LSC 0.3-0.4). While the analysis shows a strong contribution of the side wall reflections, these are partially obscured by the audience in real halls. However, this analysis shows that the upper cornice reflections, despite its longer trajectory, make a significant contribution to lateral sound.

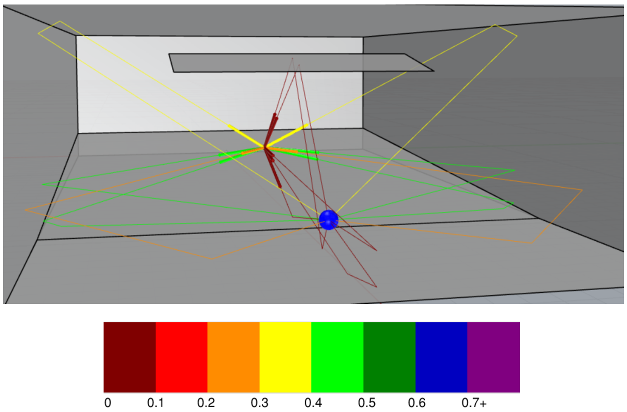

Figure 19. Example of lateral sound contribution

5. CONCLUSION

The idea of this tool started with the objective of assessing and presenting visually how much each sound reflection contributes to the early lateral sound. The case studies and preliminary use of this tool in raytracing analysis was found very beneficial providing in a clear quick way lateral sound information. Further work with this tool could include the analysis of possible masking of the lateral reflections by strong frontal reflections or show the sequence of reflections [1][8][10].

6. ACKNOWLEDGMENTS

This paper started from several conversations with Sir Harold Marshall and is dedicated to him and the enormous contribution he made to the understanding of auditorium acoustics. The authors would also thank the Marshall Day Acoustics team for their assistance with the IRIS measurements of the concert halls discussed in this paper.

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