WHY DO LARGE CONCERT HALLS NEED TO BE OPTIMIZED FOR EARLY REFLECTION COVERAGE?

E Kahle	Kahle Acoustics, Brussels, Belgium
Y Jurkiewicz	Kahle Acoustics, Brussels, Belgium
E Green	Kahle Acoustics, Brussels, Belgium
V Berrier	Kahle Acoustics, Brussels, Belgium

1 INTRODUCTION

The sound power of symphony orchestras is limited, but even in large concert halls audience members expect and demand appropriate loudness and impact. What does this mean for the design of large concert halls? In this paper, “large concert hall” means concert halls with capacities from 1,800 seats to over 2,000 seats, something which is often requested by clients for new-build halls in major cities.

Several concert halls – and still more multi-purpose halls – with insufficient acoustic impact have become well-known examples of acoustically unsuccessful halls: from London’s 5,000-seat Royal Albert Hall to the 3,000-seat multi-purpose halls built in the US during the mid-20th century; London’s Royal Festival Hall and New York’s Philharmonic Hall (then Avery Fisher Hall, now David Geffen Hall). Part of the problem was the focus on reverberation time RT as the main (or sole) design criterion, while the larger seat count and volume drove the sound to become weaker (and the audience seats further away the acoustically important reflection surfaces). Yet W. C. Sabine, the father of reverberation time and of modern room acoustics, in his seminal “reverberation” paper from 1900, had placed loudness first – and before reverberation – in his list of three factors influencing room acoustic quality.

With reverberation time taking “centre stage” during the decades following Sabine’s pioneering work, loudness – and the corresponding criterion of Strength G, with the subdivision into early loudness G_{early} and late loudness G_{late} – was not extensively studied before the second half of the 20th century. Barron[1], based on his subjective and objective studies of British Concert Halls, postulated a Strength requirement of $G \geq 0$dB for a concert hall, in order to have sufficient loudness and acoustical impact. In a subsequent paper[2], Barron analysed the situation in more detail and postulated that all seats in a concert hall should fulfil this requirement of $G \geq 0$dB, not only the hall average Strength for all seats. Achieving $G \geq 0$dB for every seat in a concert hall, including the most distant seats, necessitates the average G of the hall to be at least between 2dB and 3dB, if not more.

This corresponds to typical requirements stated in acoustic briefs for new concert halls: for the 2,400-seat Philharmonie de Paris the acoustic brief[3] required a G of minimum 3dB (average within the hall) and for the planned new 1,900-seat concert hall for the BR Orchestra in Munich, the brief proposed to obtain an average close to 5dB, if possible. To clarify, in this paper all G-values are for the empty, unoccupied concert hall (without audience), since in general objective measurements for G are only available and published for the unoccupied state of the room.

From these requirements for the room average G, and depending somewhat on the specific target for C80, it follows that the average values for both G_{early} and G_{late} must be approximately 0dB to produce large concert halls with sufficient acoustical impact and sufficiently audible reverberation. The question therefore presents itself, to what extent the early and late sound strength must be acoustically optimised, to ensure sufficient acoustical impact and loudness?

2 DISTANCE

In principle, a G_{early} of 0dB should not frighten an acoustician since the definition of G is 0dB at a distance of 10m in free field. This means that the energy of the direct sound, at a distance of 10m, will be 0dB (neglecting seat dip effect), and the acoustics of the concert hall will add some further early energy to the direct sound. But what is the average distance between a source and a receiver in a large concert hall? And, therefore, how much does the room have to add to the direct sound to achieve a sufficient level of early sound?

The average source-receiver distance has been calculated for several typical concert halls of different forms. Let's start with a typical shoebox hall, here the 1,900-seat KKL Lucerne concert hall, and use the hall's dimensions: the length of the hall is 48m, from the organ to the rear wall, and the maximum distance from the last row in the top balcony to the centre of the stage is 43,5m (measured on the centre line using the long section). With a maximum distance of 43,5m, the average distance will be more than 20m – especially as a significant portion of the audience seats are in the four rear balconies, with all seats in the balconies at a distance of more than 30m from the centre of the stage.

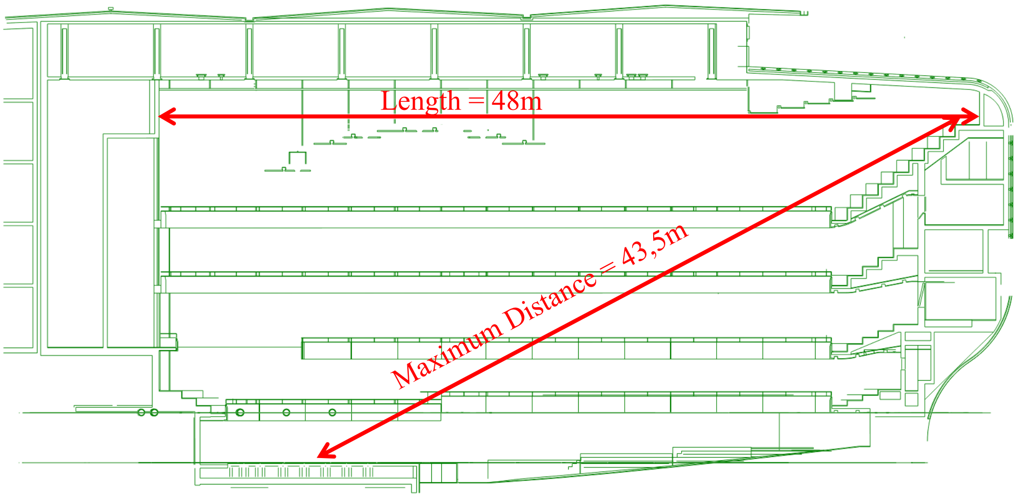

Figure 1: Long section, KKL Luzern. The length of the 1,900-seat shoebox concert hall is 48m and the maximum distance from the last row in the top balcony to the centre of the stage is 43,5m. All rear balcony seats in the hall are at distances of more than 30m, and the average distance between sources on stage and receives in the house is very significantly above 20m.

For the 2,400-seat Philharmonie de Paris, the hall proudly puts forward that the most distant seat is at a distance of only 32m from the conductor's position – significantly less distance than for example in KKL Luzern. For Philharmonie de Paris, a 3D-Rhino model of the hall was used to calculate the average distance from all seats to the centre of the stage. The calculation yields a result of an average distance of 21,5m – still above 20m.

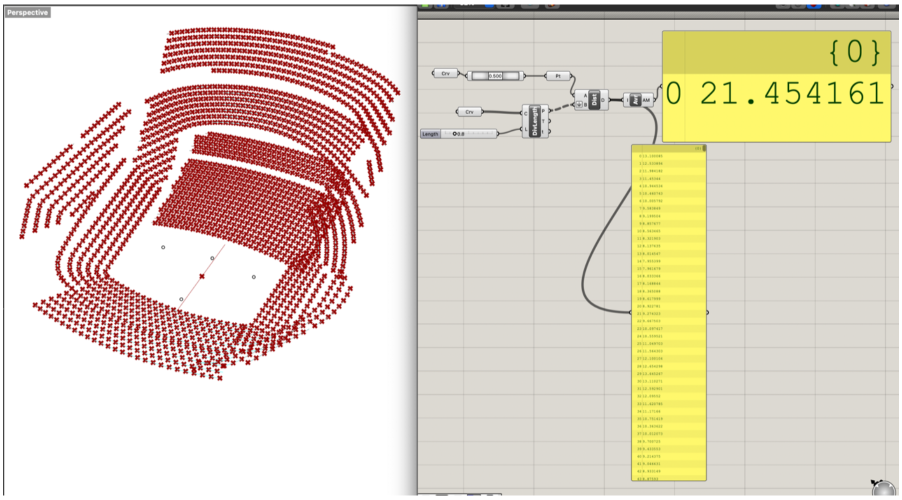

Figure 2: Philharmonie de Paris. 3D-Rhino model of the seats (left) and the result of the calculation of average distance (right). The furthest seat in PdP is at 32m from the conductor, the average distance between audience members and sources on stage is 21,5m, also above 20m.

3 ACCEPTABLE G_{EARLY} AND NUMBER OF REFLECTIONS

The precedent chapter has shown that, for large concert halls, the average distance between sound sources on stage and the listeners' ears in the audience area is more than 20m. For a distance of 20m, the Strength G for the direct sound will be -6dB (doubling of distance with respect to the reference of 10m for G). This means that three additional reflections with arrival time before 80ms would be required to achieve a G_{early} of 0dB, with these reflections each having the same energy as the direct sound. Since the reflections will arrive later than the direct sound and will therefore be weaker (for flat reflection surfaces), it is not possible to create reflections with an equal strength to the direct sound (unless focusing is involved).

Assuming an average arrival time of 60ms for the early reflections (before 80ms), the average increase in path length for reflections will be 20m compared to the direct sound. This results in a reduction in the Strength of each reflection by an additional 6dB (doubling of distance) with a final level of -12dB (again assuming flat reflection surfaces and large surfaces compared to the wavelength). Combining the above, the conclusion is that 12 early reflections each with a Strength of -12dB are required, in addition to the direct sound to achieve a G_{early} of 0dB!

This is where Beranek's Initial Time Delay Gap (ITDG) comes into play: a sufficiently long time interval is required between the initial time delay gap (arrival of the first reflection) and the end of the 80ms integration interval for enough early reflections to arrive[4]. In this respect, a short ITDG can therefore be considered as an acoustical advantage, as this extends the time interval for early reflections to arrive.

The conclusion is that, at least for large concert halls, it is not sufficient to optimize only one or two reflections for each audience seating area, but up to a dozen early reflections have to be ensured and optimised in order to guarantee sufficient loudness and impact.

4 OPTIMISATION OF GEARLY

The preferred order of arrival of reflections is not the main subject of this paper. Experience from project work and other research (see for example Miller[5] and Green[6]) seems to indicate that there should be at least one lateral reflection before the ceiling reflection, and that frontal reflections should arrive earlier than reflections from the rear hemisphere.

Early reflections can be optimised, in number, arrival time, direction and energy, both through first principles of room design or by using computer-aided design. Some acoustical design optimisations are directly linked to room shape or architectural shape and the integration and number of architectural elements. For example, the undersides of side balconies in shoebox concert halls, in conjunction with the side walls, are known to “automatically” create efficient cue ball reflections down towards the main floor parterre seats (known as “cornice” reflections); columns and statues (especially when there is a connection to the underside of a balcony above) are also known to create secondary sound sources through diffraction effects. In the future, reverse engineering as well as design processes using artificial intelligence will most likely further enhance the available solution space available to the acoustician.

In addition, there are two types of solutions that have been found to be useful in recent projects that are often excluded when using computer algorithms. One type of solution utilises cornice reflections. An angle of 90° will always send energy back towards the source, irrespective of the localisation of the source, while cornices with angles slightly above 90° will not send energy back to the source, as shown in the following images – something that can be important for on-stage acoustics design. For halls with several side balconies, a combination of 90° angles and non-90° angles can achieve an extension of the reflection coverage zone to the full width of the stage and main floor parterre seats.

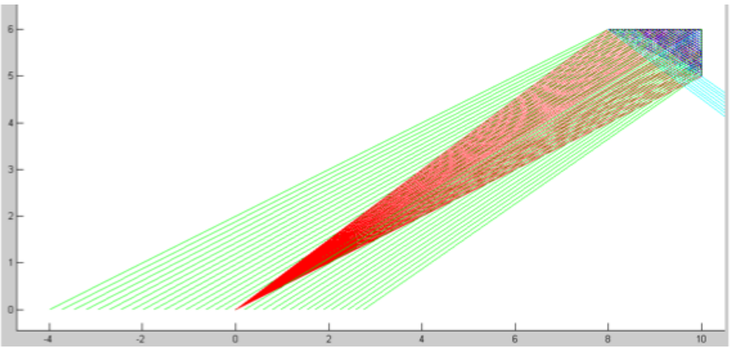

Figure 3: A 90° cornice reflection from the combination of underside of balcony and section of side wall (or vertical downstand). This essentially corresponds to the reflection coverage in a shoebox concert hall in short section.

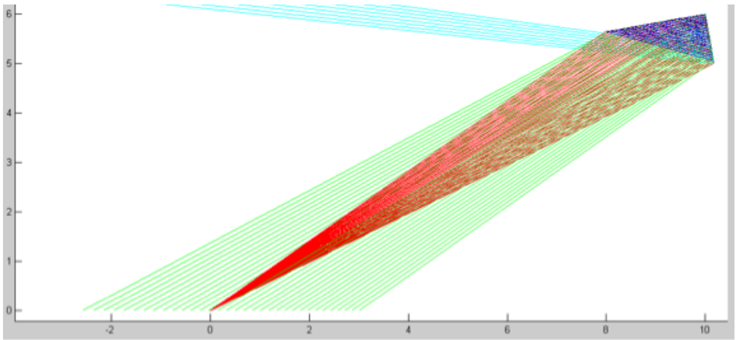

Figure 4: A 90° cornice reflection, rotated. The rotation does not influence the coverage, the sound still goes back towards the source.

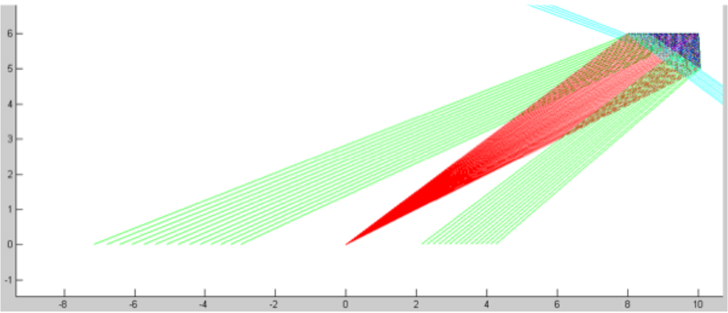

Figure 5: Reflection coverage from a 93° cornice reflection. Reflection coverage is significantly altered, as there is no reflected sound energy back towards the source.

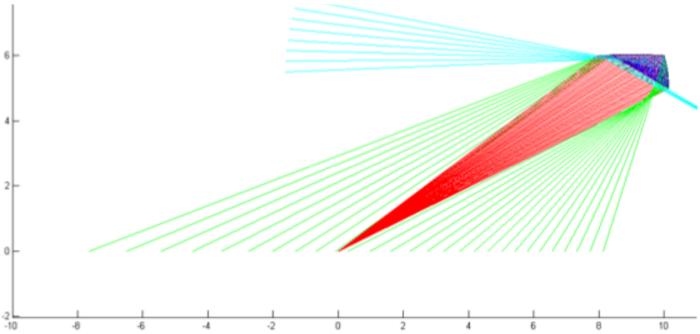

Figure 6: Cornice reflection with both the soffit and the downstand concave curved. The 2nd order reflection coverage is increased to the full width of the stage or main floor parterre. A similar coverage can be obtained with a rotated convex reflector, using 1st order reflections.

Another type of useful solution involves curved surfaces: both convex and concave surfaces have been found to be highly interesting and helpful acoustically. Curved surfaces are often ignored in computer programs as the image source method and many efficient, whole-room ray-tracing methods cannot easily be generalised to incorporate curved surfaces.

Convex-curved surfaces enlarge the zone of coverage, creating a more homogeneous coverage while preserving phase and facilitating the integration of the reflection with the direct sound by the human auditory system. In addition, for reflectors of limited size, the application of convex curvature can be beneficial to balance the strength of the high-frequency content (reduction due to the convex curvature) with the strength of the low-frequency content (reduction due to attenuation by diffraction around the limited size of the reflector). This is treated in more detail in a parallel paper by Green[7].

5 OPTIMISATION OF G_{LATE} AND RT/EDT

With the early sound optimised, how can we also make sure that there will be enough energy left for the late sound and the reverberation of the room, in particular as the reverberation should not only be measurable (and audible for stopped chords) but also be sufficiently audible during running music?

One aspect is to ensure that the early energy design is as efficient as possible, thereby reducing “the price to pay” for these reflections and leaving sufficient energy for the late sound. Jurkiewicz[8] has shown that the necessary early reflection energy is reduced when the reflections arrive from a moderate azimuth (“from low in the room”), since a reflection surface of identical size then covers a larger number of audience members. This reduces the solid angle (as seen from the source) required to create sufficient early reflection coverage, while reserving a sufficient solid angle for the generation of late-arriving sound.

Furthermore, from a perceptual point of view, late-arriving and reverberant sound should envelop the listeners, in other words the "acoustic centre" of the reverberation should be around the listeners (placing the listeners in the centre of the reverberation) rather than around the musicians on stage – see Figure 7 for an illustration of this concept. In addition, as later reflections should also, at least in part, arrive from the rear hemisphere, this suggests that a significant portion of the solid angle seen from the source directed towards the rear of the room should be reserved for late reverberation.

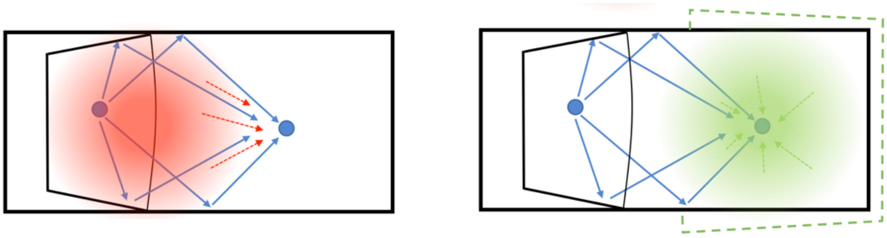

Figure 7: Illustration of the concept of "acoustic centre". In both illustrations the stage and source are on the left with audience positions on the right. Left: when insufficient late sound energy reaches listeners from the rear hemisphere, the "acoustic centre" of reverberation is localised on stage. Subjective envelopment tends to be reduced. Right: Through geometric adaptations to the hall – here a conceptual increase in the volume around the audience – the "acoustic centre" can be displaced to enhance subjective envelopment around the audience.

Discrete reflections arriving after 80ms can also be geometrically optimised in the same manner as early reflections. As shown by Green[6], reflections arriving after 80ms should arrive laterally and/or from the rear hemisphere in order to maximise their positive effect on envelopment.

Finally, two aspects should be considered concerning the late reverberation: Firstly, delaying reverberant energy tends to make this energy more audible, as the masking of the late sound by the direct sound (and early reflections) is then decreased. Secondly, concerning objective acoustic criteria as design parameters, EDT should be preferred over RT as the design parameter for reverberance. Barron[9] has shown that EDT is better correlated with the subjective listening impression of reverberance and the criterion EDT takes the energy content of the late reverberation into better account than the RT.

6 CONCLUSIONS

The average distance between sources on stage and listeners in the audience areas in large concert hall is greater than 20m. This has significant implications on the optimisation of early reflections, as the Strength of the direct sound is significantly reduced compared to the reference distance. In order to create sufficient early strength and impact, it is not sufficient to design only one or two reflections arriving within 80ms after the direct sound: the early-arriving energy necessary for this is equivalent to the order of one dozen reflections. To ensure a sufficiently audible late tail and reverberation, both the early reflection design must be as efficient as possible and a large portion of the solid angle of the source radiating towards the rear of the room should be reserved for the generation of enveloping reflections and late reverberation. The "acoustic centre" of the late reverberant tail should ideally be surrounding the listeners rather than surrounding the sources, creating a better perceptual separation between the source stream (from the stage) and the room stream (around the audience). To ensure that the late tail remains sufficiently audible, EDT should be considered as the primary objective criterion related to subjective reverberance rather than RT.

7 REFERENCES

1. Barron M., When is a concert hall too quiet? Proc. 19th ICA. Madrid (2007).
2. Barron M. Then and now - how concert hall design of the 1960s/ ’70s compares with the present. Proc. NAG/DAGA, Rotterdam (2009).
3. Kahle E., Jurkiewicz Y., Faillet N., Wulfrank T., Katz BFG., La Philharmonie de Paris Concert Hall competition, Part 1: acoustic. Proc. ISRA Seville (2007).
4. Beranek, L., personal communication and oral presentation, 147th ASA meeting, New York (2004).

5. Miller, G., Giegold, C., Pfeiffer, S., Schuette, D/, Brill, L. Orchestral Preferences for Discrete Overhead and Side Wall On-Stage Reflections, Proc. ISRA Amsterdam (2019).
6. Green E., Kahle E., Berrier V., Carayol E., Beyond 80ms: The Subjective Effects of Sound Energy Arriving Shortly After the “Early” Sound Period. Proc. ISRA Amsterdam (2019).
7. Green E., Colella Gomes O., Berrier V., Wulfrank T., Kahle E., The Influence of Reflection Surface Size in Concert Halls. Proc. Auditorium Acoustics, Athens (2023).
8. Jurkiewicz Y., Wulfrank T., Kahle E., Architectural shape and early acoustic efficiency in concert halls. JASA, 132, (2012)
9. Barron M., Auditorium Acoustics and Architectural Design, FN Spon (2009).