LA PHILHARMONIE DE PARIS – ACOUSTIC SCALE MODEL STUDY

BFG Katz Audio Acoustics Group, LIMSI-CNRS, Orsay, France
Y Jurkiewicz Kahle Acoustics, Brussels, Belgium
T Wulfrank Kahle Acoustics, Brussels, Belgium
G Parseihian Audio Acoustics Group, LIMSI-CNRS, Orsay, France
T Scélo Marshall Day Acoustics, Hong Kong, China
H Marshall Marshall Day Acoustics, Auckland, New Zealand

1 INTRODUCTION

Opened in January 2015, the new Philharmonie de Paris concert hall (Philharmonie 1) follows a modern complex architectural form, far from traditional shoebox designs. To complement numerical simulations, a 1:10 scale model was commissioned in order to evaluate various elements of the design. The interconnected nature of the architectural design, with floating balconies and surrounding volumes, raised a number of questions concerning the later portion of the acoustic response in the hall during the design phase. Investigation of late components necessitated significant dynamic range or signal-to-noise in the measurement chain in order to analyze the responses beyond early reflections and initial decay that is typically studied with scale models. This paper presents that part of the acoustic scale model study commissioned by the lead acousticians, Marshall Day Acoustics, and results of analysis. The use of professional audio hardware as compared to traditional test equipment and a miniature impulse source was investigated.

2 DESIGN OVERVIEW

The design brief for the 2500 seat Philharmonie de Paris concert hall did not specify a specific geometrical form, but did include a full set of acoustic criteria. Details of these criteria and their limits can be found in the acoustic brief.[1,2] A need was clearly expressed for "innovation and modernity in concert hall design", stating that "acoustic design should not be conservative and rigidly attached to conventions". The need for both clarity and reverberance indicated the need for some type of interconnected volume design. Arrays of large reflectors or the use of coupled reverberation chambers could create such conditions.[3]

The winning design, architect Jean Nouvel and acoustician Marshall Day Acoustics, proposed nested spaces: a single volume design with floating balconies and ceiling reflectors to create subdivisions of the volume. Contrary to traditional reverberation chamber design, the coupling areas were not variable but fixed, defined by the balcony designs. Variable absorption was included in the outer volume to provide variable acoustics. Additional details are described in a companion paper.[4]

As this proposed design was far from conventional, various design tools were employed by the design team to refine the details over the course of the project. These included geometrical acoustic computer simulations[5,6], architectural feature criteria[7], and finally a 1:10 acoustic scale model. Recent studies have highlighted similarities and discrepancies between numerical simulations and scale model measurements in the case of coupled volumes.[8,9] The use of all these methods was deemed essential for the elaboration of such a challenging design.

3 OBJECTIVES

Prior to a project design workshop in December 2008, Marshall Day Acoustics requested a series of measurements to be carried out in the scale model to investigate a number of points. First and foremost, it was desired to have an estimation of the objective acoustic parameters as specified in the design brief. These results can then be compared to the computer simulations, aiding in the calibration and use of such simulations. Such combined results would allow for the verification of the design with respect to the brief. As a specific point, the measurements were required to investigate the acoustic coupling between the inner and outer volumes, in order to determine if their design would achieve their acoustic goals.

Nagata Acoustics were instructed to carry out the model testing with the undertaking that they would provide Marshall Day with the measured impulse responses for further analysis. In the event Nagata Acoustics failed to fulfil this requirement, that situation necessitated the measurement campaign described here. This study was therefore separate from the scale model studies carried out by the Nagata team which focused primarily on low order reflections and geometry conditions to optimize balcony front and reflector shaping designs.

Scale model measurements were carried out over two 2-day sessions in 2008. This paper provides an overview of the measurements and conclusions drawn with regards to the design process.

4 SCALE MODEL

As part of the design brief a 1:10 acoustic scale model was constructed for testing purposes (see Figure 1, additional model images are available on the constructor's website[15]). Taking into account the scale factor and the desired frequency range of interest for room acoustic parameters (63 – 4000 Hz octave bands, extending to 8000 Hz if possible), the corresponding frequency range of interest in the model measurements was 500 Hz – 100 kHz.

In order to investigate the acoustic coupling between the inner and surrounding volumes, the effective coupling surface area was varied. This was carried out in order to better understand the effective degree of coupling of the design and to determine if the coupling area, which is not variable in the hall as built needed to be modified in the design.

Semi-rigid plastic plaques were constructed based on the 3D computer model of the hall in order to modify the coupling areas between the 1st and 2nd balcony and between the 2nd balcony and the ceiling (see Figure 1). Depending on the number of installed plaques, the coupling area was varied [0, 50, 70, 100% of the concerned surfaces].

Preliminary results in the 100% closed condition found the reverberation time in the hall to be significantly higher than the design guidelines. In general, the model construction, while very solid, did not represent a comparable acoustic absorption to the design. As such, addition absorption, blankets, were placed over significant portions of the audience area, while still allowing access to the various microphone locations associated to cable routes through the model (see Figure 1).

While the model was constructed to allow for operation in a sealed nitrogen atmosphere, to control for high frequency air absorption, the measurements performed here did not make use of this feature. This was due to the additional safety requirements which were incompatible with the numerous interventions within the model necessary for the coupled surface study. Instead, a compensation filter was applied to the measured RIR to account for air absorption. For each measurement, the temperature and relative humidity inside the model were measured (Velleman DVM321) and the barometric pressure was noted from a B&K piston-phone barometer. From this data, a time-frequency dependent gain function was calculated and applied to the RIR prior to resampling to full scale RIR from which acoustic parameters were derived.[10]

Figure 1. Model interior. Additional absorption and installation of coupling surface closures.

5 MATERIAL

The measurement protocol employed the Swept Sine method, chosen for its improved SNR and robustness to distortions in the sound source, which can occur at high output volumes. The sweep was a 0.5 sec logarithmic sweep, from 500 Hz to 90 kHz. 20 repetitions of the sweep were performed, with the results time aligned and averaged, in order to improve the SNR. The entire measurement and analysis was carried out using MatLab. Several source-receiver material configurations were employed in the measurement session.

5.1 Sources

A high frequency audio tweeter (12.5 mm diameter, 80 W max, Fenton CT-25) was selected as a viable source. The protective grill over the dome was removed to allow radiation of high-frequency energy and reduce directivity variations. The directivity of this source was relatively constant, with a reduction of 2–8 dB at 60° off-axis, 7–15 dB at 90°, from 630 Hz – 80 kHz octave bands. The tweeter was placed on the stage, pointing upwards. It was noted that the output power of this source was somewhat limited.

Due to the goal of investigating the effect of coupling area, it was necessary to obtain a high dynamic range in the measured RIR. As such, a high SNR was required. After trials with different HF sources, it was determined that in order to obtain the SNR desired it would be necessary to relax the “point source” assumption, while still attempting to maintain omnidirectionality.

Inspired by a previous study[11] which recommends that a tetrahedral source is advantageous over a dodecahedral source when one is concerned by frequencies with small wavelengths compared to source diameter, a tetrahedral source was constructed using three high-power tweeters (25 mm diameter, 100 W max), with the fourth face resting on the stage. The tetrahedron was 14.5 cm high, with the tweeter centers at a height of 6 cm.

Employing ISO 3382[12] regarding permissible variations in directivity as criteria for omnidirectional sources, which we have adapted according to the scale of the model, the constructed source slightly exceeds the requirements (see Table 1 and Figure 2). It was concluded however that the SNR requirements for investigating the late tail of the RIR (1) was the principal goal and (2) would not be seriously affected by small variations in source directivity.

The audio source was connected to an audio power amplifier (Samson Servo 120a, 120 W @ 1000 Hz). This amplifier was found, surprisingly, to operate well above the audible frequency range, with only a 10 dB drop from 10 kHz to 90 kHz, followed by a sharp cutoff.

As a final source option, a miniature blank pistol (Berloque Pistol, Gerhard Göbharter GmbH Mech. Werkstätte) was employed (see Figure 3). This 4 cm single shot pistol has a 2 mm barrel diameter, providing an omnidirectional source comparable to starter pistols in full scale measurements. Comparable to a spark source, the sound power output of the pistol was significantly greater.

Table 1. Characteristics of the tetrahedral source compared to 1:10 extrapolated ISO 3382 criteria.

Octave band center frequency, Hz		1250	2500	5000	10000	20000	40000	
ISO permissible variations, dB		± 1	± 1	± 1	± 3	± 5	± 6	
Octave band center frequency, Hz	630	1250	2500	5000	10000	20000	40000	80000
Measured variations, dB	± 2.5	± 3	± 5	± 5	± 3	± 7	± 7	± 7

5.2 Receivers

A pair of omnidirectional miniature microphones (1/8" diameter, GRAS 40DP) were used as reference measurement microphones. This microphone model, connected via a preamplifier (GRAS 26AC) and signal conditioner (B&K Nexus 2690), offered a flat response up to 100 kHz. The directivity of this microphone was verified, with only 5 dB attenuation at 90° off-axis in the 80 kHz band. As there is little expected energy arriving from below in the model, the microphone was mounted vertically at head height (see Figure 4).

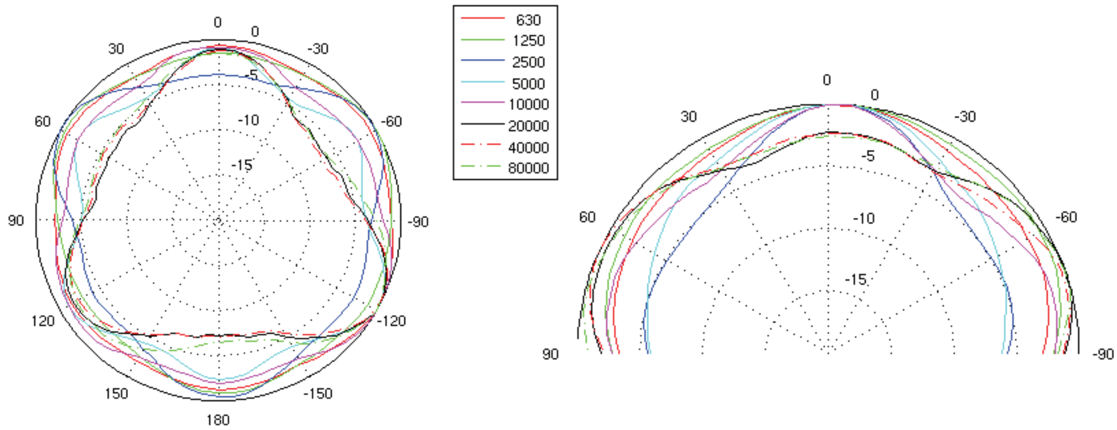

Figure 2. Tetrahedral source directivity patterns in the horizontal and vertical planes.

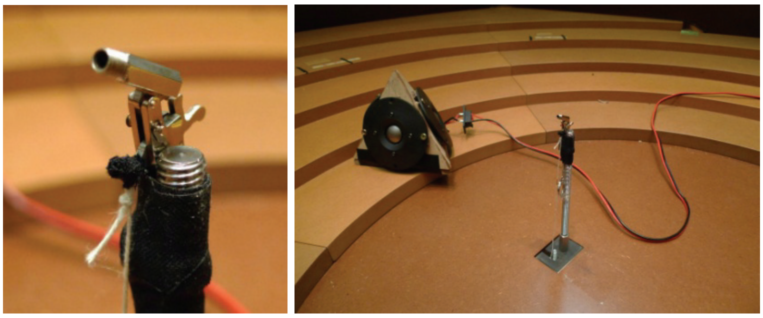

Figure 3. (left) Miniature blank pistol. The pistol was mounted on the model's stage trap door with a string attached to the trigger allowing it to be activated from outside the model by an operator situated under the model. (right) Miniature pistol and tetrahedral sources in the scale model.

A secondary receiver chain was included. A pair of miniature omnidirectional microphones (5.4 mm diameter, DPA 4060) typically used in professional audio conditions were employed. Despite their stated frequency range of 20 kHz, their response was found to drop only 35 dB from 20 to 70 kHz when compared to the GRAS 40DP. While not flat, their increased sensitivity (20 mV/Pa vs. 1.11 mV/Pa) when compared to the measurement microphone offered certain advantages. The microphone pair was installed in a modified audience member in order to produce a simplified dummy head construction, allowing for the determination of the Inter-aural cross correlation (IACC), while noting that the dummy head had no pinnae, comparable to a sphere stereo microphone.

Source and receivers were connected to an audio interface (RME, Fireface 800) operating at a sample rate of 192 kHz. The two GRAS 40DP were connected via the Nexus conditioner as line level inputs. The two DPA 4060 were connected as microphone inputs, benefiting from the phantom power and microphone preamplifier. A final input channel was connected as a loop back from the amplifier to provide a reference stimuli signal for the sweep deconvolution. Receiver positions in the model are indicated in Figure 5.

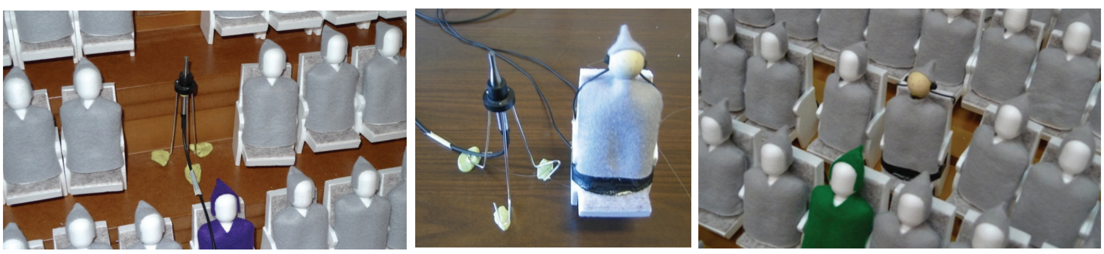

Figure 4. Images of the DPA 4060 dummy head and GRAS 40DP omnidirectional microphones.

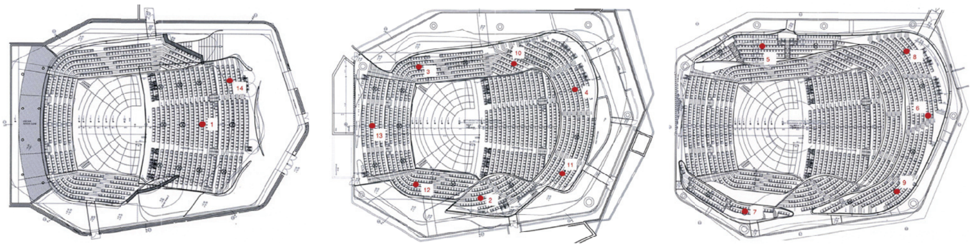

Figure 5. The 14 measured receiver positions indicated by red dots.

5.3 Signal-to-Noise ratio

There was a definite effect on the measurement chain with regards to the obtained SNR in the measured RIR (see Figure 6). Using the simple audio tweeter and the reference measurement microphone, an SNR of 35 dB was attainable for an example distant position in the second balcony. Using the tetrahedral source, an SNR of 50 dB was attainable. Using the pistol source improved the SNR by 10 dB, although at the expense of repeatability between measurements. Using the high sensitivity pro-audio microphones improved the SNR by another 10 dB. It was not possible to obtain results using the DPA4060 and the pistol as the produced sound pressure level was too excessive for these microphones, resulting in microphone saturation. The coupled volume response of the hall should be able to be clearly examined with the obtained 70 dB of reverberant decay.

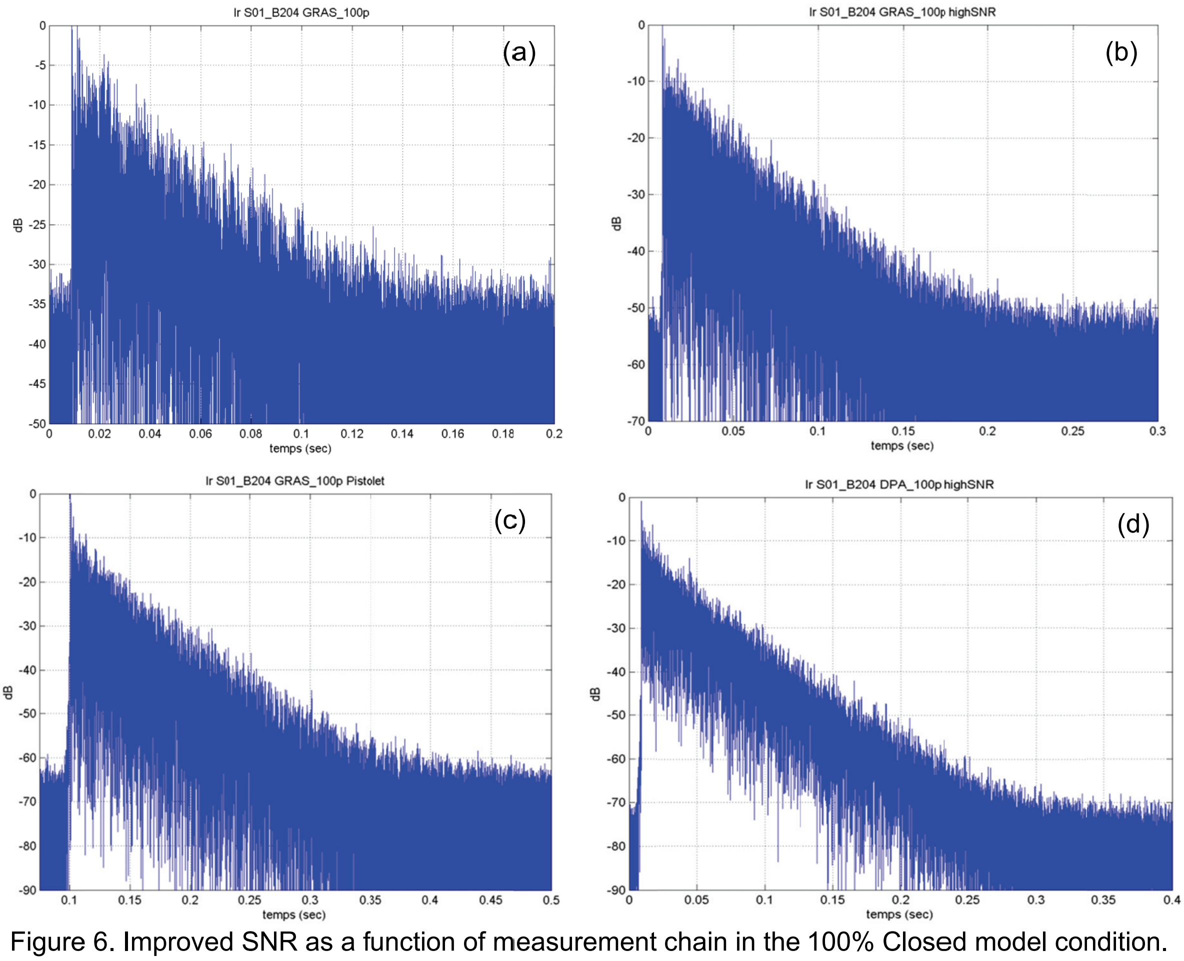

Figure 6. Improved SNR as a function of measurement chain in the 100% Closed model condition.
(a) GRAS & Tweeter, 30 dB; (b) GRAS & Tetra source, 50 dB;
(c) GRAS & Pistol, 60 dB; (d) DPA & Tetra source, 70 dB.

6 ACOUSTIC PARAMETER RESULTS

Table 2 compares the scale model results with the criteria set in the Acoustic brief for the main parameters for the symphony mode. Certain parameters in the brief were specified in the “Unoccupied” condition. However, while the model was available only in the “Occupied” condition, the total absorption achieved was less than was predicted for the constructed room, thereby corresponding more to a semi-occupied condition. As such, the values may be inferred from the measured values in the model with reasonable accuracy and checked via computer simulations. Global values are averaged for comparison with the brief.

Table 2. Summary results at mid frequency (average of 500 Hz and 1 kHz). Symphony mode concerns the configuration of the stage risers and reflector “clouds” over the stage.

Acoustic Parameter	Brief for Symphony Mode	1:10 Scale Model Semi-Occupied room & bare stage
RT - Occ. with orchestra	Mean 2.2 – 2.3 s	2.67 s
C80	Unoccupied –3 to 0 dB	–0.1 dB
G	Unoccupied 3 – 6 dB	3.5 dB
G_{late}	Unoccupied 0 to –4 dB	0.41 dB
G_{early} (80ms)	Unoccupied –2 to +2 dB	0.34 dB
1-IACC[E, mid]	Unoccupied Mean > 0.55 > 0.50 for at least 80% seats	Mean 0.71 >0.50 for 87% of seats measured

Reverberation Time (RT) – The reverberation time measured in the model is higher than required in the brief. As discussed above, the residual absorption from the “hard” surfaces in the real room will be greater than that of the model. Based on these measurements, however, it was estimated that a reverberation time of 2.2 – 2.3 s could be achieved in the real room.

Strength/Loudness (G) – The measured values of loudness are high for a room of this volume. In the fully occupied room with an orchestra on stage, one would expect the values will be lower. The loudness will be favorable if G in the fully occupied room (with orchestra) is greater than 0 dB at most seats. Based on the measured values and computer simulations this can expected to be the case.

1-IACC – The values measured in the scale model using the miniature spherical dummy head are uniformly high and comfortably comply with the brief.

Clarity – Clarity values generally increase slightly with reduced RT, and decrease slightly with increased RT. Based on the scale model measurements, the unoccupied clarity values in the real room can be expected to comply with the brief. In the fully occupied room with an orchestra on stage an average clarity value around 0 is predicted. This is a favorable and consistent with the intentions to achieve good clarity.

Coupling – The design consists of two acoustic “coupled” volumes. Definition of the coupling area is difficult in such a complex room shape and it was intended that the model study would clarify effects too difficult to calculate in the light of this uncertainty. Table 3 summarizes these results. Four conditions were studied: Coupling area fully open, 50%, 70%, and 100% fully closed.

As the coupling area is reduced, the reverberation time measured in the inner volume decreased and the corresponding reverberation time in the outer volume increases, as expected.

G_{late} remained approximately constant down to 50% opening and then declined. G_{early} similarly remained about the same with only a small rise and fall as the opening is closed, again as expected as the Strength of the sound will be largely controlled by the early reflections. The change in C80 is negligible for the same reason. With the coupling area reduced by 50% there is good balance between the early and late G values and a subjectively noticeable increase in RT in the outer volume relative to the inner volume.

Table 3. Summary results at mid frequency for different coupling area conditions.

	Coupling opening condition			
	All open	50% Closed	70% Closed	100% Closed
RT inner vol.	2.65 s	2.61 s	2.56 s	2.37 s
RT outer vol.	2.78 s	2.82 s	3.08 s	3.53 s
G	3.5 dB	3.5 dB	3.6 dB	3.3 dB
G_{late}	0.41 dB	0.37 dB	0.09 dB	–0.05 dB
G_{early}	0.34 dB	0.38 dB	0.79 dB	0.20 dB
C80	–0.1 dB	0 dB	0.7 dB	0.2 dB

Overall, the acoustical effect of the coupled spaces on measured acoustic parameters in the model was less than expected. The effect would be increased by any changes that reduce the coupling area, increase the outer volume, and decrease the inner volume (width). Room modifications that would achieve this and reduce the coupling area to about 50% were recommended.

7 CONCLUSION

A complete set of measurements in the scale model allowed for verification of the acoustic performance of the design phase as-built model against the acoustic brief for the real room. In this complex space the 1:10 scale model study provided measured data confirming that predictions to date were adequately accurate and that the brief was met in the model design and its modifications.

It is the opinion of the authors that without this scale model measurement campaign the acoustic performance of the Philharmonie de Paris would have remained a matter of computer prediction with its relative uncertainty. The measurements carried out led to the following:

- Derivation of the objective parameters as specified in the Acoustic Brief.
- Verification that the design functions as intended in the Acoustic Brief.
- Determination of the appropriate balance between inner/outer volumes, coupling opening and absorption.
- Comparison and validation of the design teams computer simulations.

While the scale model measurements were useful during the design stage, it must be emphasized that the acoustic properties of the model were rather different than the final constructed hall, as was mentioned earlier. As such, there were many details of the acoustics which could not be adequately predicted in the model, for which the numerical simulations can be better suited, being more flexible to design modifications and iterations.

The final constructed hall is a result of these numerous design iterations, for which the scale model was just one. In addition, recent studies concerning coupled volumes have shown that the audible acoustic effect of coupled spaces is much stronger than the effect on traditional room acoustic parameters.[13] Details concerning the final hall design can be found in a companion paper.[14]

Acknowledgments - The authors would like to thank all those who assisted with achieving these measurements within the allotted time. Specific thanks are offered to Nagata Acoustics and the Philharmonie de Paris for organizing the access to the model on the available dates. Additional thanks to Richard Denayrou, Altia acoustique, for his help, limberness, and flexibility in working inside the model.

8 REFERENCES

1. E. Kahle, Y. Jurkiewicz, N. Faillet, T. Wulfrank, and B. Katz, “La Philharmonie de Paris concert hall competition, part 1 : Acoustic brief,” in Intl. Symp. on Room Acoustics (ISRA), (Sevilla), pp. 1–6, 2007.
2. E. Kahle, N. Faillet, T. Wulfrank, and Y. Jurkiewicz, “Philharmonie de Paris – the acoustic brief,” in Intl. Conf. on Auditorium Acoustics, (Paris), Institute of Acoustics, Nov. 2015.

3. E. Kahle, T. Wulfrank, Y. Jurkiewicz, N. Faillet, and B. Katz, "La Philharmonie de Paris concert hall competition, part 2 : The competition," in Intl. Symp. on Room Acoustics (ISRA), (Sevilla), pp. 1–6, 2007.
4. H Marshall and C. Day, "The conceptual acoustical design for La Philharmonie de Paris, Grand Salle," in Intl. Conf. on Auditorium Acoustics, (Paris), Institute of Acoustics, Nov. 2015.
5. T. Scelo, H. Marshall, and J. Valentine, "Theoretical considerations in the prediction of decay times for the Philharmonie de Paris," *J. Acoust. Soc. Am*, vol.123(5), p. 3911, 2008, doi:10.1121/1.2935913.
6. H. Marshall, J. Valentine, and T. Scelo, "Acoustical considerations in the design for 'La Philharmonie de Paris'," *J. Acoust. Soc. Am*, vol. 123(5), p. 2973, 2008, doi:10.1121/1.2932464.
7. Y. Jurkiewicz and E. Kahle, "Early reflection surfaces in Concert Halls - a new quantitative criterion," *J. Acoust. Soc. Am*, vol. 123, pp. 3908-3908 (2008), doi:10.1121/1.2935902
8. P. Luizard, J.-D. Polack, and B. F. Katz, "Sound energy decay in coupled spaces using a parametric analytical solution of a diffusion equation," *J. Acoust. Soc. Am*, vol. 135, pp. 2765–2776, 2014, doi:10.1121/1.4870706.
9. P. Luizard, M. Otani, J. Botts, L. Savioja, and B. F. Katz, "Comparison of sound field measurements and predictions in coupled volumes between numerical methods and scale model measurements," in Proc. of Meetings on Acoustics, vol. 19, (Montreal), pp. 015114:1–9, June 2013, doi:10.1121/1.4799138.
10. J-D Polack, X. Meynial, and V. Grillon, "Auralization in Scale Models: Processing of Impulse Response," *J Audio Eng. Soc*. vol. 41(11), pp. 939-945, 1993.
11. T. Leishman, S. Rollins, & H. Smith. "An experimental evaluation of regular polyhedron loudspeakers as omnidirectional sources of sound." *J. Acoust. Soc. Am*, vol. 120(3), pp. 1411-1422, 2006, doi:10.1121/1.2221552
12. ISO 3382-1:2009, "Acoustics—Measurement of room acoustic parameters. Part 1: Performance spaces" (International Organization for Standardization, Geneva, Switzerland, 2009).
13. P. Luizard, B. F. Katz, and C. Guastavino, "Perceptual thresholds for realistic double-slope decay reverberation in large coupled spaces," *J. Acoust. Soc. Am*., vol. 137, no. 75, pp. 75–84, 2015, doi:10.1121/1.4904515.
14. T. Scélo, J. Valentine, H. Marshall, and C. Day, "Implementing the acoustical concept for La Philharmonie de Paris, Grand Salle," in Intl. Conf. on Auditorium Acoustics, (Paris), Institute of Acoustics, Nov. 2015.
15. http://www.ackermanngmbh.de/index.php/en/projects/philharmonie-de-paris.html, Georg Ackermann GmbH, last visited 02-Sep-2015.