The Philharmonie de Paris - Acoustic design and commissioning

Christopher Day[1], Harold Marshall[1], Thomas Scelo[2], Joanne Valentine[1] and Peter Exton[3]

[1]Marshall Day Acoustics, Auckland, New Zealand
[2]Marshall Day Acoustics, Honk Kong
[3]Marshall Day Acoustics, Melbourne Australia

ABSTRACT

30 years in the planning and 8 years in the design and construction, the Philharmonie de Paris, Grande Salle opened in January 2015. The 40 page acoustic brief, prepared by Eckhard Kahle, was probably the most comprehensive acoustic brief ever written for a concert hall. The brief called for great clarity and high reverberance, considered by some to be mutually exclusive, and specified more than 10 acoustical parameters to be achieved in the room. The architectural brief also stated; 'The design must be a new typology: it could not be a shoebox, vineyard, fan or arena shaped hall.' The design team headed by French architect, Jean Nouvel and lead acoustician, Sir Harold Marshall, conceived the room during a synergetic design workshop with the architect, acoustician and theatre consultant working in a highly collaborative environment. The concept design for the Philharmonie aimed to balance early and late acoustic energy by nesting an intimate audience chamber within a larger acoustic volume. The complex geometry of the hall, with its inner and outer volumes with multiple curved surfaces, was beyond the capabilities of common acoustic simulation packages and processors. New technologies in 3D modelling and parametric design were developed along with an interactive approach, followed by the formal acoustic simulation in ODEON. The latter was subsequently validated by a physical scale model study. This paper presents the steps in the acoustic design process and the tools used to deliver a radical but successful design. Commissioning the Grand Salle of the Philharmonie de Paris was never going to be straight forward due to its multiple uses, encompassing classical symphonic, choral and recital repertoire, contemporary music, Jazz, and World Music. Add in highly adaptable stage and seating arrangements, and the mechanics of making these changes, and a protracted series of measurements both occupied and unoccupied, were inevitable. Complicating this task have been cost overruns, construction delays, politics and an extensive programme booked out months in advance. The measurements were made in a series of brief windows of availability, using the MDA-developed IRIS system. The Philharmonie opened on the 14 January 2015, after many weeks of 24 hours a day construction. The building however was incomplete and the architect refused to attend in protest. Reviews by musicians and the press are summarised in the paper.

1. INTRODUCTION

The Philharmonie de Paris was the vision of the late Pierre Boulez - the potentate of late-twentieth-century music, who dreamed of launching a “Centre Pompidou for music” in the Parc de la Villette. The dream has come to fruition, with the Philharmonie forming part of a music precinct which includes the Cité de la Musique and the Conservatoire de Paris. The Philharmonie is located in the Nineteenth Arrondissement on the border between central Paris and the eastern suburbs in an attempt to ‘bring the music to the people and bring the people to the venue’. This move was controversial as the élite regular concert goers from the centre of Paris would have to travel 20 to 30 minutes to hear the symphony rather than walk. However, advance ‘sell out’ performances throughout the first year of operation, with a high ratio of new audience, have proved the concept a success.

The project gained critical momentum at the beginning of this century led by Laurent Bayle, the head of the Cité de la Musique with financial backing from the City of Paris and the Ministry of Culture. A comprehensive architectural and acoustic brief was prepared to form the basis of an international selection process for the design team.

2. PROJECT BRIEF

In 2006 the project brief was published along with a request for ‘expressions of interest’. 98 teams submitted including teams led by international architects Frank Gehry, Zaha Hadid and Jean Nouvel. Nouvel contacted Harold Marshall following a recommendation that Marshall Day Acoustics (“MDA”) had a reputation for responsible innovation in concert hall design. The project documentation was the most comprehensive our team had ever seen and contained an Architectural Brief and an Acoustic Brief, the ‘Programme Acoustique’.

2.1 The Architectural Brief

The Architectural brief, 'Le Programme General', consisted of a 153 page document plus a further 14 Appendices. The brief was reasonably specific without wanting to stifle the creativity of the design team. The requirements included; *'the hall is to be highly adaptable and suitable for symphony, jazz, rock and world music', 'the hall is to be a surround hall with significant audience behind and beside the stage (in symphony mode)'* . This strong directive from the Client was supported by the comment*, 'The objective here is to limit the distance between the audience and the musicians by installing the latter at the heart of the auditorium amongst a present and perceptible audience that will share the musician's feelings (the complete opposite of the frontal and exclusive relationship is required).'* Clearly the Client was not after a conservative concert hall with an end stage for this project.

The following table summarises the various physical parameters specified in the Architectural Brief and the Acoustic Brief.

Table 1: Table summarising the Architectural/acoustical criteria

Criteria	Requirement
Volume per person of the audience	Ideal: between 12m^3 and 13m^3 Acceptable: between 11m^3 and 14m^3
Total volume	Approx. 30000m^3 (between 28000 and 32000m^3)
Reflective surfaces	1400m^2 including 500m^2 close to the musicians (less than 15m from a point on the stage).
Height of the auditorium	The height to obtain 30,000m^3 Can be greater than 20m The ceiling will not necessarily be flat
Height of over-stage reflectors	Variable between 10m and 16m
Variable acoustic absorption (curtains and other mobile elements)	Greater than 1200m^2 of deployable absorbing material
Maximum distance from conductor to furthest listener	38m, preferably no greater than 35m

A number of these criteria were quite radical – notably the volume of 30,000m^3 is approximately 50% larger than existing halls of similar seating capacity.

The last criterion in the table is interesting in that a rectangular shoebox hall with similar seating capacity would have a 'conductor to furthest listener distance' of well over 40m. Clearly the Client was requiring significant visual intimacy.

However, the most significant and courageous requirement from the Brief was; *'This design must be a new typology – it cannot be one of the existing concert hall forms; shoebox, vineyard, fan or arena.'* What an exceptional challenge for the design team!

2.2 The Programme Acoustique

The Client's acousticians, Eckhard Kahle and Richard Denayrou, were deeply involved with the preparation of the brief. The 40 page acoustic brief or 'Programme Acoustique', is probably the most comprehensive acoustic brief ever written for a concert hall. The document included a comprehensive summary of the current state of knowledge in the acoustical design of auditoria. The brief required great clarity and high reverberance – thought by some acousticians to be mutually exclusive. In addition to these general requirements and the architectural criteria, the brief also specified more than 10 objective acoustical parameters to be achieved in the room. Certainly the most comprehensive design brief the Marshall Day team has ever experienced.

Table 2: Summary of acoustical criteria

Criteria	Value
RT	Mean between 2.2 and 2.3s when the variable acoustic absorption is completely compensated for (*full house with complete orchestra*) Mean between 1.4 and 1.6s when the variable acoustic absorption is maximum (*empty auditorium*) Mean between 1.2 and 1.4s when the variable acoustic absorption is maximum (*full house, empty stage*)
G (amplification of the room, loudness), empty room	Mean between 3 and 6dB. The variation with respect to the position of the source and receiver (ΔG) must be ±3dB. Acoustic variability (mean of G using the variable acoustic features) must be greater than 2dB.
G80, empty room	Mean between -2 and +2dB. Required variability: >3dB.
G[80ms,∞], empty room	Mean between 0 and 4dB. Required variability: >1.5dB
C80, empty room	Mean between -3 and 0dB. Required variability: >2dB
LF, empty room	Mean > 0.16 And >0.15 for at least 80% of the seats.
1-IACC,empy room	Mean >0.55. And >0.5 for at least 80% of the seats.
Bass ratio, full house	Between 1.1 and 1.3.
Treble ratio, full house	Between 0.9 and 1.0 at 2kHz and between 0.75 and 0.85 at 4kHz.
ST1, full house	Mean between -17dB and -13 dB Variation across the stage: ±2dB

3. COMPETITION DESIGN PROCESS

At the beginning of 2007, the Jean Nouvel/Marshall Day team, was announced as one of six teams selected from the 98 submissions to enter into a 10 week design competition. Subsequently, Nagata Acoustics were added to the Nouvel team in a peer review role. Following two weeks of mobilisation, a two week design workshop commenced in Paris with the Architects, Theatre Consultants, Harold Marshall and Chris Day in attendance.

Marshall Day have an attitude to architecture and acoustical design that rejects the idea that there is only one possible form for a successful hall and only one “proper” sound. Marshall Day do not follow acoustical recipes but prefer to work collaboratively with the Architect to develop innovative forms that are based on an underlying foundation of research-based knowledge that illuminates why the historically successful forms work acoustically.

During the various design workshops, there were several moments when ideas crystalised. These generally involved the dying art of drawing, as far as the acousticians were concerned. With the exception of Nouvel himself, the architects were generally reluctant to draw – for them it was computers first!

The following Marshall sketch (with all its limitations) sufficed to allow the conversation to proceed. The sketch (Figure 1) was prepared during a breakfast design session involving Marshall and Day and is the first record of the ‘inner and outer volume’ concept that is discussed further below.

Figure 1: Marshall ‘Restaurant’ Cross-section – origins of the bicameral concept

The solution to the challenging brief was found in two nested chambers - an inner space producing visual and acoustical intimacy between audience and performer and an outer space with its own architectural and acoustical presence providing the high reverberance required by the brief. This was later presented to Nouvel and the team, who developed it into the architectural concept shown further below with the inner volume providing great clarity and the outer volume providing high reverberance. Marshall termed this the Bicameral Adaptable Concert Hall.

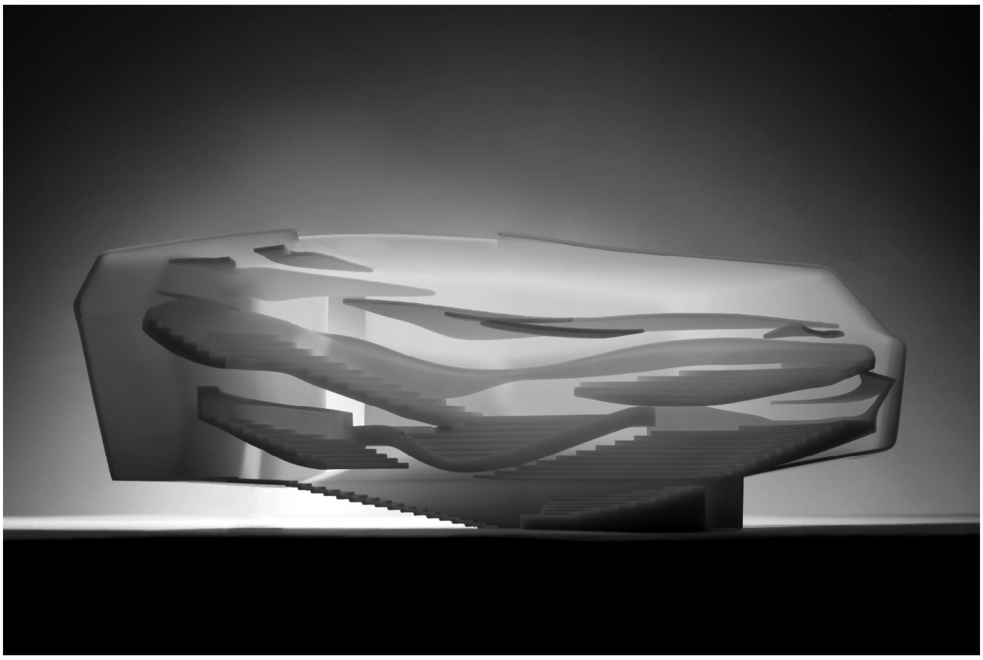

Figure 2: The competition 3-D printed model of the bicameral space.

As with other great architects, Jean Nouvel was able to take the acoustical elements conceived by MDA and turn them into architectural features. The floating ‘inner reflectors’ from Marshall’s concept sketches became the ‘nuage’ (clouds) which determine the visual character of the room when you first enter the inner space.

The early reflections required to make this design work are provided by these nuage along with the ribbons (reflectors at the rear of the seating pods), the balcony fronts and the overstage reflectors. These surfaces all contribute to defining the inner volume. Figure 3 is a computer rendering submitted with the competition documents and is a view from within the inner volume showing the seating pods, the floating nuage and the outer volume backlit in orange.

Figure 4 shows a similar view from the ‘outer volume’. A bridge can be seen which provides the dual function of a cantilever support for the seating pod and also an access way for the audience to enter the seating area.

It is noteworthy that the competition documents (computer render, video, 3D printed model etc) were completed in effectively 8 weeks of design and documentation – a remarkable body of work in such a short time frame. It is also remarkable that the finally constructed building remains true to this original concept design.

Figure 3: Competition computer render of the interior space

Figure 4: Competition computer render from the 'outer space'

4. DETAILED DESIGN IMPLEMENTATION

The winning design for the Philharmonie aimed at balancing early and late acoustic energies by nesting an intimate audience chamber within a larger acoustic volume. Although this description is accurate, it does not convey the complexity of the geometry and the extensive iterative design process that enabled this concept to actually work. The design of the nuage and ribbons surfaces, critical to the provision of early lateral energy and the relationship between the two volumes, was a complex iterative design process between architect and acoustician.

The detailed acoustical design began in Auckland with the traditional technology of physical scale modeling using mirrored surfaces and lasers. Figure 5 shows the 1:50 scale model being used to determine useable reflection sequences within the inner volume.

The architects were using the 3D computer modeling software Rhinoceros 3D and MDA commenced using Rhino for the reflector design and also for conversion into acoustical modeling software. However, the complex geometry of the hall, with a multitude of inner and outer curved surfaces, exceeded the capabilities of common acoustic simulation packages and processors. An interactive approach was adopted where the new technologies of 3D computer modeling and parametric design took an essential role, followed by the formal acoustic simulation in ODEON later in the design process.

Considerable time was spent during the detailed design phase on the mathematics of coupled spaces for the relationship between the inner and outer volumes. The concept design provided the ability to control the energy transfer between the two volumes with the use of variable elements however budget constraints meant these were not included in the final design.

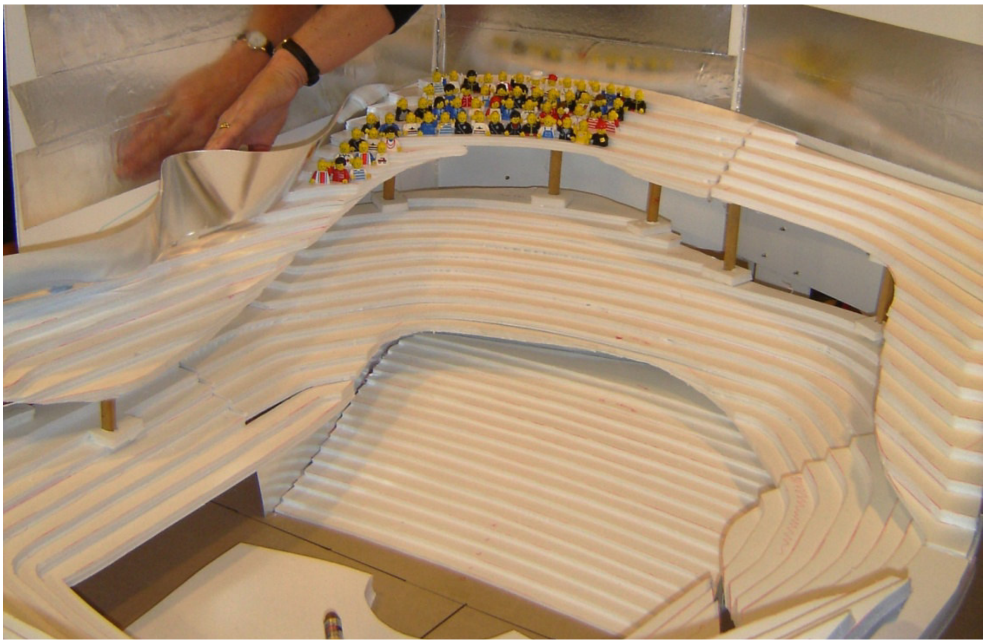

Figure 5: 1:50 Acoustic Scale Model

4.1 Rhino Based Design

In 2008-2009, during the schematic design phase, most of the acoustic work was carried out directly in Rhinoceros 3D modeling software. If it is an obvious option today, it was not common practice at the time.

Potential early reflecting surfaces, "nuages", the balcony fronts and the balcony walls "ribbons", were subdivided into small elements. Basic ray-tracing was carried out manually, one ray at the time, in Rhino to determine the desirable orientation for each element - we called them "pixels", representing the subdivision of the reflecting surface.

Information such as time delay (Δt), level difference (ΔL) with the direct sound and the reverberant sound level became readily available to optimize the design and ensure that the right "pixel" was creating early lateral reflections for the right audience area. At the end of the schematic design, more than 40 pixels where used for "nuages", 34 for the "ribbons" and 19 for the balcony fronts.

Though the ‘pixel technique’ was a great tool to explain the acoustic design intention to the architects, they were not necessarily the most efficient tool to convey our requirements in terms of dimensions of the appropriately orientated section of "nuage". From the detailed design phase, the concept of the pixel had become an intermediate step and the "nuages" were directly rebuilt according to our requirements before the 3D model was re-issued to the team.

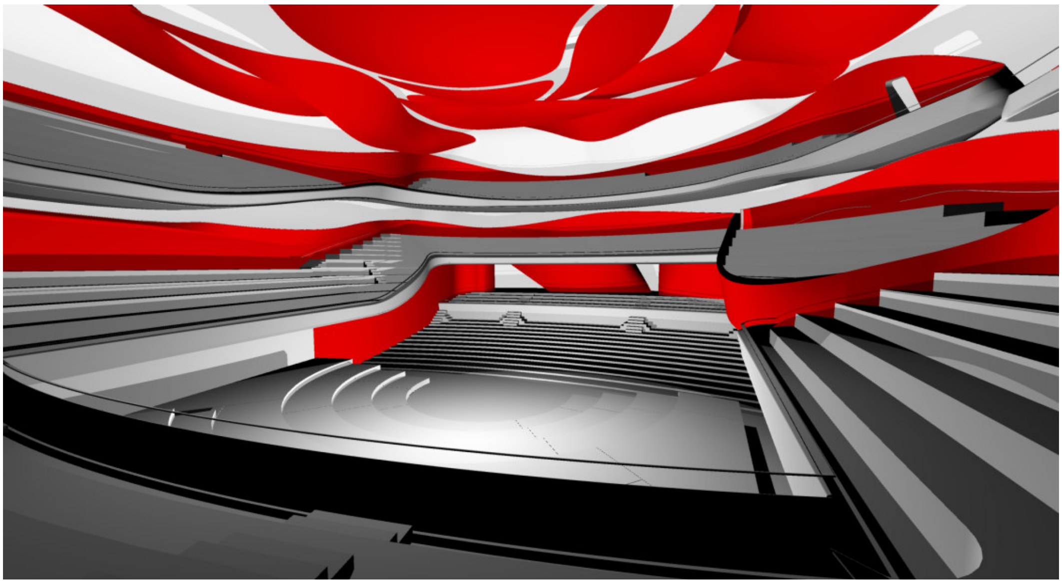

Figure 6: Rhino model with Early Reflecting Surfaces shown in Red

4.2 Grasshopper Design

In 2008, the parametric design tool Grasshopper became available. MDA developed a tool within Grasshopper that allowed ray tracing to take place in real time while a surface was being manipulated in 3D. This allowed not only the rapid analysis of the models received from the architect but also the rapid regeneration of surfaces. The tools developed within Grasshopper to assist with the Philharmonie de Paris were presented in separate paper (Scelo, 2015).

The Rhino/Grasshopper suite of tools includes routines to reorient surfaces, adjust curvature of surfaces, automate the coverage of a large audience area by combining the coverage from multiple reflectors and ensure that all reflections met the requirements for early lateral reflections as defined by Barron and Marshall (Barron & Marshall, 1981).

This approach was used for all surfaces identified as potential sources of early lateral reflections, including stage support. Most of these where finalized during week long workshops, in real-time with the architects, builder and client.

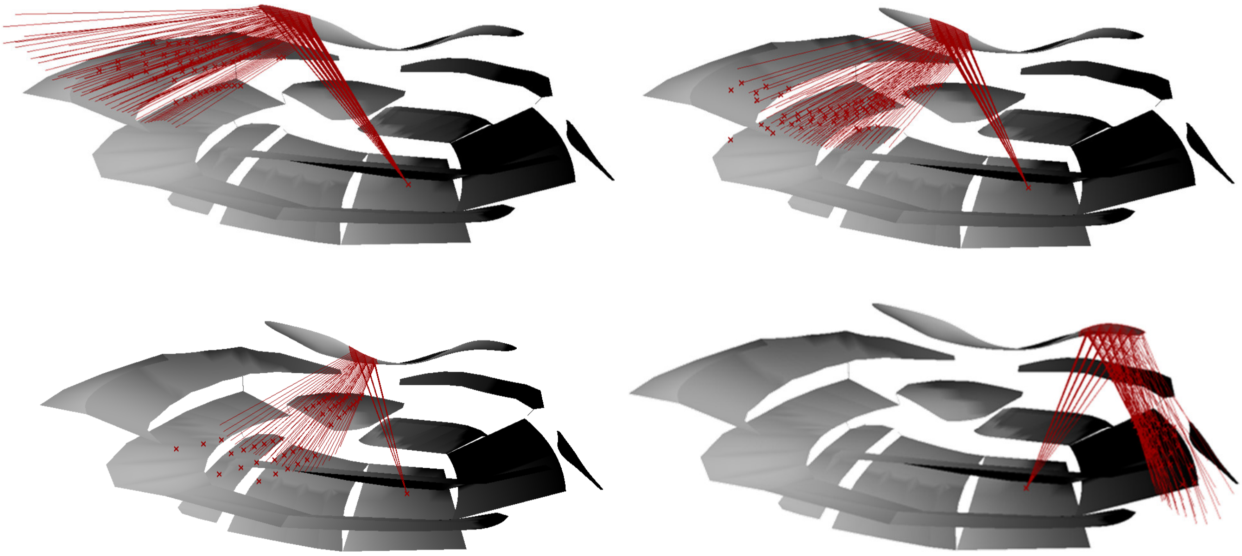

Figure 7 The reflection pattern from one nuage

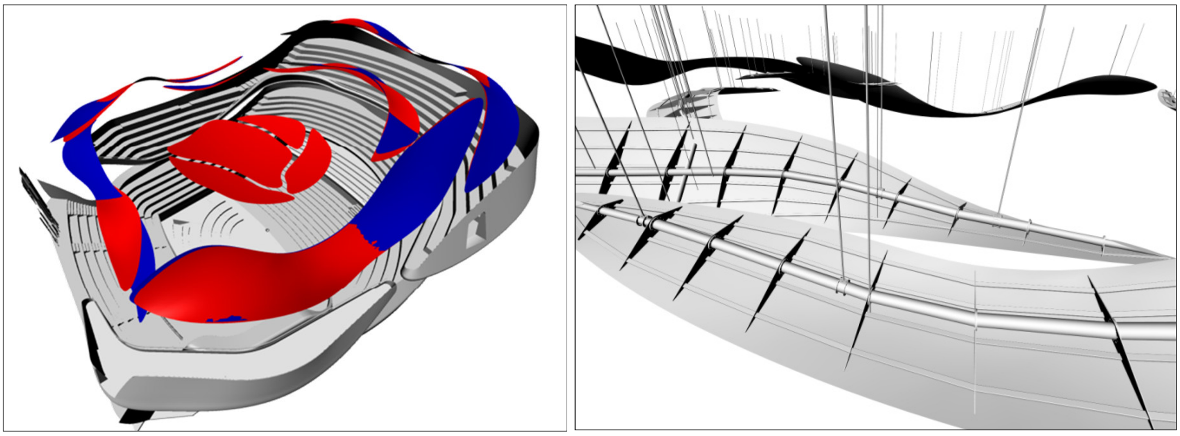

Figure 8 The suspended reflectors optimised for acoustics (red on left), with structure (right)

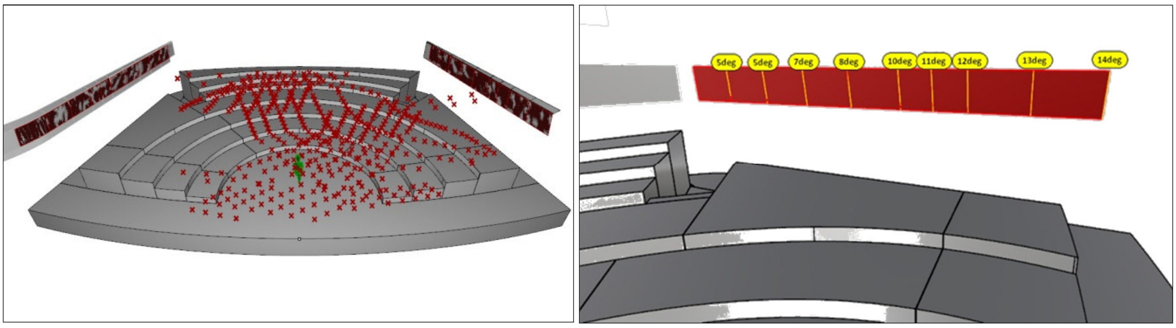

Figure 9 Stage support design using the balcony fronts. Ray tracing on left, advice on the right.

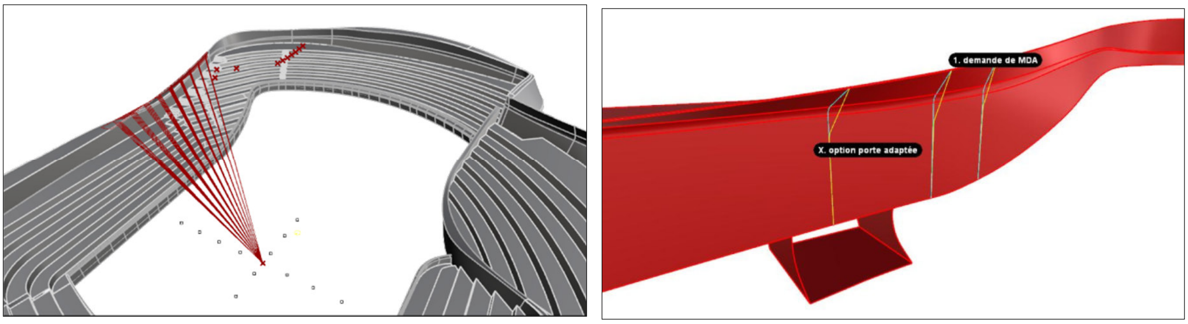

Figure 11 Ribbon walls design for early lateral reflections. Ray tracing on left, advice on the right.

4.3 Odeon Simulations

With such complex geometry in the Philharmonie, Odeon simulations remained a luxury during the early stages of design and were carried out only when the effects of accumulated design changes were significant. With over 140,000 surface elements constituting the complete 3D model of the Philharmonie de Paris, and using only a single core processor (all that was available during the initial design), a complete Odeon grid response would require up to 24 days per source position. The accuracy of such simulations was questioned as the complexity far exceeded the 1,000 surfaces limit specified by the Odeon development team. These results were however to be confirmed at a later stage of the project with the help of the 1:10 scale model study mentioned below.

Later in the design process, two core processing became available in Odeon and computation times reduced to hours rather than days at which stage Odeon became a useful tool.

4.4 Physical 1:10 Scale Model

Validating such a new paradigm, and providing the needed confidence that Odeon simulations were meaningful with 140,000 surfaces, Marshall Day Acoustics recommended to the Philharmonie de Paris that a 1:25 scale model be built for the sole purpose of validating the concept and calibrating our simulations. The recommendation was accepted and, to provide additional exposure and public interest to the project, the decision was made to commission a 1:10 scale model instead.

Nagata Acoustics, who were at that stage completing a 1/10 scale model study of a small concert hall for Radio France, were commissioned to carry out an echo study in the 1:10 model as the primary component of their peer review for Jean Nouvel. As no measurements had been made in the 1:10 model of the objective parameters specified in the brief, MDA engaged a Paris based acoustician Brian Katz, to do a vast campaign of measurements under significant time pressure. His valuable work is summarised in a paper presented to the IoA in the Philharmonie in 2015 (Katz, 2016). The Katz's measurements included reverberation time RT, EDT, Clarity C80 and Loudness G.

The final room had increased room volume as the ceiling was raised by one meter following the model construction.

4.5 Construction Phase

It is impossible to report within such a paper, the specifics of the construction phase of this project, and most notably the two months leading to the opening. However, for the "acoustics to prevail" (Rattle, 2015), one cannot simply hope for the best. It is the combination of a science, engineering common sense, patience and diplomacy, that allows one to decide whether a ‘non-conforming’ reflector is acceptable or needs to be reassembled (and how) even if planning, costs and politics say otherwise. Not all debates have been won and nor should they be. The authors would like to think that in addition to a successful design, our regular site visits, detailed and sometimes stubborn inspections and interactions with the team on site have contributed to the success of the project.

The last months prior to opening were chaos on site. The main contractor had 200 people working on the project 24 hours per day working shifts in an attempt to get it completed.

Thomas Scelo from MDA was based in Paris for the last two months and had his hands full. The opening date was set in place as 15 January 2015 with musicians and dignitaries committed. In the end, the building opened unfinished and Jean Nouvel refused to attend on the basis that the architecture was incomplete. The exterior and a number of ancillary spaces were far from complete however the auditorium was 95% complete with all the key acoustical elements in place for opening night. A very reassuring ‘light-bulb moment’ occurred during a site inspection in final week. A large ‘light ring’ was perched temporarily on the stage and the view from the rear seating revealed optical reflections of the ring in a large number of the ‘high gloss’ acoustic surfaces. Figure 11 shows this effect. It was clear that the rear seats were going be supplied with a large amount of early lateral energy.

Figure 11: The Philharmonie, three weeks to opening

5. OPENING AND COMMISSIONING MEASUREMENTS

The commissioning of facilities such as the Philharmonie would normally take place well in advance of the opening along with rehearsal sessions for the orchestra to get used to the new hall (the heading for this section of the paper would normally be in the reverse order). In this case, the orchestra did not get the chance to play a single note in the room before the ‘Hard Hat Concert’ which took place 48 hours before the official opening. The first set of commissioning measurements wasn’t able to take place until 4 days after the opening with a window made available from 10pm to 5am. There were two subsequent measurement campaigns over the following 9 months. A summary of the various measurements is reported below.

The acoustical measurements were made using the IRIS system developed by MDA and were generally in accordance with International standard ISO 3382-1 Acoustics – *Measurement of Room Acoustic Parameters Part 1: Performance Rooms*.

5.1 The IRIS Measurement System

The 3-D measurement system, “IRIS” is an integrated software and hardware room acoustics measurement system. It utilises a compact tetrahedral microphone array, a Core Sound TetraMic, which is able to resolve incoming sound in terms of level, time and direction (Figure 12).

Figure 12: The tetrahedral microphone in the inner volume (left) and in the outer volume (right)

An example of the “IRIS plot” produced by this system is shown in Figure 13. It graphically represents the sound arriving at the receiver as a series of vectors with magnitude, direction and arrival time all represented. The vectors are normalised to the direct sound intensity and the angle of incidence. The colour of the vector corresponds to the time of arrival after the direct sound.

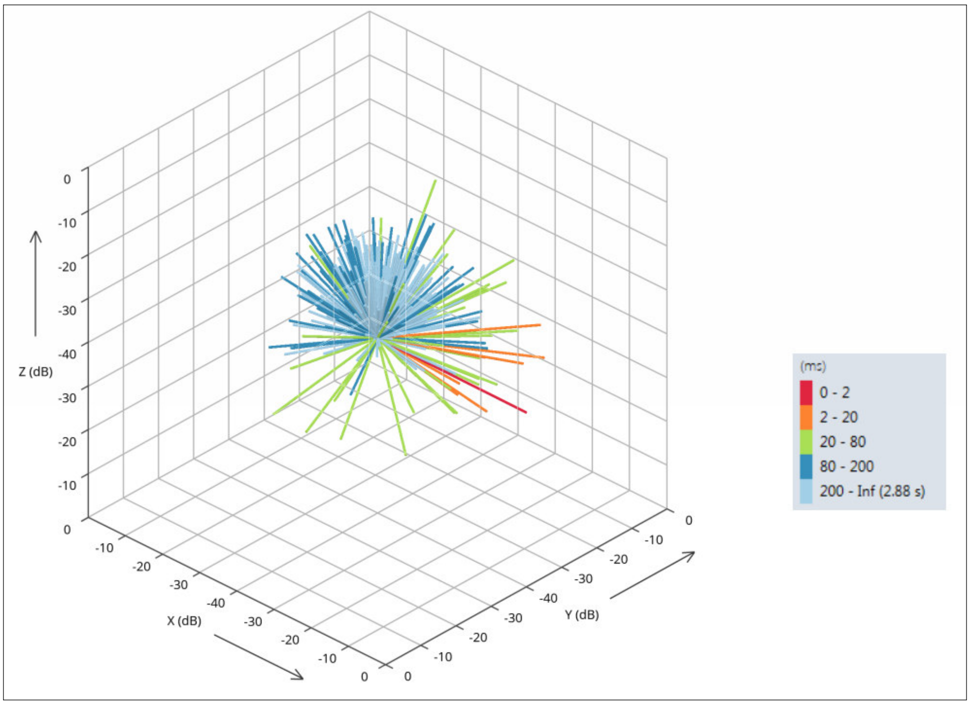

Figure 13: Example Iris plot measured in the Philharmonie de Paris

The number of measurement position required is described in ISO 3382-1 and is related to the volume of the room. MDA used 3 source positions and 14 receiver locations which exceeded the requirement in the Standard. The IRIS system is exceptionally fast to run and 43 source receiver combinations were measured in approximately 5 hours in a physically challenging room. A plan of the source and receiver locations for one level out of three is shown below (Figure 14).

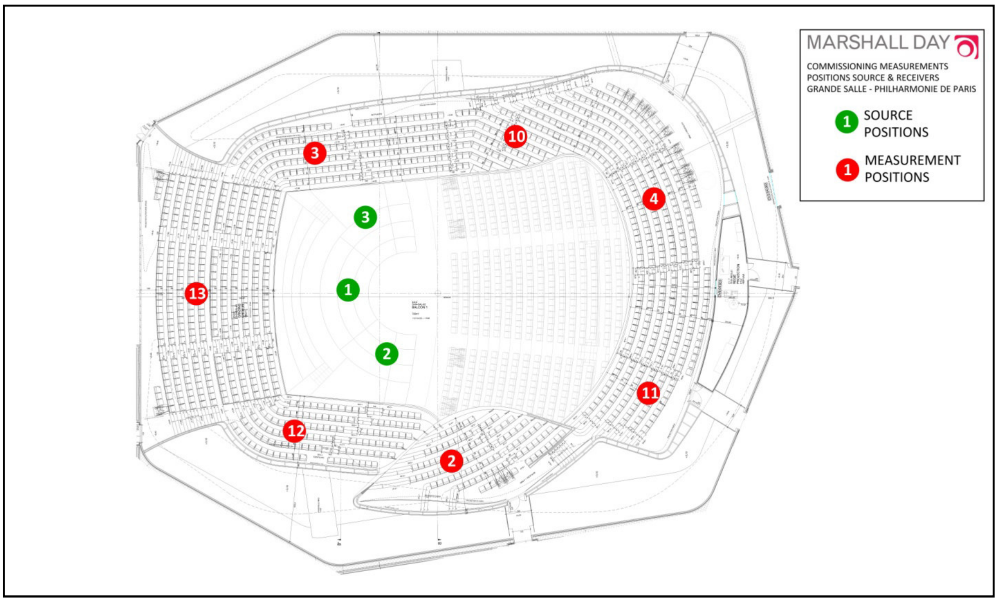

Figure 14: Measurement positions on the mid level

5.2 Results – Averaged Values

The following table provides a summary of the measured results compared with the requirements of the Programme Acoustique.

Table 5: Results - average values across all measurements (mid-frequencies)

Acoustic Criterion	**Physical Conditions**	***Programme Acoustique***	**Measured averaged value (mid freq)**
Reverberation Time (RT)	Symphony Mode: Occupied with Orchestra	2.2 to 2.3s	2.5s
	Jazz/World Music Mode: Occupied with acoustic banners	-	2.1s
Clarity (C80)	Symphony Mode: Unoccupied	-3dB to 0dB	-0.2dB
Loudness (G)	Symphony Mode: Unoccupied	3dB to 6dB	2.2dB
Early Loudness (Gearly)	Symphony Mode: Unoccupied	-2dB to +2dB	-1.3dB
Late Loudness (Glate)	Symphony Mode: Unoccupied	0dB to +4dB	-0.6dB
Lateral Fraction (LF)	Symphony Mode: Unoccupied	> 0.16	0.20
Bass ratio	Symphony Mode: Occupied	1.1 to 1.3	1.1
Treble ratio 2kHz	Symphony Mode: Occupied	0.90 to 1.00	0.90
Treble ratio 4kHz	Symphony Mode: Occupied	0.75 to 0.85	0.80
Stage Support (ST1)	Chairs in place but no orchestra	-	-15.1dB

Note 1 - Occupied measurements were made during the ‘Hard Hat’ concert on 12 January 2015. At this time the hall was approximately 70% to 80% occupied and there were 200 seats missing and temporary seats in some locations.
Note 2 - Measurements made on 11 April 2015 with four of the six banners installed in the outer volume, one full height drape suspended behind the stage, and two short drapes suspended between the overstage lighting bars. Occupancy 90-85%.
Note 3 – Measurements made on 18 January 2015 in the hall under completion with excessive residual absorption due to dust and construction equipment.
Note 4 - Stage support ST1 octave band values averaged for 250Hz to 2kHz bands, then averaged for 9 measurement positions on stage.
Note 5 – The original extent of variable acoustics was not achieved due cost constraints during the design and construction.

5.3 Results – Spectral Values

Figure 15 provides the measured reverberation time (RT) of the Philharmonie in four different conditions, as measured between January and October 2015.

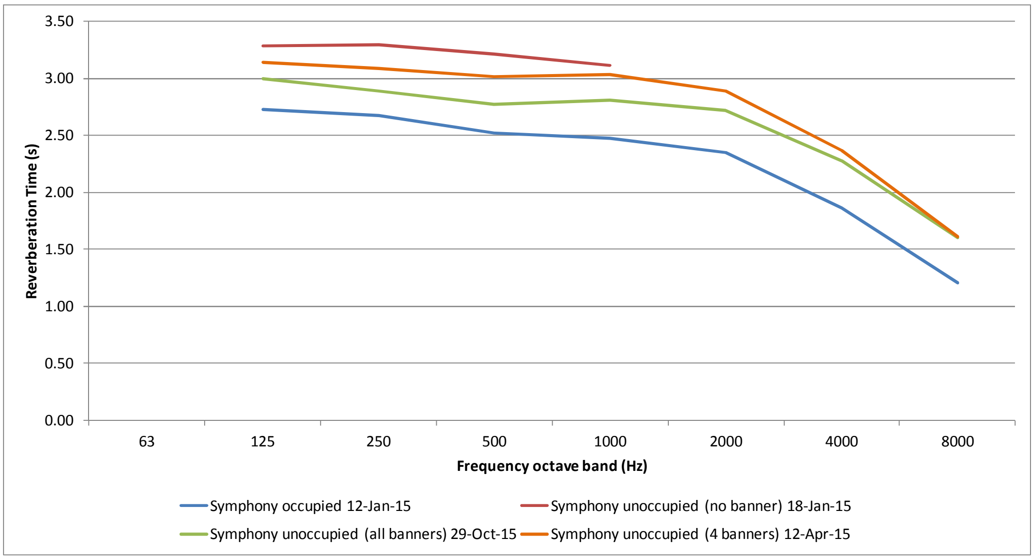

Figure 15: Reverberation Time vs Frequency

5.4 Results – Early Energy

Figure 16 shows the Clarity C80 for each source receiver combination plotted against distance from source to receiver. The results show the measured Clarity is generally much higher than the statistical theory calculated for this room. This is an expected result and is due to the significant early reflections achieved during the design process which in turn aligns with the subjective experience of high clarity.

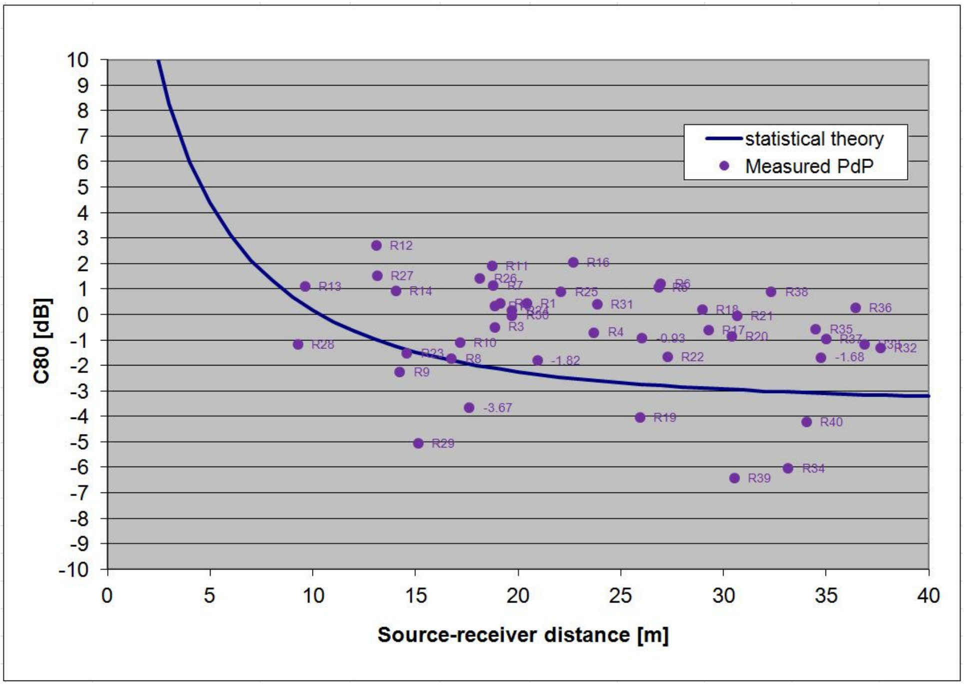

Figure 16: C_{80} @ 1kHz versus distance from source to receiver

5.5 Results – Iris 3D

Figure 17 shows the IRIS plots at a number of the receiver locations. Each of these plots has been examined in detail however in general they show the desired characteristics for the specified clear and reverberant sound. They show a number of individual green spikes (20-80ms delay) with an asymmetrical form (providing clarity and spacial impression) and also a large collection of blue spikes which indicate a balanced and strong reverberant field.

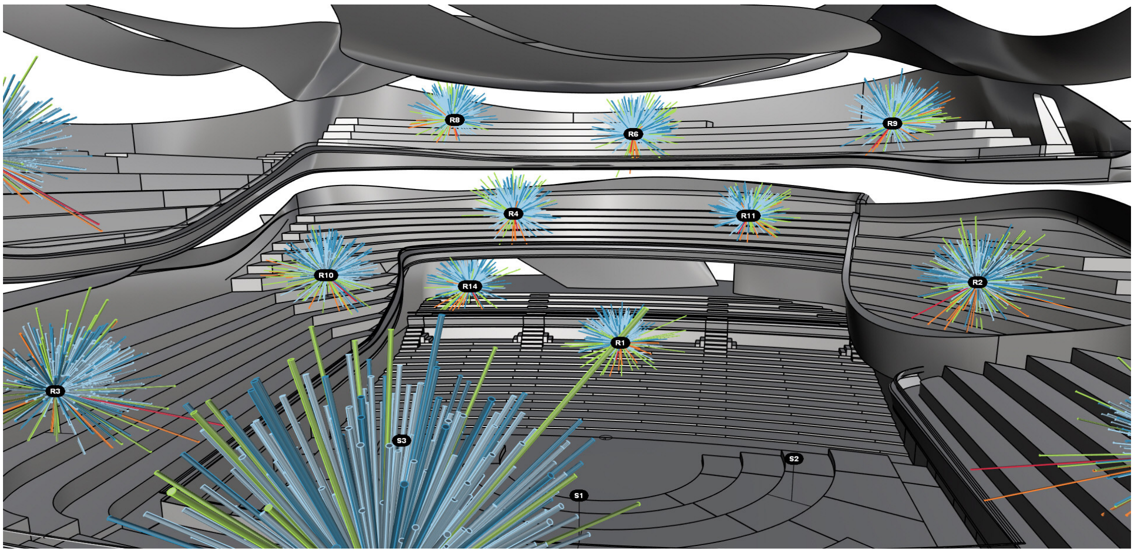

Figure 17: IRIS Plots at several seat locations

5.6 Musicians and Stage Conditions

There is not time in this paper to report the subjective surveys done with the orchestra and the stage condition measurements. This work is reported separately (Scelo, 2015).

6. CONCLUSIONS

This paper documents how the acoustic design of the Philharmonie de Paris was handled from the conceptual design through to the opening. This new concert hall is an example of a highly successful outcome, underpinned by creative design, science and engineering, through a collaborative interaction between Architect, Acoustician and Theatre Consultant.

Marshall has often discussed the role of the acoustician in the design process, a role that oscillates constantly between scientist, engineering and designer. Indeed, the success of any creative design needs to be proven in the fields of physical science and engineering. The difference between indifferent acoustics and the acoustic success of the Philharmonie de Paris has, we believe, been the systematic bridge between the non-linear realm of design and the linear fields of science and construction.

Finally, the project outcome seems to confirm conformity with the objectives set by the Programme Acoustique and subjective acceptance by stakeholders. It would seem appropriate to end this paper with two quotations:

From Marshall Marcus, former Head of Music at London's Southbank (Marcus, 2015); "*Well done Paris, well done master acousticians Marshall Day Acoustics*".

From Sir Simon Rattle, OM CBE, (Rattle, 2015) Artistic Director of the Berliner Philharmoniker who conducted his orchestra in the Philharmonie de Paris in February 2015:

> *“…. playing one of the very early concerts in the Philharmonie de Paris and realising that this is one of the world's greatest acoustics.”*

ACKNOWLEDGEMENTS

The authors wish to acknowledge a number of people who have been involved in this project.

- Laurent Bayle, the President of the Philharmonie de Paris and Director General of the Cite de la Musique, who drove the project from start to finish and whose courageous vision to require a ‘new typology’, initiated the creative masterpiece that has been born.
- Patrice Januel and Geoffroy Vauthier from the PdP, for their dedication and perseverance throughout the project.
- Eckhard Kahle and Richard Denayrou who developed the most comprehensive acoustic brief ever produced for a concert hall project and worked harmoniously with the design team throughout the project.
- Jean Nouvel who entrusted us with the acoustic design and took onboard our concepts and said “*Tell me what you need for the acoustics and I will make it work architecturally*”, and delivered on this promise.
- Yasu Toyota of Nagata Acoustics who fulfilled his peer review role responsibly, by staying away from the design process and commenting on specific issues such as potential echoes.
- Brian Katz who carried out a comprehensive measurement campaign in the 1:10 scale model under significant time pressure.
- Federico Cruz-Barney who was responsible for the noise control design for the project and the resultant low levels of background noise which contribute to the wonderful success of the project.
- The Orchestre de Paris musicians and management for their patience, enthusiastic participation and extraordinary appreciation of this new acoustic paradigm.

REFERENCES

Barron, M & Marshall, AH 1981 '*Spatial impression due to early lateral reflections in concert halls*', J. Sound Vib. 72, 211–232

Kahle Acoustics and ALTIA 2006 '*Le Programme Acoustique de la Philharmonie de Paris*'.

Katz, B 2015 '*La Philharmonie de Paris - Acoustic scale model study*', Proc. Auditorium Acoustics, Paris

Marcus, M 2015 https://marshallmarcus.wordpress.com/2015/01/14/ce-soir-nous-sommes-tous-la-philharmonie/

Marshall, AH 1983 '*The acoustical design of concert halls*', Study Paper No.75, School of Architecture, University of Auckland

Rattle, S 2015 http://philharmoniedeparis.fr/en/node/3584, Interview of Sir Simon Rattle

Scelo, T 2015 *'Integration of acoustics in parametric architectural design'*, Acoustics Australia, Vol(43).

Scelo, T & Exton, P & Day, CW 2015 '*Commissioning of the Philharmonie de Paris, Grande Salle*', Institute of Acoustics Vol. 37. Pt.3