IMPACT OF CURVED SURFACES IN PERFORMANCE SPACES

By

Eva M. Johnston-Iafelice

B. Arch., Carleton University, 2014; M. Sc. Arch., Tampere University of Technology, Finland, 2016

A Major Research Project

presented to Ryerson University

in partial fulfillment of the requirements for the degree of Master of Building Science

in the Program of Building Science

Toronto, Ontario, Canada, 2018

Author's Declaration

I hereby declare that I am the sole author of this MRP. This is a true copy of the MRP, including any required final revisions.

I authorize Ryerson University to lend this MRP to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this MRP by photocopying or by other means in total or in part, at the request of other institutions or individuals for the purpose of scholarly research. I understand that my MRP may be made electronically available to the public.

I understand that my MRP may be made electronically available to the public.

Abstract

Impact of Curved Surfaces in Performance Spaces

Master of Building Science 2018

Eva M. Johnston-Iafelice

Building Science

Ryerson University

Current acoustic practices deem that curved surfaces as room envelopes do not provide good acoustical performance. In contrast, old cathedrals, churches, and enclosed performance spaces with curved interiors seem to work very well even though their envelopes are comprised of curved surfaces (walls, ceilings, etc.) The aim of this project was to analyze curved surfaces and evaluate the resulting acoustic performance of these occupied spaces. The evaluations were achieved with both experimental methods, and computer simulations. After these evaluations were performed, results showed that in these conditions, the curved surfaces had minimal negative impact as perceived by the audience.

Keywords: *acoustics, absorption, reverberation time (RT), sound pressure level (SPL), extended circle, diffusion, Ray Theory, Wave Theory*

Acknowledgements

This work would not have been possible without my professor and research advisor Dr. Ramani Ramakrishnan. I would like to thank Dr. Ramakrishnan for his support and dedication towards encouraging me to further my education in acoustics. My interest in the architectural aspect of room acoustics led me to study the impact of curved surfaces in performance spaces. Due to his knowledge, direction and reassurance, I completed and truly enjoyed this journey.

I would also like to thank my second advisor Dr. Mark Gorgolewski for his constructive feedback and guidance during the final stages of this major research project, John O'Keefe as a mentor and guide, and William Crosthwaite for his technical writing support. I am grateful to Plenary Group Canada, who has been supportive of my educational goals and aspirations.

I would further like to thank my family, whose love and guidance are with me in whatever I pursue, and for always encouraging me to shoot for the moon, and once you get there, to reach for the stars. To my friends, for their understanding and support throughout this journey. Without all these wonderful people this would not have been possible.

TABLE OF CONTENTS

List of Figures

List of Tables

List of Appendices

1.0 Introduction

Conventional wisdom states that having concave surfaces as the envelope of any occupied space does not produce good sound (1). It is well known that the focussing effect produced by concave surfaces can be problematic. Focussing can cause high sound pressure levels, coloration, and echoes (2). However, throughout history there have been many enclosed rooms with large curved surfaces as envelopes which seem to produce good acoustics. Many churches, opera theatres, auditoriums, and concert halls alike were designed with curved features. Princess of Wales Theatre, located in Toronto, Ontario is a horseshoe-shaped room, with a traditional double balcony, and modern interior design as shown in Figure 1. The theatre was designed with a focus on producing good room acoustics due to the activities required to be orchestrated within the space.

Figure 1: Princess of Wales Theatre, Toronto, Ontario (3)

Although there seem to be hesitations in the modern field of architecture regarding curved interiors, the introduction of concave surfaces as envelopes seems to be increasing. Recently, researchers have found that performance spaces with barrel-vaulted ceilings, domes, and other curved shapes seem to produce very good acoustics (1) (4) (2).

Concave curved surfaces can produce four types of reflections: elliptic, circular, parabolic and hyperbolic. These reflections are differentiated by the location of the source relative to the centre of the curved surface. Elliptic reflection occurs when the source to curve distance is larger than R/2, as shown in Figure 2 (5). When the source to curve distance is equal to R, circular reflection occurs, as shown in Figure 3 and 4 (5). Parabolic reflection occurs when the source to curve distance equals R/2, as shown in Figure 5 and 6 (5). Hyperbolic reflection occurs when the source to curve distance is less than R/2 (5). Dependent on the source location and the type of reflection, the focal area can either aid or be detrimental to sound pressure level distribution within a room.

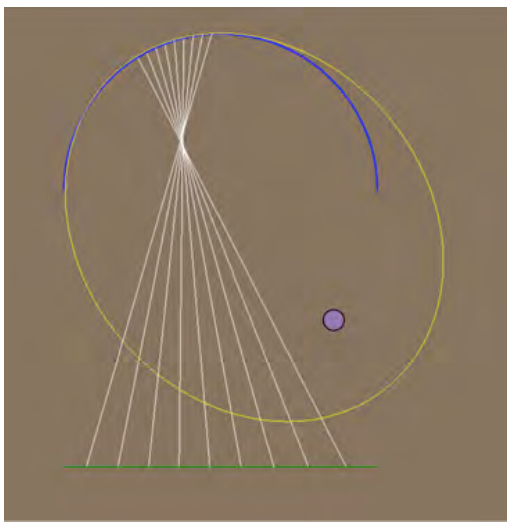


Figure 2: Elliptical reflection (showing two foci) [From O'Keefe, (4)]

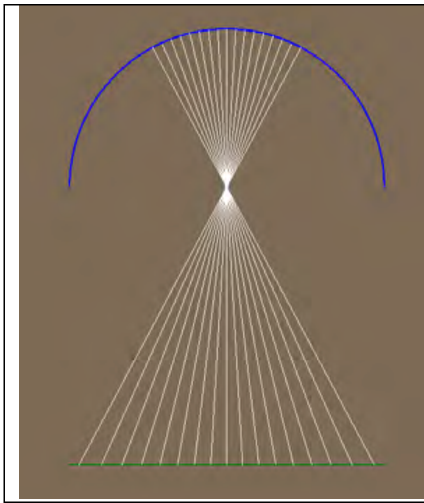


Figure 3: 2D Representation of circular focussing [From O'Keefe, (4)]

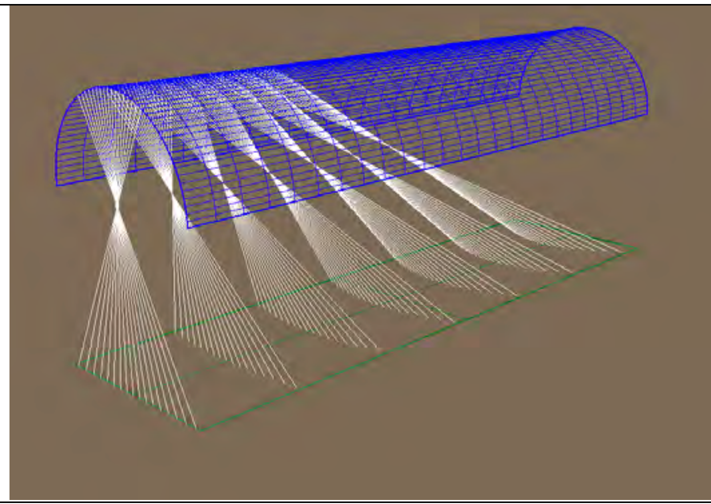


Figure 4: 3D Representation of circular focussing [From O'Keefe, (4)]

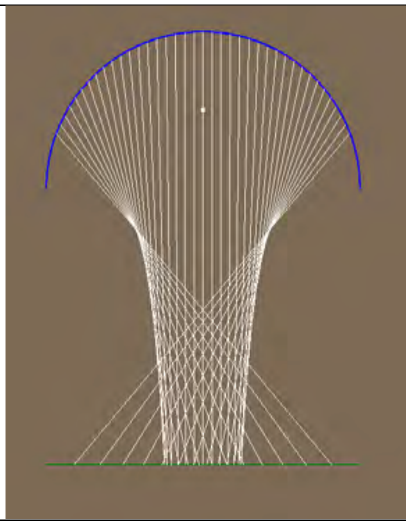


Figure 5: 2D Representation of parabolic focussing [From O'Keefe, (4)]

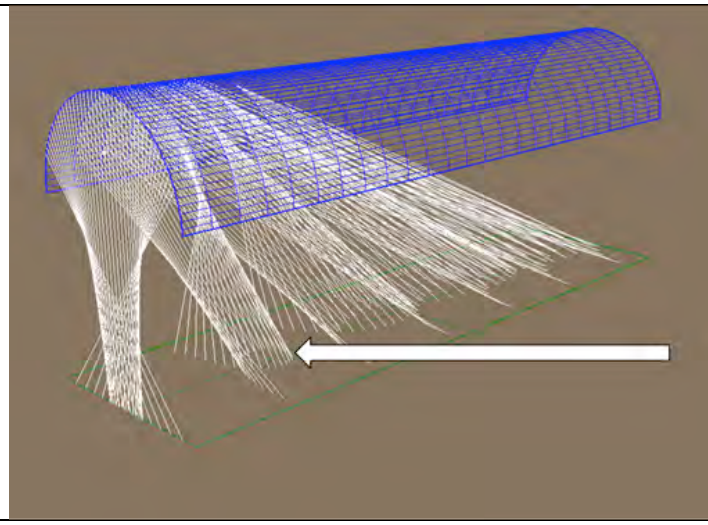


Figure 6: Parabolic reflection pointing to circular pattern which increases towards the back of the room [From O'Keefe, (4)]

The current Major Research Project ("MRP") investigated, researched, and evaluated curved spaces for their acoustic performance. To analyze the effect of curved surfaces at different frequencies, three enclosed rooms with curved surfaces were used to measure the sound pressure levels throughout an audience space. The three enclosed spaces were (a) the Paul Crocker Gallery ("Gallery") in the Ryerson Architecture Building, Toronto; (b) St. Martin-in-the-fields Anglican Church ("St. Martin's"), Toronto; and (c) Wigmore Hall, United Kingdom. The research was completed through Pink Noise and Impulse Response measurements, and computer simulations which were validated by the initial on-site measurements in the Toronto locations.

2.0 Literature Review & Research Questions

2.1 Literature Review

Many enclosed rooms, old and new, have curved envelopes. Some of these curved envelopes encounter issues with focussing, but others do not. Focussing is based on the source, receiver, medium, and the distance in and around these locations. The following literature reviews provided information on room acoustics, curved surfaces, concave envelope case studies, reverberation time, focal planes, material composition and general acoustic knowledge.

John O'Keefe studied the acoustical effects of churches with curved envelopes (4). O'Keefe analyzed the dome of St. Paul's cathedral, the barrel-vaulted ceiling of St. Martin's, and the focussing zones of concave surfaces. The paper stated that the barrel-vaulted ceiling of St. Martin's produced some of the finest acoustics in Toronto, with a four second reverberation time when the unoccupied space had a choir performing, and two seconds when occupied. The focal planes of the vaulted ceiling are hypothesized to be located above the audience space which is why there were no negative implications for the observers. St. Paul's Cathedral uses late lateral reflections to create envelopment within the space, where the sound reaches the listener from the sides. These focal planes can be seen in Figure 7 at the intersection of the blue X's. Beyond the focal plane, the dome scatters the sounds to the side walls, where it diffuses towards the congregation. O'Keefe also discussed the main three focussing zones of concave surfaces: circular, parabolic and elliptical. Figures 2 to 6 are taken directly from his paper, where O'Keefe used Non-Uniform Rational Basis-Splines ("NURBS") to model the curves. The current investigation studied in detail the acoustics of St. Martin's Anglican Church.

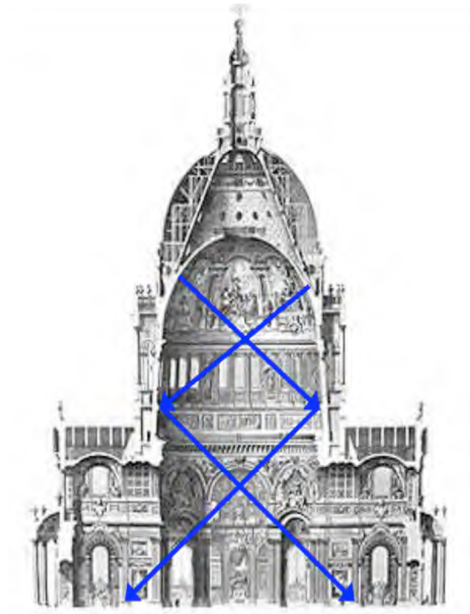


Figure 7: St. Paul's cathedral [From O'Keefe, (4)]

Wulfrank and Orlowski conducted computer simulations of Wigmore Hall in London (5). Wigmore Hall is of the Renaissance style architecture and dates from 1901. The hall is a basic rectangle, with an elliptic vaulted ceiling while the stage platform has a cylindrically shaped apse and a spherical cupola above, as shown in Figure 8.

Figure 8: Wigmore Hall (6)

Wigmore Hall has a mid-frequency reverberation time of approximately 1.5s when occupied which is ideal for chamber music. The positive acoustical performance of the room is affirmed by its description as “loud, spacious, reverberant yet clear” (5). The elliptic ceiling of the hall is a curve with a continuously varying radius, whose foci do not pose any acoustic problems as they are above the audience and musicians. There is the highest amount of amplification in the areas of the curve with the largest radius, and diffusion occurs as the radius becomes smaller. The cylindrical apse of the stage platform creates five different projections depending on where the source is located on the stage. Of these five projections, there are three main types of reflective behaviour: backward elliptic projection, forward elliptic projection and hyperbolic projection. With an ensemble on the stage, the apse creates a more coloured sound, enhancing the musical performance. The analysis found that the spherical cupola does not produce any focusing in the audience space – though many believe that the cupola would direct and project sound straight to the audience, as the apse does. The diffusion created by the cupola reduces the risk of false localization. The current investigation extended the work of Wulfrank and Orlowski through simulations.

Due to high cost and design modification, acoustics tends to be the last consideration in modern architecture. However, Barron found that architects have recently found a new respect for acoustics (2). Barron’s book on auditorium acoustics commences with the basic acoustic principles, and discusses and analyzes many case studies, with concave designs as shown in Figure 9.

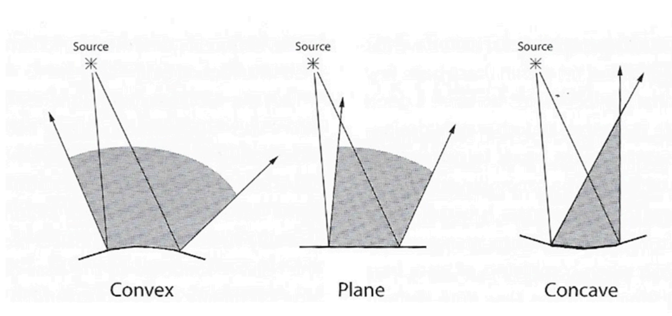


Figure 9: Surfaces reflecting sound [From Barron, (2)]

Barron stated that acceptable reflection for concave surfaces can occur if the source and receiver are outside the extended circle of the concave surface, where the concave surface disperses the sound. Concave surfaces with tight radii can disperse sound very well if far away from the audience, as shown in Figure 10.

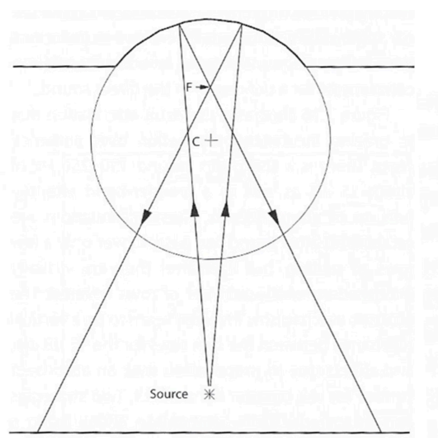


Figure 10: Focussing off a remote curved surface [From Barron, (2)]

Barron also stated that wood panels are not good for acoustics as they absorb acoustic energy, especially at low frequencies, as shown in Figure 11.

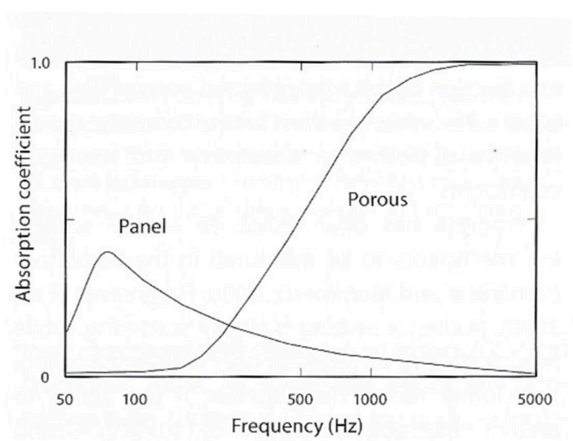


Figure 11: Absorption coefficients of porous and panel absorbers (From Barron, (2))

Therefore, to have ideal acoustic absorption, a room would require a mix of panel and porous absorbers to provide absorption over an entire range of frequencies. The current investigation developed and validated the research on acceptable reflections based on source and receiver locations, through a series of simulations.

New architectural styles, and improved building technology has increased issues surrounding acoustic reflections, such as focussing. When sound is reflected from a concave surface, the concavity of said surfaces concentrates the energy into one location, due to the focussing effect. As part of Vercammen's doctoral dissertation, he studied the impact of curved systems on the acoustical performance of occupied spaces (7). He investigated the influence by considering various halls such as Wigmore Hall, St. Paul's Cathedral and Tonhalle in Dusseldorf. The impulse response measured in Tonhalle showed a strong echo. Tonhalle has a cupola type domed ceiling, and the focal plane happens to be within the audience area. Vercammen also studied the sound pressure level ("SPL") of hemispheres and half-cylinders. Vercammen found that hemispheres are prone to produce high SPLs at higher frequencies, and cylinders have an increase in SPL, but less than that of a dome shape. The SPL study determined that the maximum SPL in the focal point is dependent on the radius for cylinders but not for spheres. The paper explained that reflection on concave surfaces can provide better sound at lower frequencies in comparison to higher frequencies, due to less diffusion, and a larger foci. It also stated that wave extrapolation methods provided the most accurate calculation of acoustics for curved surfaces. In addition, the investigation included theoretical models of curved configurations to evaluate the character of the reflected sound by using Maximum Length Sequence sound signature. The main conclusion of Vercammen's work was that the impact of sound on curved surfaces can only be evaluated through the application of wave analytical techniques for low frequencies, and not through ray acoustics. The current MRP investigation applied wave analysis methods to the different configurations at low frequencies.

Prior to 1985, acousticians had mainly been studying reverberation time ("RT") in chamber-type rooms. But in 1984, A. C. Gade published a paper on the room acoustics of Danish concert halls which hinted at the notion that reflected sound pressure levels in concert spaces decreased as the receiver moved further away from the source (8). The previous statement did not adhere to traditional diffuse theories, which assumes the reflected sound level is constant throughout the space. The 'revised theory' of sound level in rooms was derived from Barron's paper, Gade's research, as well as an additional paper by Barron in 1985 (9) (10). The revised theory states that reflected sound is not constant throughout an audience space, it decreases as a function of source-receiver distance. The paper found that RT as a form of acoustic measurement tends to be quite accurate in concert spaces. Barron measured twenty-one halls as unoccupied spaces. He measured the unoccupied reverberation time in Wigmore Hall to be 1.63s at 500Hz, 1000Hz and 2000Hz. Barron's paper also investigated modifying the revised theory, but evidence proved that it was not warranted, and that revised theory is most accurate on average. The current investigation used Barron's RT values in the Wigmore Hall simulations to validate the acoustic absorption coefficients of the materials in the enclosed room.

2.2 Research Questions

The literature review showed that even though curved surfaces are thought to be a poor geometry, acoustically, for auditorium spaces, they can actually produce good acoustics. The above conclusion lead to the following research questions:

1) Is sound pressure level equal throughout an audience space in an enclosed room with a curved envelope?
2) Beyond the focal plane, does the sound diffuse equally, producing good acoustic performance in enclosed rooms with curved surfaces?

3.0 Methodology

The main focus of the current investigation was to research the uniformity of the sound field produced by curved surfaces. It studied the impact of the focal plane on the overall sound distribution within an enclosed space. Both experimental methods and computer simulation methods were applied in this research work. For the purpose of this study, three enclosed spaces were used.

An overview of the methodology can be seen in the following flow charts, shown in Figures 12 through 15.

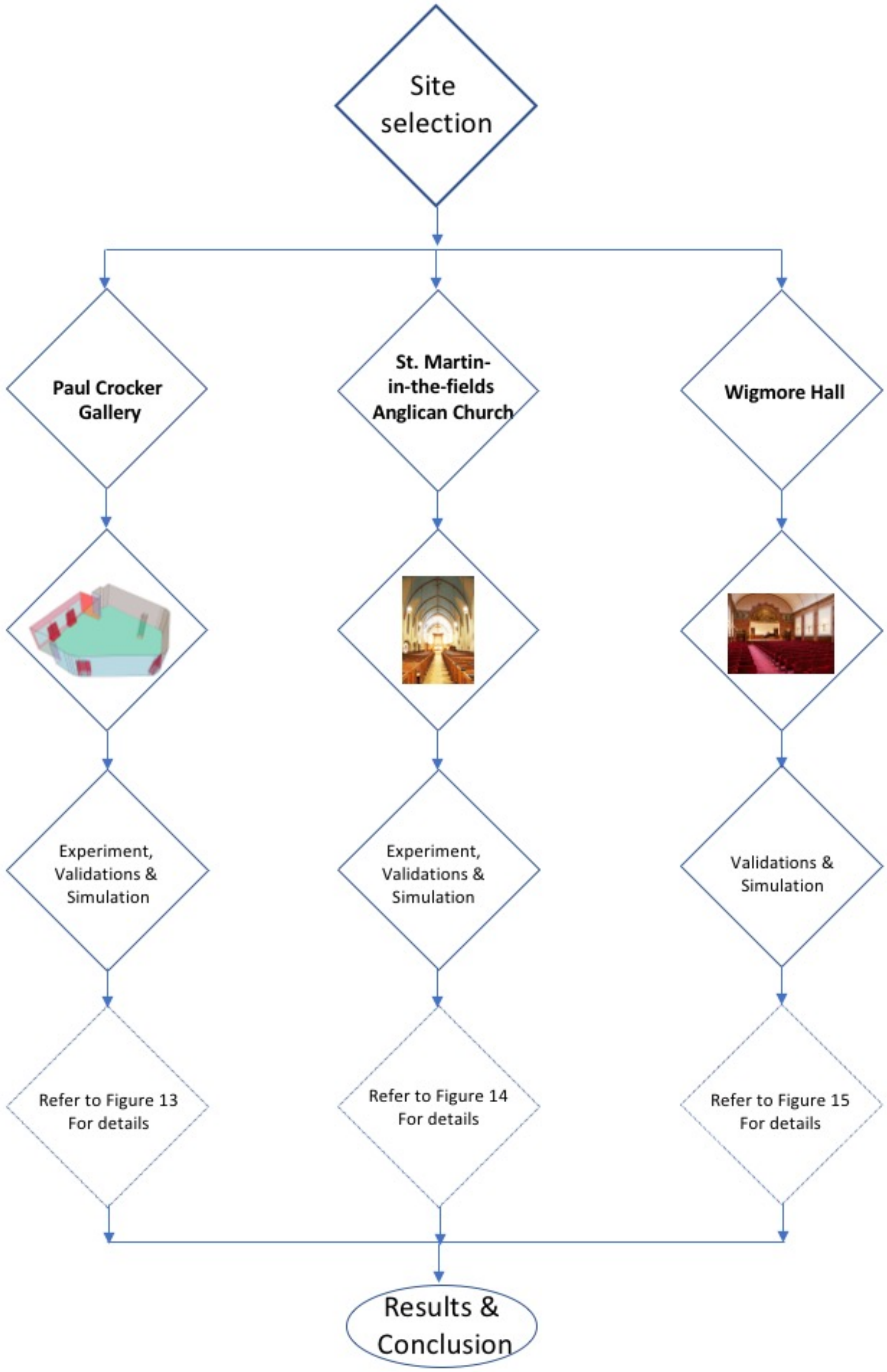


Figure 12: Methodology Overview - Flow Chart A

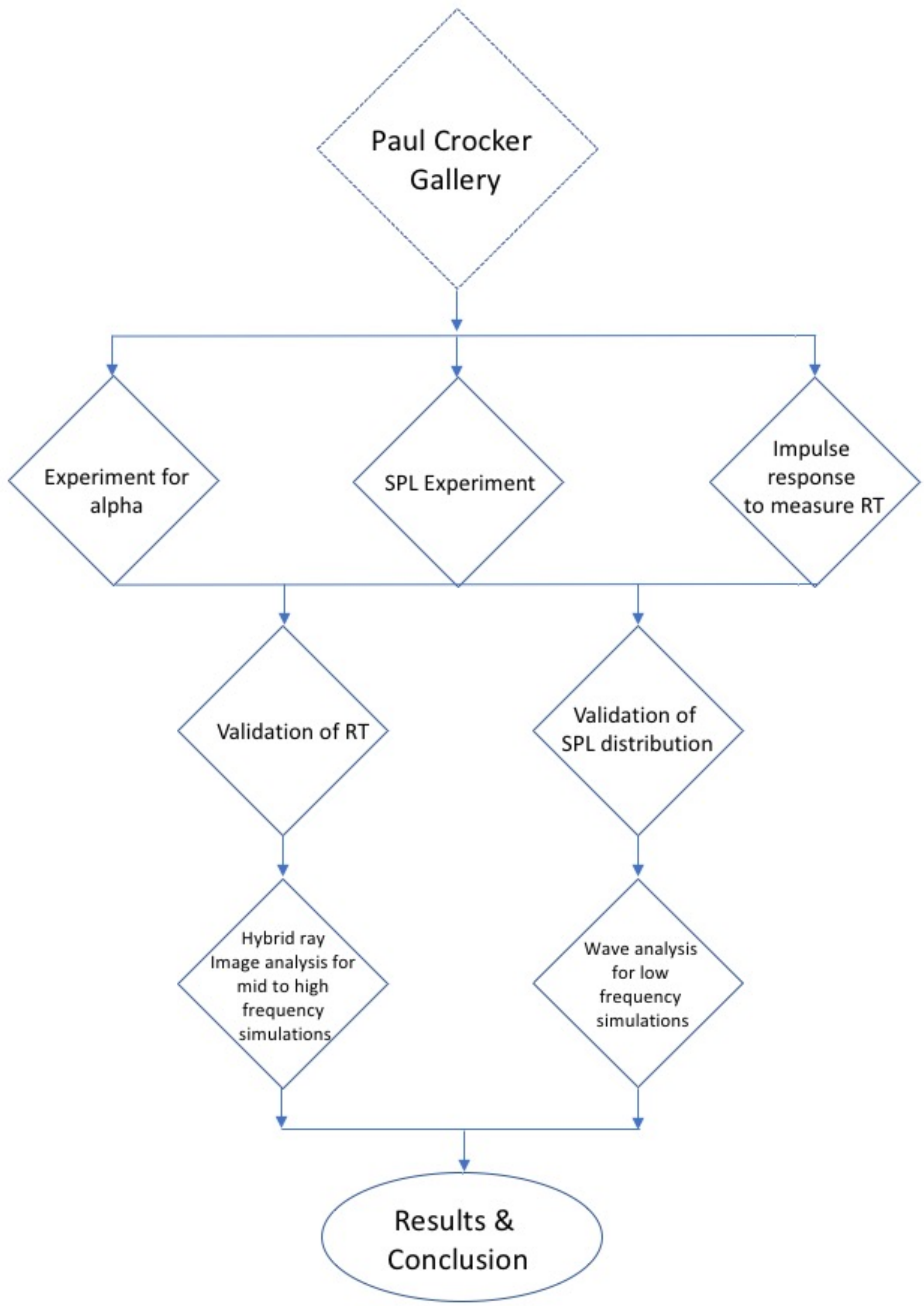


Figure 13: Methodology for Paul Crocker Gallery - Flow Chart B

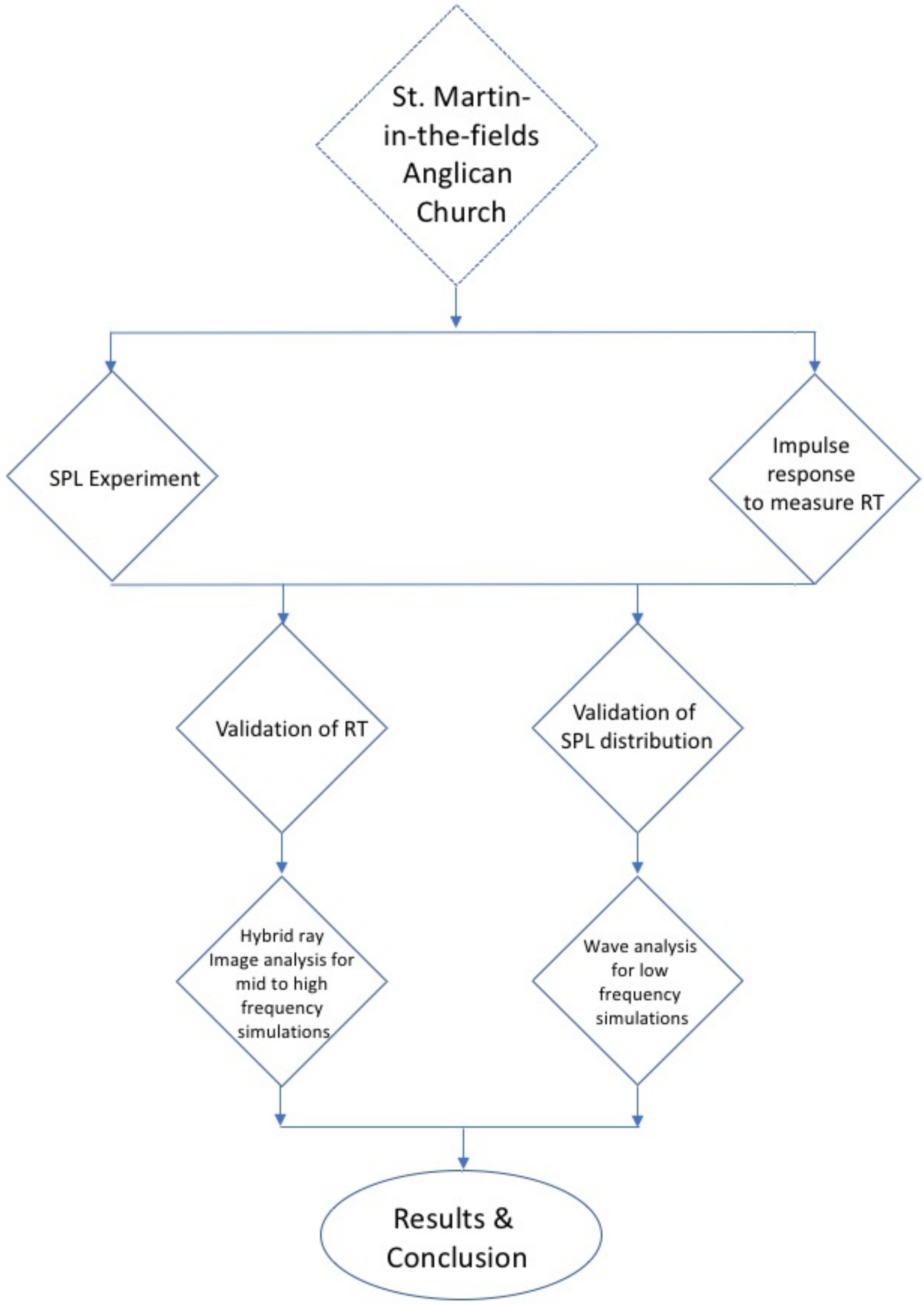


Figure 14: Methodology for St. Martin-in-the-fields Anglican Church - Flow Chart C

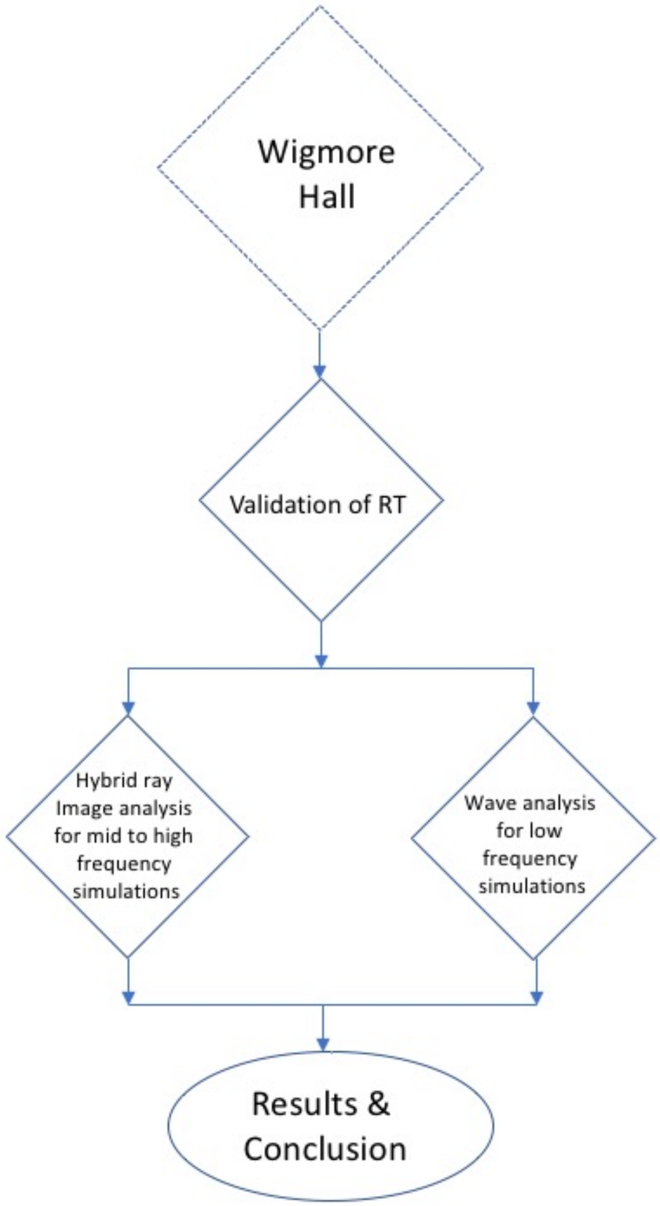


Figure 15: Methodology for Wigmore Hall - Flow Chart D

3.1 Locations

3.1.1 Paul Crocker Gallery

The Gallery space, located in the Ryerson Architecture Building, is in the downtown core of Toronto, Ontario. The enclosed room is composed mainly of gypsum board on the walls, curtain wall glazing, felt (shown in red in Figure 16), and painted concrete for the ceiling. The space has a volume of 350m^3 and is a mix of geometric and organic forms. It has four dominating walls, one of which is mainly glazing. To reduce the highly reflective impact of the glazing on the room, four additional perforated boards, shown in burgundy, with high absorption values, were introduced to reduce the overall RT, as shown in Figure 17.

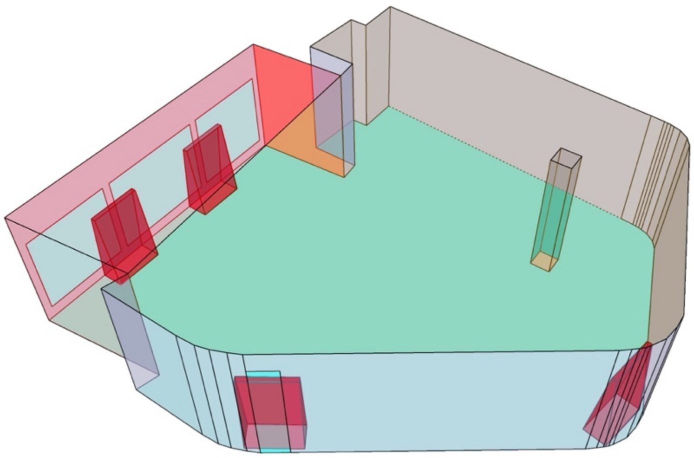


Figure 16: Paul Crocker Gallery - Sketchup Model

Figure 17: Paul Crocker Gallery - Glazing area with two perforated boards

3.1.2 St. Martin-in-the-fields

St. Martin's, located in the west-end of Toronto, has barrel-vaulted ceilings, wooden accents and good acoustics (4). The material composition of the space is wood floors and pews, plaster ceilings, gypsum board walls, ornamental wood accents, glazing for windows, and a brick skirting. Figure 18 shows the view from the back of the nave, where the congregation sits, looking forwards to the sanctuary, where the altar is located, and the presbytery, where the priest conducts the readings / mass. At present, there is a PA speaker system which has microphones in certain areas of the sanctuary and projects through four speakers in the centre of the nave. St. Martin's has a volume of 3,455m^3.

Figure 18: St. Martin-in-the-fields (view from the back of the nave)

3.1.3 Wigmore Hall

Wigmore Hall, shown in Figure 8, is of the Renaissance style architecture and dates from 1901. It is a world renowned modern concert venue praised for its acoustics. The hall is a basic rectangle, with an elliptic vaulted ceiling; the stage platform has a cylindrically shaped apse and a spherical cupola above. It was built by the German piano firm Bechstein and designed by English architect Thomas Collcutt (11). The walls, flooring and stairwell were constructed from wood, alabaster and marble, while the seating is upholstered (11). Wigmore Hall has a volume of 3,063m^2. The hall continuously attracts some of the world's leading musicians for performances and recording sessions (11). The cupola was refurbished during 1991-1992 while the remainder of the hall was redone from 2004 to 2014 (11) (5). The main goal of the refurbishment was to maintain the existing acoustic conditions. Arup Acoustics was commissioned for this project. Wulfrank and Orlowski investigated the aspects of Wigmore Hall's acoustic qualities and published the results in reference 5.

3.2 Experiment

These three enclosed spaces with curved envelopes were analyzed for the MRP. To complete the analysis, there was a combination of on-site acoustical measurements and computer simulations. The impedance tube was used to measure the absorption coefficients of materials; sine-sweep measurements allowed for the analysis of acoustical measurements of the Gallery and St. Martin's. Pink Noise was used to measure SPL distribution within the Gallery.

3.3 Simulations

For room acoustics, it is important to study if sound is "good" in a quantitative way, by analyzing acoustic parameters. An acoustical analysis can be done through real time measurements and simulations. There are many simulation programs available which provide such results. The two programs used for this major research project were ODEON and COMSOL Multiphysics (12) (13).

***3.3.1 ODEON– Hybrid-Ray Theory* (12)**

ODEON is a computer software used to simulate and measure interior acoustical parameters of buildings. It uses a hybrid method, image-source combined with modified ray tracing, for simulating the acoustical impact. The acoustic parameters can be measured with a 3D-model, and materials assigned to each layer. The simulation method uses a hybrid of algorithms for optimized results. It uses the mage-source method to predict early reflections, ray radiosity (ray-tracing) for late reflections, reflection-based scattering for scattering and diffraction, and one and two-point diffraction paths over screens to calculate sound attenuation in behind. The geometries of the room and absorption properties of the materials are entered as the physical characteristics of the room.

***3.3.2 COMSOL Multiphysics ("COMSOL") – Wave Theory* (13) (14)**

COMSOL has an Acoustics Module that provides the necessary tools to model acoustics and vibrations. It has the capability to analyze, solve and simulate acoustical problems using Finite Element Analysis ("FEA"). COMSOL can simulate devices that produce, measure and use wave acoustics. The Pressure Acoustics interface can model the modal behaviour of a room. In low frequencies, room resonance dominates, as the number of room modes are smaller. The modal behaviour of rooms is best solved with the wave equation using the FEA method. The modal simulation relates architectural geometries and physical metrics to provide room acoustic measures. Between the high and low frequencies there is a transition zone. In the higher frequencies, the wavelength is smaller than the geometries within the room. Before this transition, the modal behaviour of the room is most important, where standing waves dominate over the reverberant nature of the room. The software measures RT, early decay time, clarity, echo, centre time, and many other acoustic parameters.

By using both ODEON and COMSOL the entire frequency range was covered, allowing for the acoustical analysis of curved surfaces.

4.0 Experiment

The experimental measurements were conducted at the Gallery and St. Martin's. The measurements included sound distribution within the space as well as the determination of absorption coefficient of materials used for the Gallery. In addition, impulse responses through a sine-sweep acoustics signal were used to determine the RT of the two sites in Toronto.

4.1 Paul Crocker Gallery

The Gallery, shown previously in Figure 16, is enclosed with three large walls of drywall and one mainly of glazing, which both have low absorption coefficients. As the space is highly reverberant, four absorbing walls were introduced into the room. Two of these were located along the glazing, and the other two were located along the edges of the room. The perforated walls are highly absorptive structures, filled with Rockwool insulation, as can be seen in Figure 17 and 19, which shortens the overall RT of the room. Rockwool is a stone wool insulation and is one of the best porous absorption materials available (15). Porous materials are ideal as "sound energy is dissipated in a porous material owing to the friction involved in movement of air particles in the pores" (2).

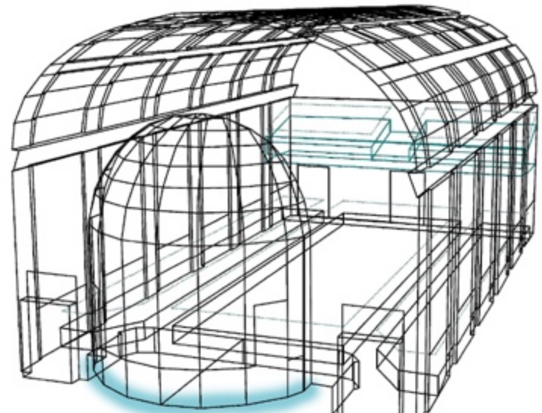
4.1.1 Absorption Coefficient

As ray theory computer simulations rely heavily on absorption coefficients and room geometries, it was important to understand each room's composition as well as any additional structures put into them. The acoustic absorption of the Curve and perforated boards were tested in the impedance tube, while all other acoustical absorptions coefficients of existing room materials were derived from the computer simulation database and Reynolds' textbook (16).

Figure 19: Perforated Board

Though the Gallery does not have extreme curved surfaces like St. Martin's and Wigmore Hall, an additional curved structure was integrated into the study for testing purposes, as shown in Figure 20. The Curve was designed as a dead wall, and to reflect sound. It was formed with a wooden structure, filled with Rockwool insulation, and covered with medium-flex plywood. The Curve added to the Gallery is representative and based on Wigmore Hall, having a curve as the back of the stage wall, as shown in Figure 21.

The arches from the surfaces were cut using a CNC machine for accuracy, and medium-flexible plywood was glued and stapled to the exterior of the frame. Following this, Roxul insulation was carefully measured, cut and placed into the curve, and then the interior part of the curve, made of plywood, was stapled and glued on. The details are presented in Appendix A. The acoustic absorption of the curves and the perforated boards were tested in an impedance tube. The perforated boards are highly absorptive and the Curve is reflective.

	
Figure 20: Curve for Gallery	*Figure 21: Gallery Curve based off Wigmore Hall back of stage (From Wulfrank, (5), edited by Eva Johnston-Iafelice)*

The impedance tube, shown in Figure 22 was used to measure the acoustic absorption coefficients, and acoustic impedance of the materials used in the Curve as well as in the perforated boards. The two-microphone impedance tube method uses a digital frequency analysis system, Lab View, to acquire the absorption coefficients of materials. Sample sizes of the Curve and the perforated boards were created for measurement in the impedance tube, as shown in Figure 23. The digital frequency analysis system evaluates the absorption coefficient and normal acoustic impedance in complex variables. Schematic details of the impedance tube are shown in Figure 24. The impedance tube measures sound absorption coefficient and sound transmission loss, in addition to other acoustic properties of porous materials (17).

Figure 22: Impedance Tube

Figure 23: Test sample of perforated wall

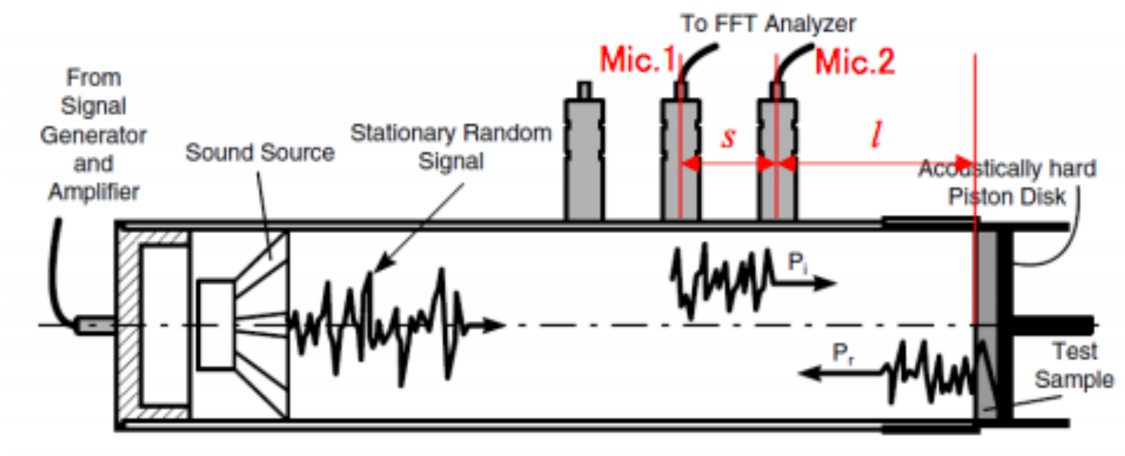


Figure 24: Schematic drawing of 2 microphone method for the impedance tube [From Kimura, (17)]

4.1.2 Sound Level Distribution

A floor grid showing receiver and source locations was created to measure if there was equal sound distribution throughout the room, as shown in Figure 25 and 27. Two of the receiver locations, R1 and R2, in the Gallery were used for validating computer simulations. Locations 1 through 21 used Pink Noise for SPL distribution measurements at one-third octave band frequencies. There were two source locations, S1 and OS1. All Gallery locations can be seen in Figure 26. The Curve, later introduced into the space, had a radius of 27"; its location can be seen in Figure 26. The naming conventions for the measurement set-ups can be seen in Table 1.

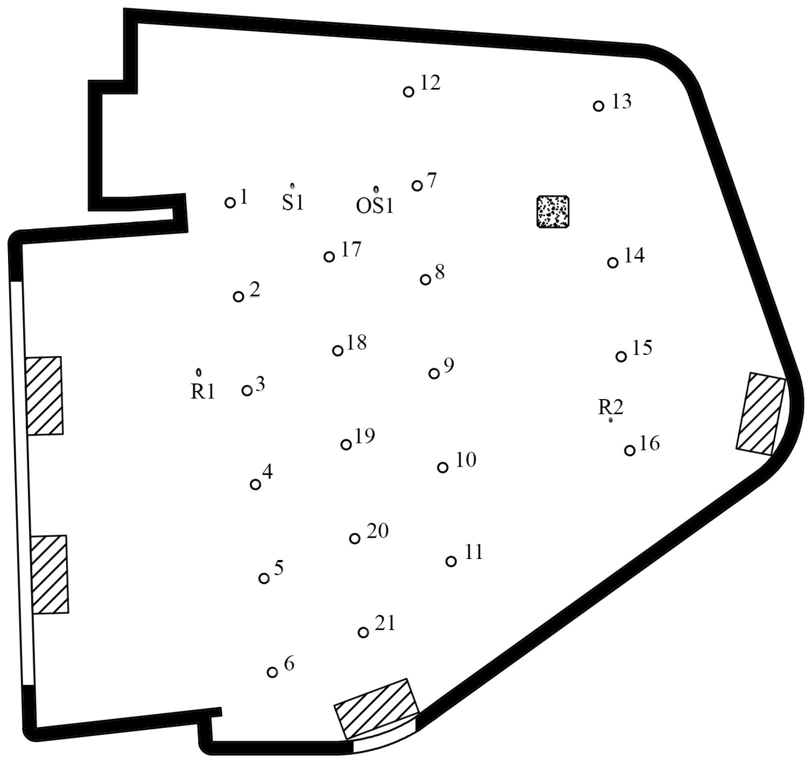


Figure 25: Paul Crocker Gallery as Bare Room with source and receiver locations

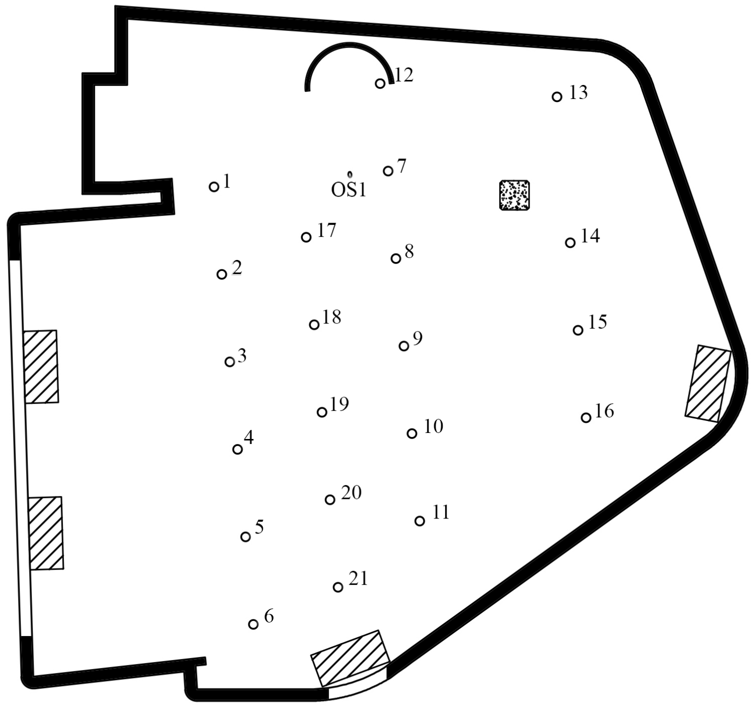


Figure 26: Paul Crocker Gallery with Curve, source and receiver locations

Figure 27: Paul Crocker Gallery Source Location OS1

Table 1: Naming Convention

Gallery	Location S1	Location OS1
Bare Room	BR-S1	BR-OS1
Curve	/	C-OS1

4.1.3 Reverberation Time Evaluation

The Gallery was acoustically measured on-site as a Bare Room using ray theory. ODEON sent a sine-sweep signal, and the impulse response of the sine-sweep signal calculated the acoustic parameters. The signals were 8-10 seconds long and occurred at each one-third octave band frequency. The Bare Room set-up consisted of the Gallery and perforated boards. The sine-sweep measurement results from the Bare Room were used to validate the ray theory simulations. The receiver locations for the sine-sweep measurements for Bare Room were R1 and R2, as can be seen in Figure 25 and 26, and were tested at a height of five feet.

Once the on-site acoustic measurements were completed for Bare Room and the Curve, its receiver locations were tested along the grid points from 1 to 21. The measurements conducted were for Pink Noise and impulse response measurements for Bare Room, but only Pink Noise at one-third octave band frequencies for the Curve. An omni-directional speaker was used for all the Gallery tests. For the Curve, source location OS1 was used, and was located approximately 89" away from the curve.

4.1.4 Room Acoustic Metrics

The 3D model for the Gallery is shown in Figure 28 from a bird's eye view. To validate the model, materials were chosen from the acoustical software database which matched the materiality of the room. The RT values from the Bare Room on-site measurements were used to validate the simulations of the Gallery. To match the RT of the Gallery to the simulation, the absorption coefficients of some of the materials were further adjusted using Reynolds' textbook (16).

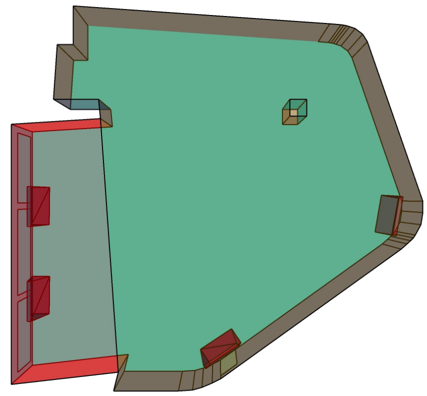


Figure 28: Paul Crocker Gallery

4.2 St. Martin-in-the-fields Anglican Church

4.2.1 Room Acoustic Metrics

The important room acoustic metrics for this research were RT and SPL. RT was gained through on-site acoustical measurements, it was used for validation purposes in simulations to analyze SPL distribution throughout the enclosed spaces.

On-site acoustical measurements were taken at the unoccupied St. Martin's Anglican Church. The interior composition of St. Martin's is mainly wood, plaster, drywall and glazing, as can be seen in Figure 29 and 30. The PA speaker system, located in the centre of the room, as shown in Figure 31, was connected to the acoustical software to receive a sine-sweep signal for impulse response measurements. The microphone moved through four receiver locations, along the centre of the room to acquire RT. The data collected was used to validate the ray theory computer simulations.

Figure 29: St. Martin-in-the-fields – View of the Sanctuary

Figure 30: St. Martin-in-the-fields - Looking towards the back of the nave

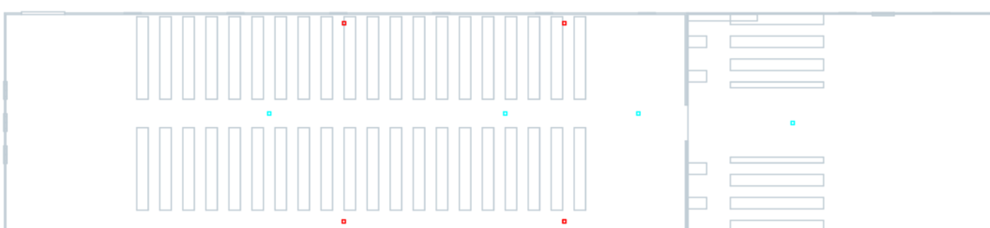


Figure 31: St. Martin-in-the-fields Speaker (red) and Receiver (blue) Locations. The Receiver Locations from left to right are 4, 3, 2 and 1.

5.0 Experimental Results

On site measurements were taken in the Gallery and in St. Martin's as they are both located in Toronto. Absorption coefficients, sound level distribution and room RT were measured in the Gallery. The Gallery measurements also incorporated the introduction of a Curve as shown and described in Chapters 3 and 4. In addition, room acoustic parameters, such as RT, were measured at St. Martin's. Some of the measurement results were used in the computer simulation to validate additional simulations. Details of the experimental results are described below.

5.1 Paul Crocker Gallery

5.1.1 Absorption Coefficient Results

The impedance tube measured the acoustic absorption coefficients of the perforated boards and the Curve using samples, results can be seen in Table 2.

Table 2: Measured Absorption Coefficients of Perforated Boards and Curves

Centre Frequency (Hz)	Metric – Perforated Boards	Metric - Curve
63	0.51	0.23
125	0.71	0.22
250	0.84	0.26
500	0.84	0.25
1000	0.85	0.24
2000	0.96	0.23
4000	0.96	0.22
8000	0.96	0.20

5.1.2 Reverberation Time Results

Sine-sweep measurements for impulse response were completed using computer software, a microphone at receiver locations, and an omni-directional speaker to acquire RT data. The RT data from the measurements for Bare Room, with source location OS1 are listed in Table 3, with the receiver location 1 ("R1") and receiver location 2 ("R2"), as detailed in Figure 25. When validating the 3D model of the Gallery for the computer simulation, the RT results were used. As can be noted from the results of Table 3, the RT were quite similar independent of receiver location.

Table 3: Bare Room, Source OS1 RT Results

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
RT – R1	0.97	1.46	1.65	1.78	1.67	1.13	0.78	0.5
RT – R2	0.99	1.43	1.63	1.89	1.73	1.08	0.78	0.51

After the BR-OS1 measurements were completed, Pink Noise measurements were taken of the Curve; see Figure 32 for a view of the of the set-up.

Figure 32: On-site measurements in Paul Crocker Gallery – C-OS1

5.1.3 Sound Pressure Level Variation

Additional measurements were completed at the grid receiver locations throughout the room to measure the SPL distribution, as shown in Figure 25. The grid receiver locations were tested with Pink Noise for the Curve at source location OS1. The results of the band sound pressure levels along all grid points are compared between BR-OS1 to C-OS1 in Figures 33 through 35. In the Gallery, BR-OS1 is the Bare Room including the introduced perforated boards. C-OS1 is the Gallery with the perforated boards and Curve.

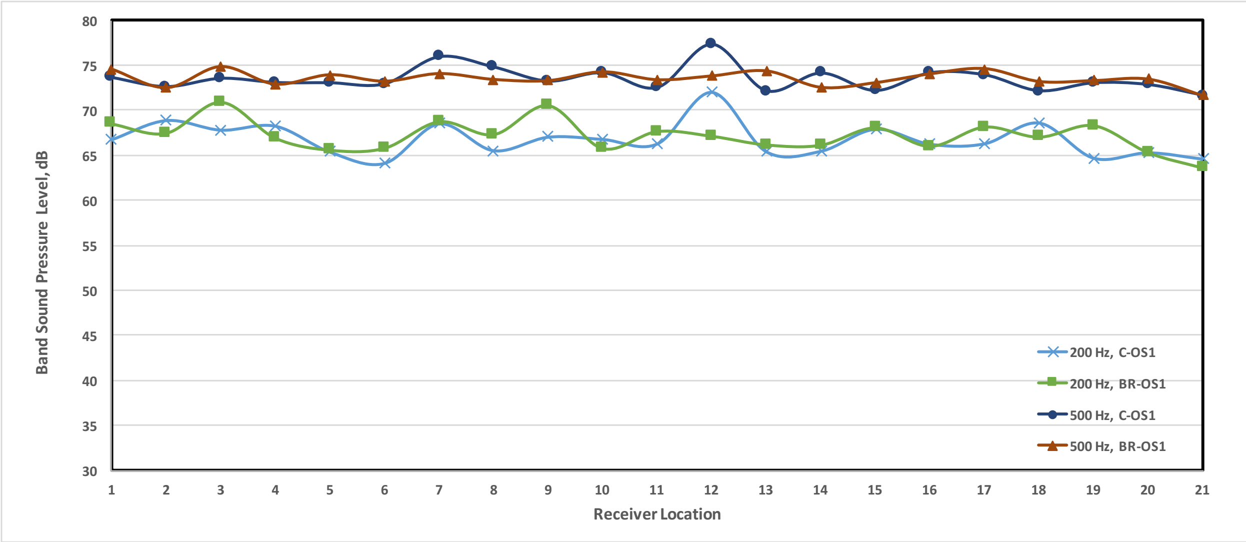


Figure 33: Band Sound Pressure Level with C-OS1 vs. BR-OS1 at 200Hz and 500Hz

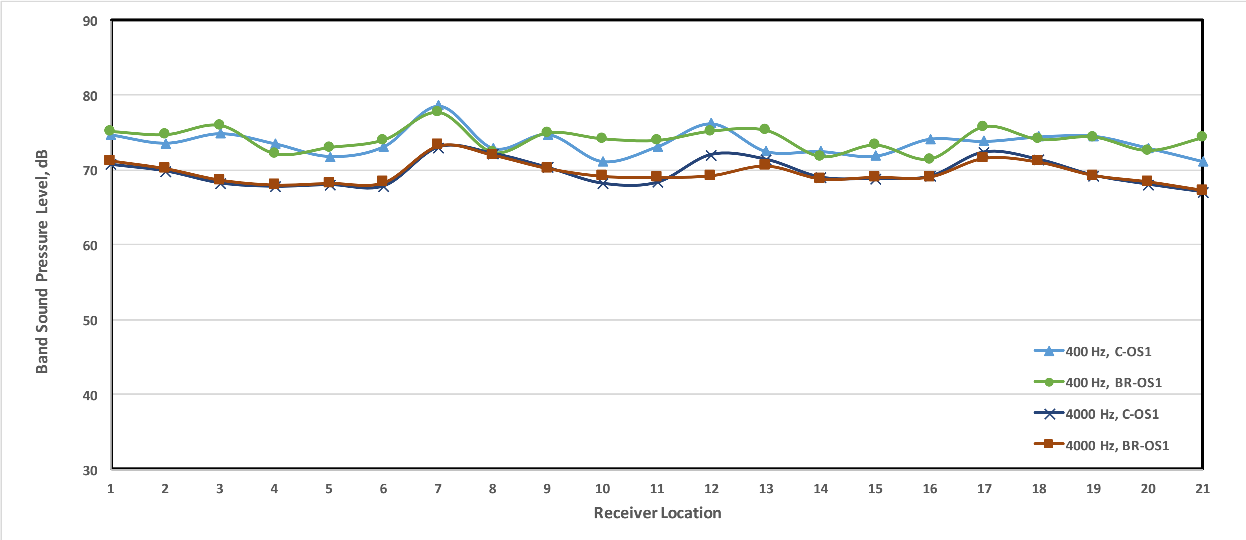


Figure 34: Band Sound Pressure Level with C-OS1 vs. BR-OS1 at 400Hz and 4000Hz

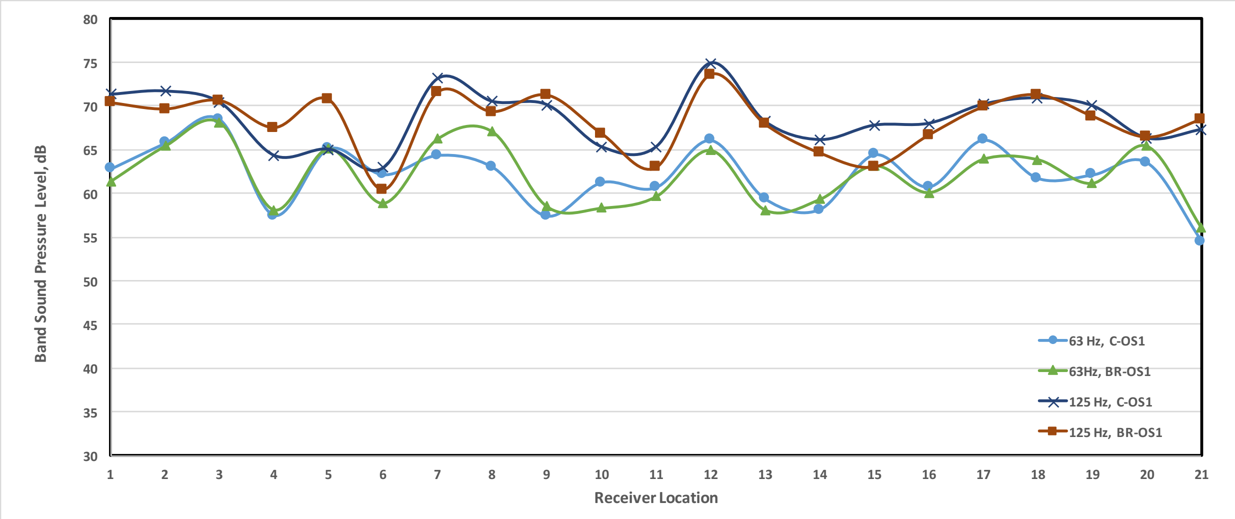


Figure 35: Band Sound Pressure Level with C-OS1 vs. BR-OS1 at 63Hz and 125Hz

As can be seen from the Gallery measurements, at certain frequencies some inflexion occurs near Point 12 for C-OS1, as shown in Figure 33 and 35. At other frequencies, also shown in Appendix B, the C-OS1 curve also had very little impact on the audience space. The SPL distribution is fairly uniform, and the reason for the kinks are due to the impact of room modes. All rooms have resonant frequencies where the room is divided into antinodes and nodes. Antinodes have the maximum pressure, while nodes have zero pressure (18). If the source is located at an antinode for that specific frequency the room will respond very well, but if at a node, the room will not respond well (18). Room modes, also known as standing waves, are created from two waves travelling in opposite directions, it can alternate between zero and a maximum amplitude (19). Standing waves are not absorbed as strongly as other sounds therefore they have a longer decay time at the frequency in which the standing wave occurred. Room modes store energy and therefore decay more slowly than other reflections which can cause ‘boominess’. Due to this differential decay, the longest decay in a room is usually due to standing waves, whereas the diffuse sound field produces shorter decay times (19). A rectangular room encourages certain frequencies with wavelengths which are related to the dimensions of the room, these are known as axial, tangential or oblique modes, depending on how many surfaces the room is comprised of (20). As frequency increases, so does the number of room modes, as does the closeness of the modes within an enclosed room (21).

Due to the above measurement results, it was pertinent to compare the difference between the BR-S1 versus BR-OS1, as well as C-OS1.

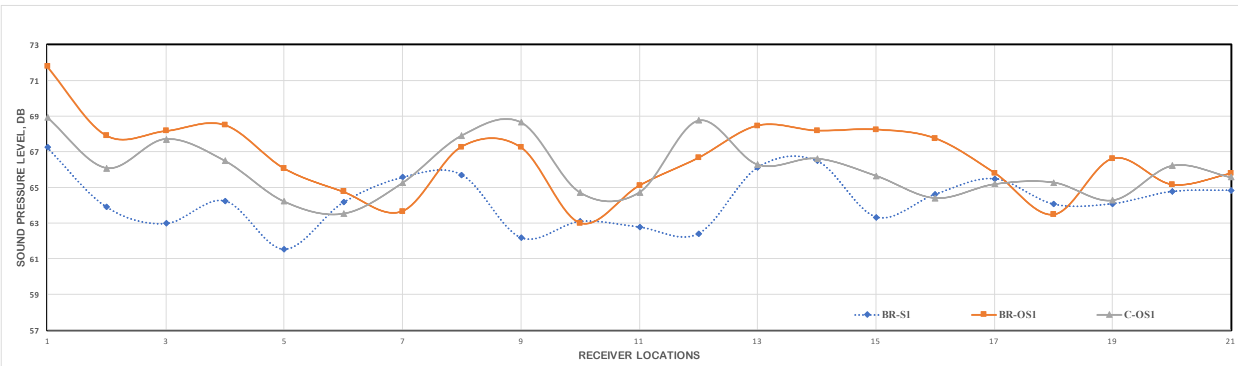


Figure 36: Band SPL Distribution – S1 vs OS1 vs C-OS1at 160Hz

Figure 36 shows that there was a larger difference between the source locations, S1 versus OS1, than between OS1 and C-OS1, showing again that the Curve did not impact the sound pressure distribution throughout the room.

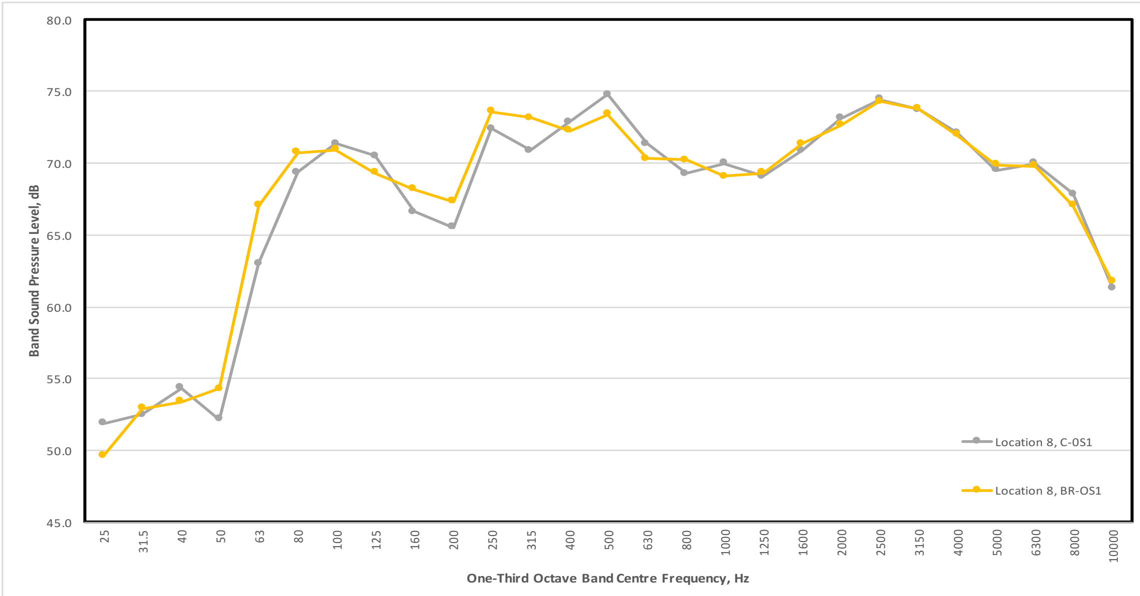


Figure 37: SPL Distribution - Gallery Point 8 - C3A-OS1 vs. BR-OS1

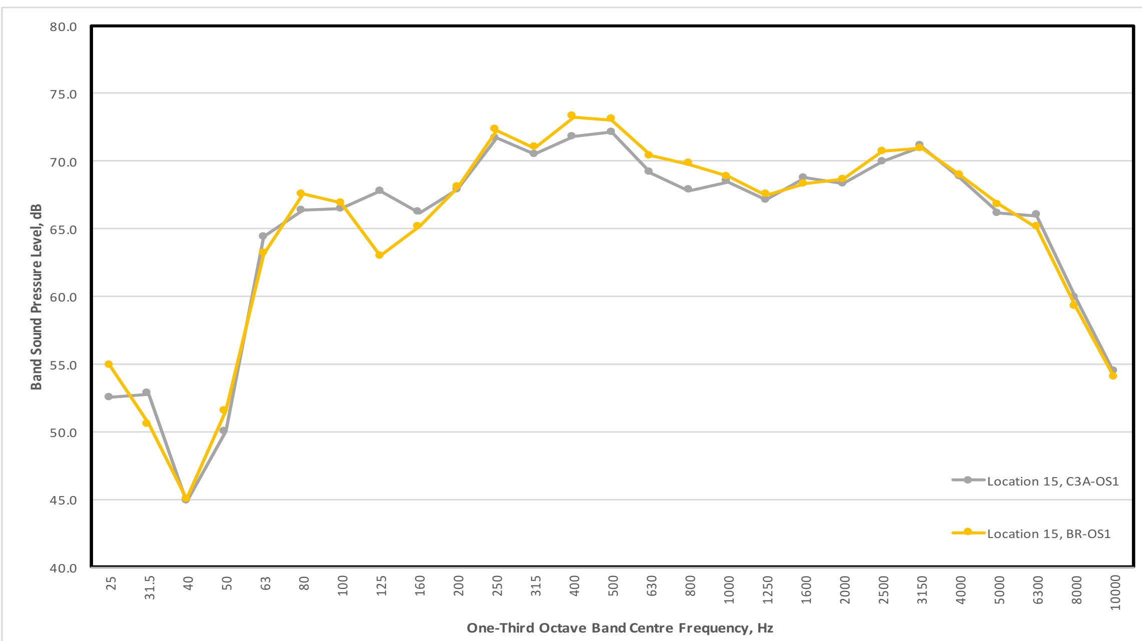


Figure 38: SPL Distribution - Gallery Point 15 - C-OS1 vs. BR-OS1

It can also be noted that multiple receiver locations on the grid have fairly equal band sound pressure levels from 63Hz to 5000Hz. Points 8 and 15, Figures 37 and 38 respectively, are shown as examples. As noted previously, there is little change between Bare Room and the Curve; a larger curve was later studied to see if it had a greater impact the audience space. Excluding the 160Hz-200Hz frequencies, the remainder of the one-third octave bands between 80Hz and 6300Hz had approximately a 5dB difference. For this research project, if the SPL distribution has a change of less than 5dB overall, or +/- 2.5dB, then the SPL distribution is considered equal, as this amount of change is not perceptible by most humans (2). Thus, excluding a few one-third octave bands the Gallery seems to have equal SPL distribution at receiver location 8 and 15, refer to Figure 37 and 348 The potential reasons that the band SPL had more than 5dB of difference at certain frequencies can be due to human error or background noises. Another reason for the decrease in band SPL for the highest and lowest frequencies may be due to the microphone or omni-directional speaker. The speaker might not be able to properly emit those frequencies, and the microphone may not be capable of picking them up. Additional figures and tables are available in Appendix B for further comparisons.

5.2 St. Martin-in-the-fields **(12)**

St. Martin's measurements were completed within the unoccupied church. Four receiver locations were used for measurements with the existing speakers as the source. The data in Table 5, shows the RT for all four receiver locations. The data from Receiver Location 2 was used to validate the computer simulations.

Table 4: St. Martins, Source 1 (Speakers), Receiver 2 measurement results

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
RT L1	-	2.8	2.92	3.2	2.98	2.67	1.89	0.96
RT L2	-	3.11	2.88	3.27	2.99	2.71	2	1.01
RT L3	4.08	3.36	2.96	3.06	2.66	2.44	1.85	0.92
RT L4	-	2.97	2.86	3.27	3.05	2.75	1.94	0.8

As can be seen from the measurement results, St. Martin's has a long reverberation time, which can be ideal for music. It is not quite 4s as had been anticipated from reading O'Keefe's paper (4), but still nearly 3s at most frequencies, which is quite high. It is a mixture of the materials and building geometry, that provide such a lengthy RT. Simulations tested the SPL distribution throughout the space to see if the barrel-vaulted ceiling impacts the audience space negatively. It will also show if there are focussing issues. Focussing is only an issue when at the audience's ear level, therefore if it is above the audience space there are no issues because sound diffuses beyond the focal plane. O'Keefe suggested that there are no focussing problems in St. Martin's (4). The distance from the source to the curve, barrel vaulted ceiling, is ideal, to the point that it creates just enough diffusion while still locating the focus above the listener's head (4). The focal area is not within the audience area, otherwise the graph representations would show high sound pressure level concentration in one area.

It is also highly likely that St. Martin's barrel vaulted ceiling caused envelopment, alike to the cathedral dome in St. Paul's (4). Envelopment occurs when later reflections, such as 3rd, 4th and 5th reflections arrive at the listener from the side (4). This is an enjoyable acoustic quality for musical performance.

O'Keefe also discusses the importance of modelling with splines for curves as opposed to a multitude of small lines as flat segmented surfaces, which provided inaccuracy in the past (4). Programs like COMSOL Multiphysics allows the use of wave theory, which does not break the curves down. These simulations are shown in Chapter 6.

6.0 Simulation Results

Two commercially available acoustics softwares were used to evaluate sound distribution across the Gallery, St. Martin's and Wigmore hall. The Gallery Bare Room and unoccupied St. Martin's church were validated first so that additional simulations provided acceptable results. The simulation results are described below.

6.1 Paul Crocker Gallery

The Gallery used sine-sweep measurements to evaluate impulse response from which different acoustic metrics were calculated. The RT was used to validate the computer simulation. Hybrid-ray theory acoustic software was used for mid- to high-range frequencies, while wave theory acoustic software was used for low frequencies.

6.1.1 Bare Room Hybrid-Ray Theory Validation

The site measurements taken from the Gallery as a Bare Room (BR-OS1) were used to validate the acoustic parameters of the Gallery. The measured RT from the on-site measurements was used and matched for the simulation. The materials chosen were from the software database, see Table 5 for the database materials (12). The source location in the Gallery can be seen in Figure 25.

Table 5: Gallery – Pre-adjusted material absorption coefficients

Materials (a)	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Floor	0.02	0.02	0.02	0.03	0.04	0.04	0.05	0.05
Ceiling	0.01	0.01	0.01	0.02	0.02	0.05	0.05	0.05
Wall	0.28	0.28	0.12	0.1	0.17	0.13	0.09	0.09
Felt (7001)	0.03	0.03	0.09	0.25	0.31	0.33	0.44	0.44
Glazing (10004)	0.15	0.15	0.05	0.03	0.03	0.02	0.02	0.02
Perforated Boards	0.51	0.71	0.84	0.84	0.85	0.96	0.96	0.96
Concrete (102)	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Curve	0.23	0.22	0.26	0.25	0.24	0.23	0.22	0.96

ODEON's database was used for determining material absorption coefficients, as shown in Table 6.

Table 6: Measured and pre-adjusted RT for Gallery Bare Room

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
BR RT measured (s)	0.97	1.46	1.65	1.78	1.67	1.13	0.78	0.5
BR RT pre-adjusted (s)	1.64	1.52	1.9	1.74	1.3	1.2	0.96	0.68

The RT values were validated by modifying the various surface coefficients using Reynold's textbook (16). The material database coefficients are shown in Table 7, followed by the final simulated RT, as shown in Table 8.

Table 7: Gallery - Adjusted material absorption coefficients

Materials (a)	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Floor	0.02	0.025	0.02	0.025	0.02	0.05	0.05	0.05
Ceiling	0.05	0.01	0.01	0.017	0.055	0.01	0.07	0.15
Wall	0.28	0.26	0.14	0.07	0.13	0.15	0.16	0.1
Felt	0.03	0.03	0.09	0.25	0.31	0.33	0.44	0.44
Glazing	0.15	0.15	0.05	0.03	0.03	0.02	0.02	0.02
Perforated Boards	0.51	0.71	0.84	0.84	0.85	0.96	0.96	0.96
Concrete	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Curve	0.23	0.22	26	0.25	0.24	0.23	0.22	0.96

Table 8: Measured and adjusted RT for Gallery Bare Room

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
BR RT measured (s)	0.97	1.46	1.65	1.78	1.67	1.13	0.78	0.5
BR RT adjusted (s)	1.26	1.48	1.67	1.6	1.18	1.12	0.79	0.55

The results of Table 8 show that the simulation with the modified data is producing validated RT results, as majority are within the 10-15% range of engineering precision. Excluding the 63Hz one-third octave band, which seems to be shorter than expected based on the ODEON simulation, the largest difference from the final simulation compared to the measured RT is 0.49s. As all other frequencies are within acceptable range, the 100Hz frequency data is acceptable for the purpose of this research. The measured data for 1000 Hz is presumed to differentiate due to HVAC equipment in the room. Figure 39 shows the ray theory software set up with source location OS1 (P1).

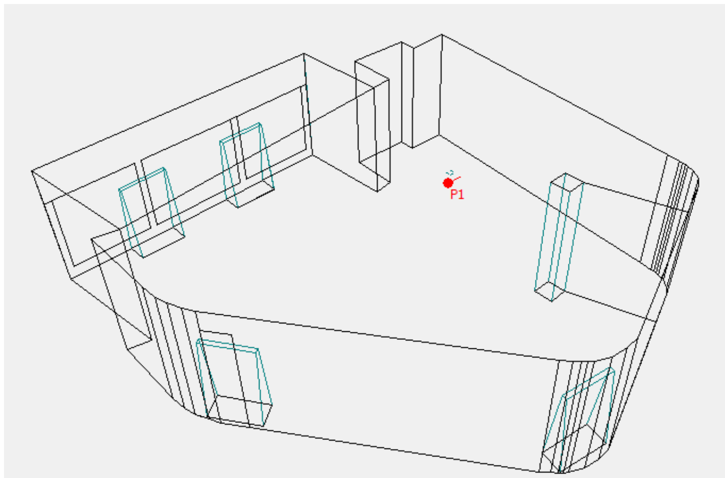


Figure 39: ODEON Set-up for Gallery Bare Room - OS1

The Gallery with the BR-OS1 set up uses ray theory to show SPL distribution throughout the room at 125Hz in Figure 40.

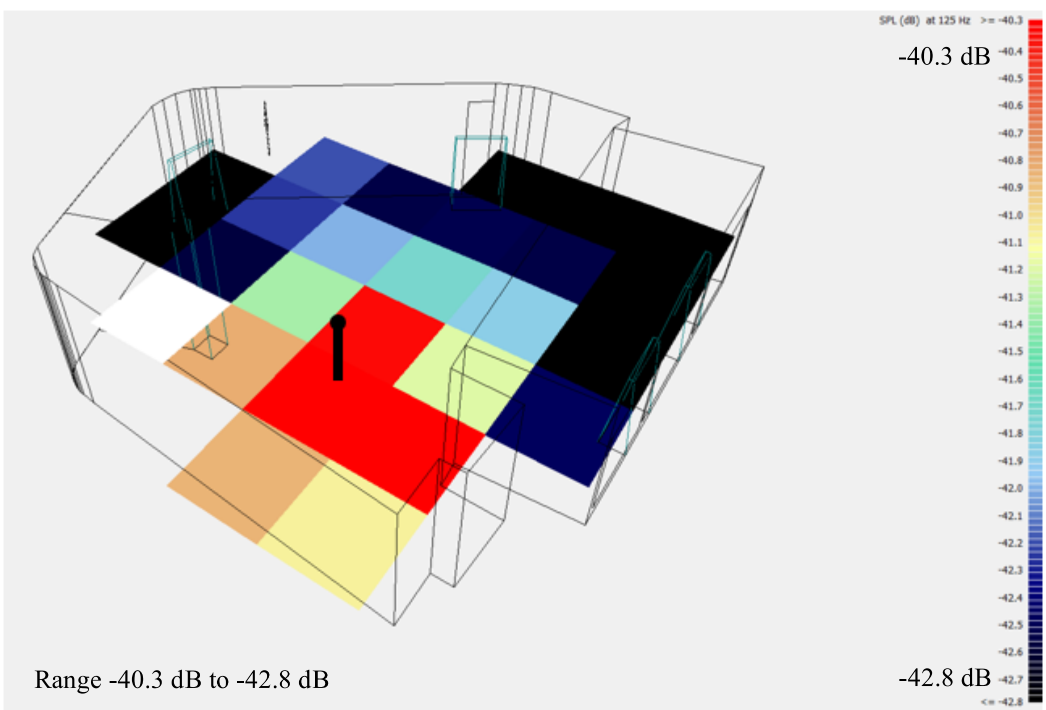


Figure 40: Gallery – BR-OS1 SPL Distribution at 125 Hz

The ray theory simulation is validated by the on-site measurements from receiver locations 1 through 21 as shown in the band sound pressure level graph, Figure 41.

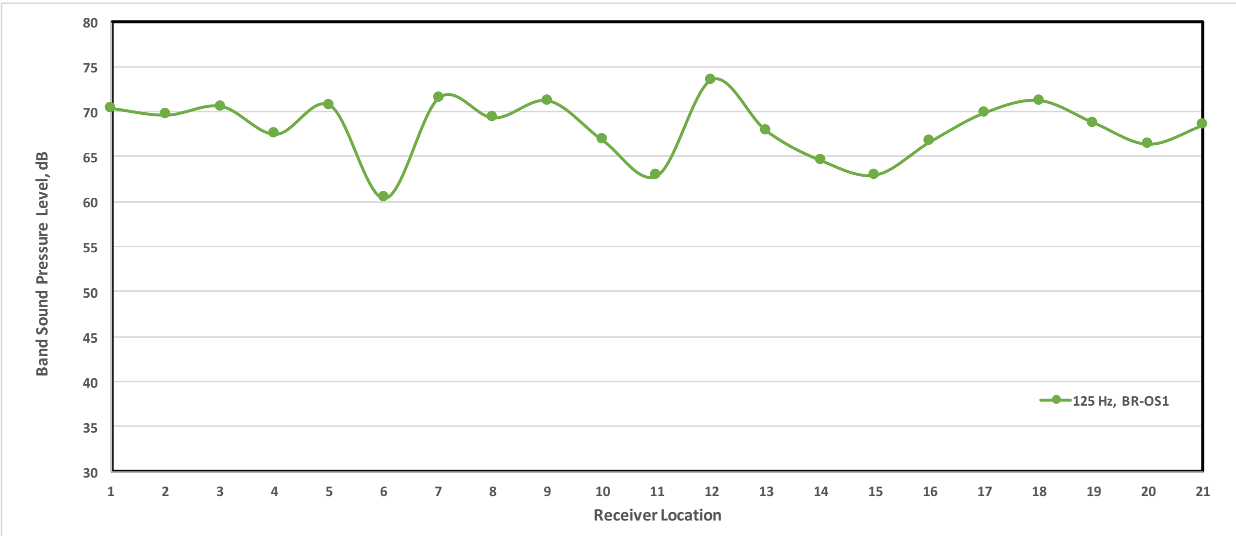


Figure 41: Band Sound Pressure Level BR-OS1 at 125Hz

SPL distribution throughout the Gallery space is shown for 500Hz in Figure 42.

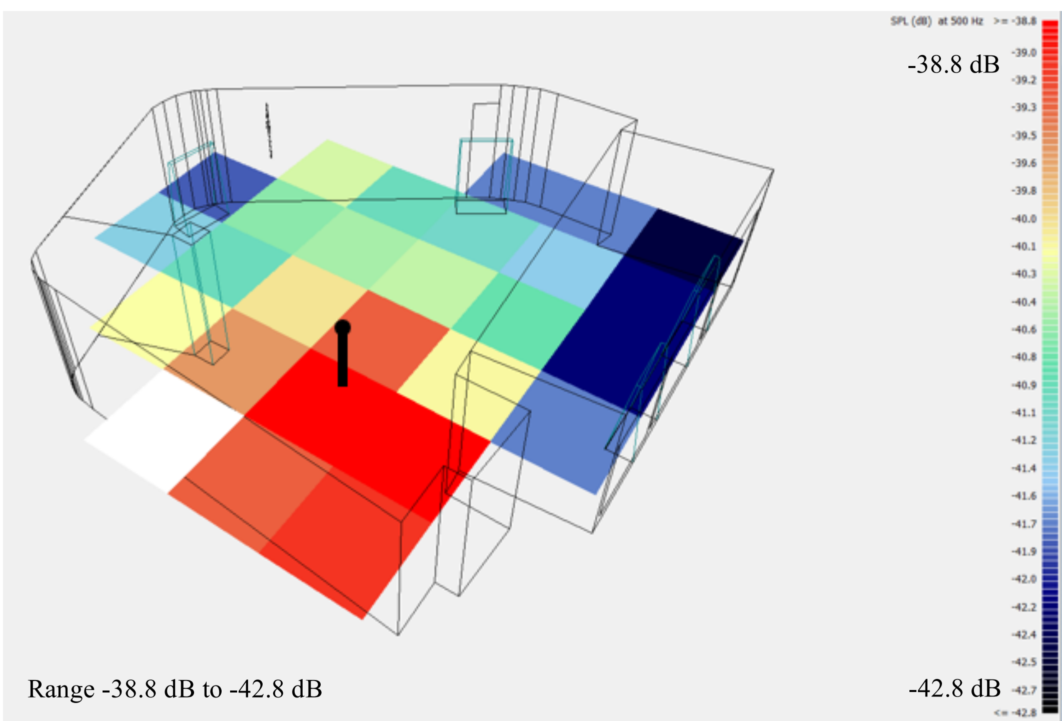


Figure 42: Gallery – BR-OS1 SPL Distribution at 500 Hz

The SPL distribution range of 2.5dB from Figure 42, is validated by the BR-OS1 graph for band sound pressure level at 500Hz, as shown Figure 43.

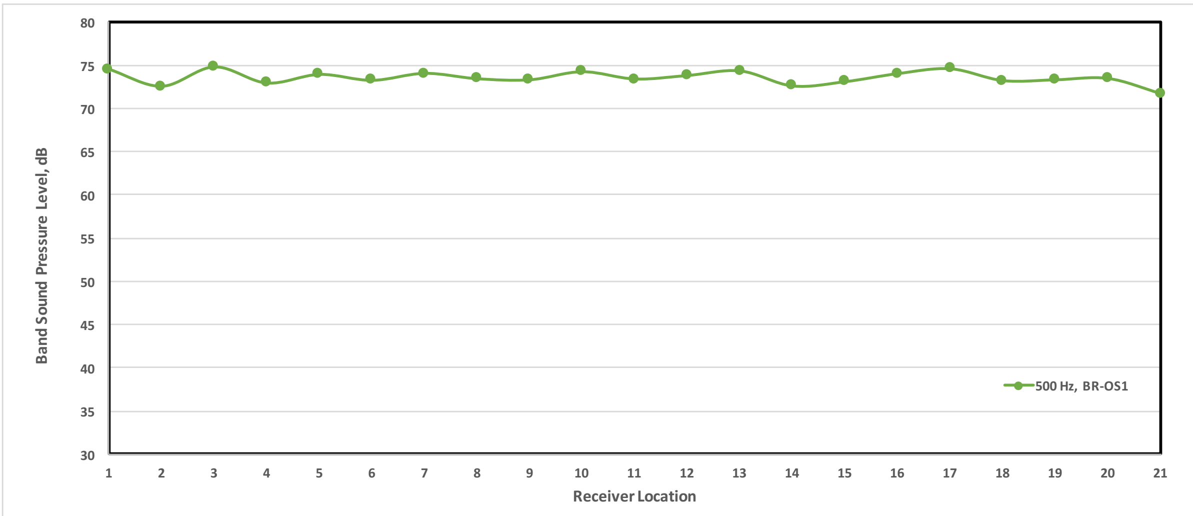


Figure 43: Band Sound Pressure Level with BR-OS1 at 500Hz

SPL distribution throughout the Gallery space is shown for 2000Hz in Figure 44 and validated in Figure 45.

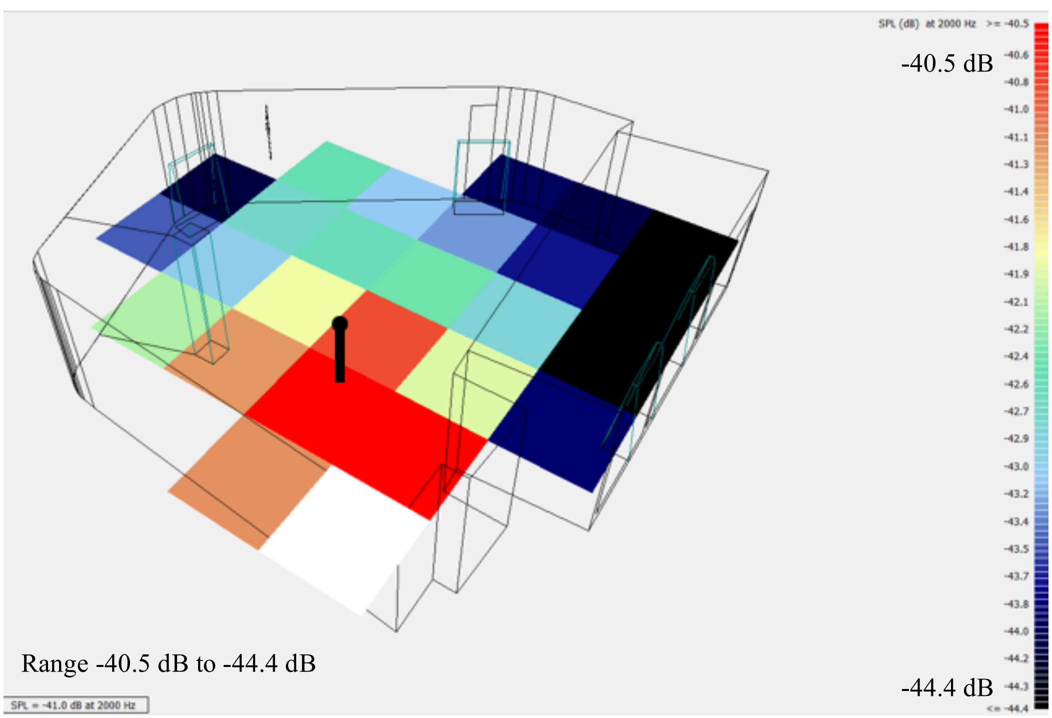


Figure 44: Gallery – BR-OS1 SPL Distribution at 2000 Hz

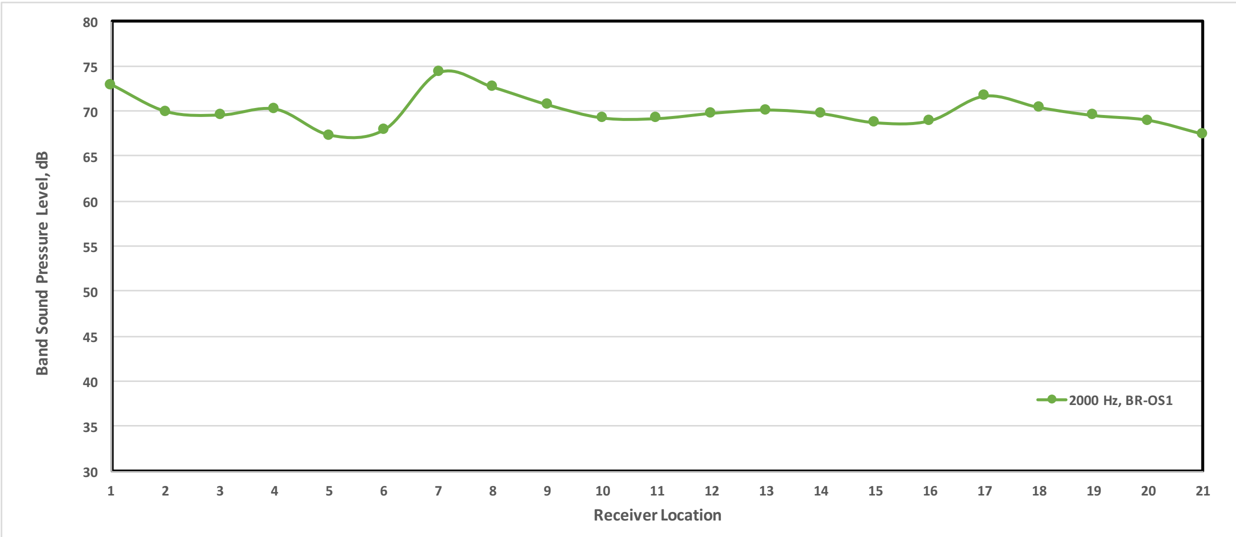


Figure 45: Band Sound Pressure Level with BR-OS1 at 2000Hz

The validation simulation of the gallery was able to reproduce the measured results within engineering accuracy. The differences for 63Hz and 1000Hz, is presumed to be due to mechanical ventilation noise and background noises, which were noted on site during the measurements.

The simulation of BR-OS1 can be seen in Figure 40, 42 and 44 showing the SPL distribution throughout the room. The source is shown in black. The simulations show that there is a difference of 2.5dB at 125Hz, 4dB at 500 Hz and 3.9 at 2000 Hz in the enclosed room. As mentioned in previous chapters, as long as the room SPL only differs by 5 dB throughout the room, it is considered to have equal SPL distribution. Therefore, it can be stated that the Gallery BR-S1 has equal SPL distribution throughout the audience space.

These grid representations of sound pressure in the room are also validated by graphs from the on-site ODEON measurements. As it can be seen by comparing Figure 40 and 41, the SPL difference across the room at 125Hz matches in terms of range of decibel levels. The same can be said about the 500Hz band, by comparing Figures 42 and 43, and then the 2000Hz band by comparing Figures 44 and 45. Additional frequency bands are shown in Appendix C.

6.1.2 Low Frequency Analysis of the Gallery with the Curve

Typical room acoustic softwares use ray theory to evaluate the room acoustic parameters. The process for ray theory is valid for frequencies above the Schroeder cutoff frequency. Below the cutoff frequency, the room modes start to dominate and wave theory analysis must be applied to solve for sound distribution. The formula to solve for the cutoff frequency within a room is shown by the following equation:

$$f_{cutoff} = 2000\sqrt{\frac{RT}{V}} \tag{1}$$

Where V is measured in m^3.

FEA is used to solve the fundamental wave theory, as is required for low frequency acoustical simulations. In order to solve for sound distribution throughout an enclosed space with curved elements, wave theory analysis must be applied.

Room modes are known as standing waves, two waves travelling in opposite directions; standing waves form when the distance between two surfaces is the same as half the wavelength of the frequency. The Multiphysics software was used to solve for low frequencies for the Gallery at 25 Hz, 50 Hz, and 100 Hz. The horizontal distribution of sound pressure level for 25Hz, 50Hz, and 100 Hz tones are shown in Figures 46, 47 and 48.

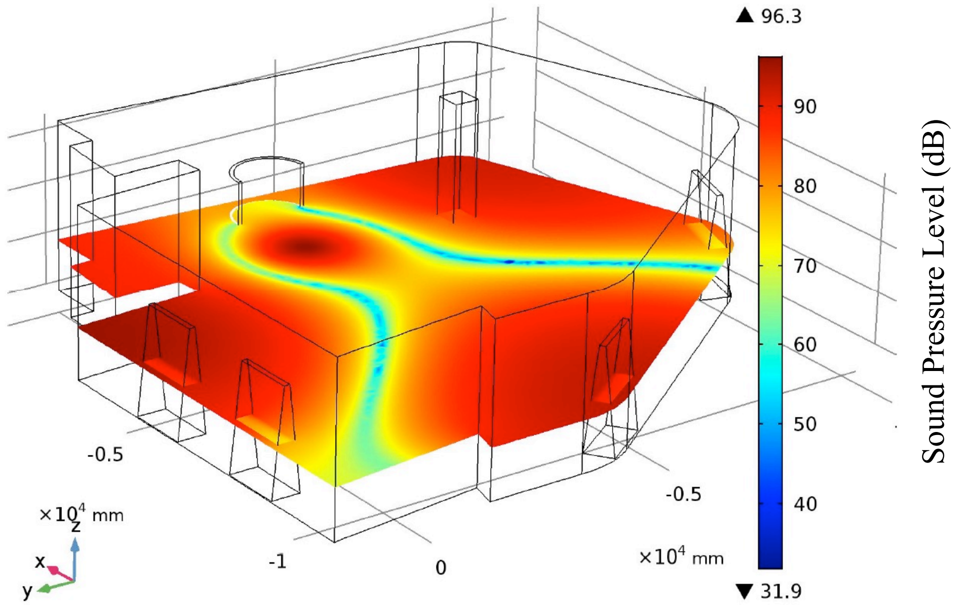


Figure 46: Gallery with Curve - Source outside curve 25Hz

The SPL distribution shows strong influence of the room modes due to very small modal density. The SPL distribution is controlled by these modes. One main conclusion, as shown, is that the curve does not have any major influences on SPL distribution in the audience area. Though the room modes are more distinct at lower frequencies, musicians tend not to play a 25Hz note alone, as it is nearly three octaves below middle C. Thus, when played alongside other notes, some of the deconstructive waves will disappear, due to frequencies superimposing on one another. As the frequency increases, so do the amount of room modes, as is shown in Figure 47 and 48.

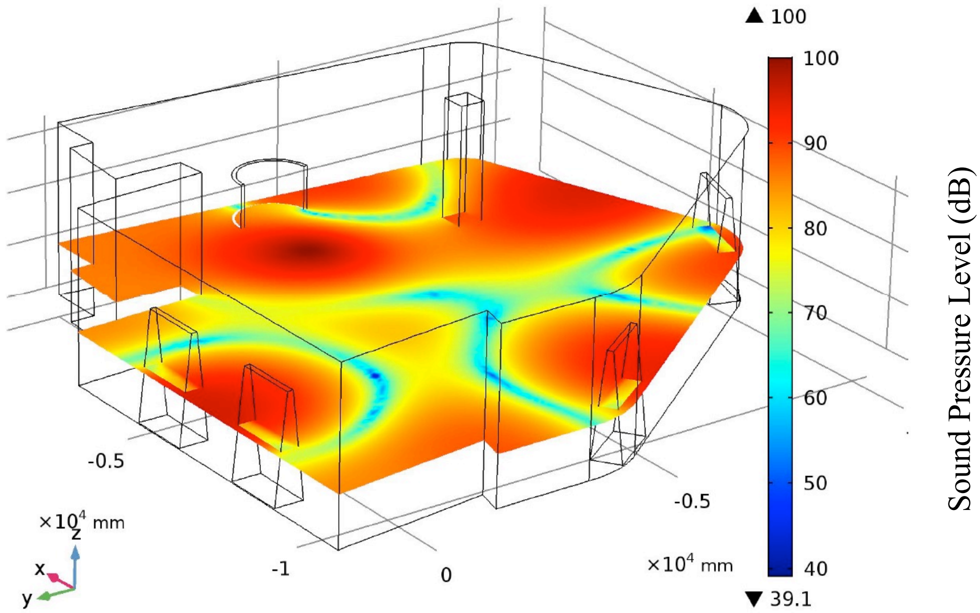


Figure 47: Gallery with Curve - Source outside curve 50 Hz

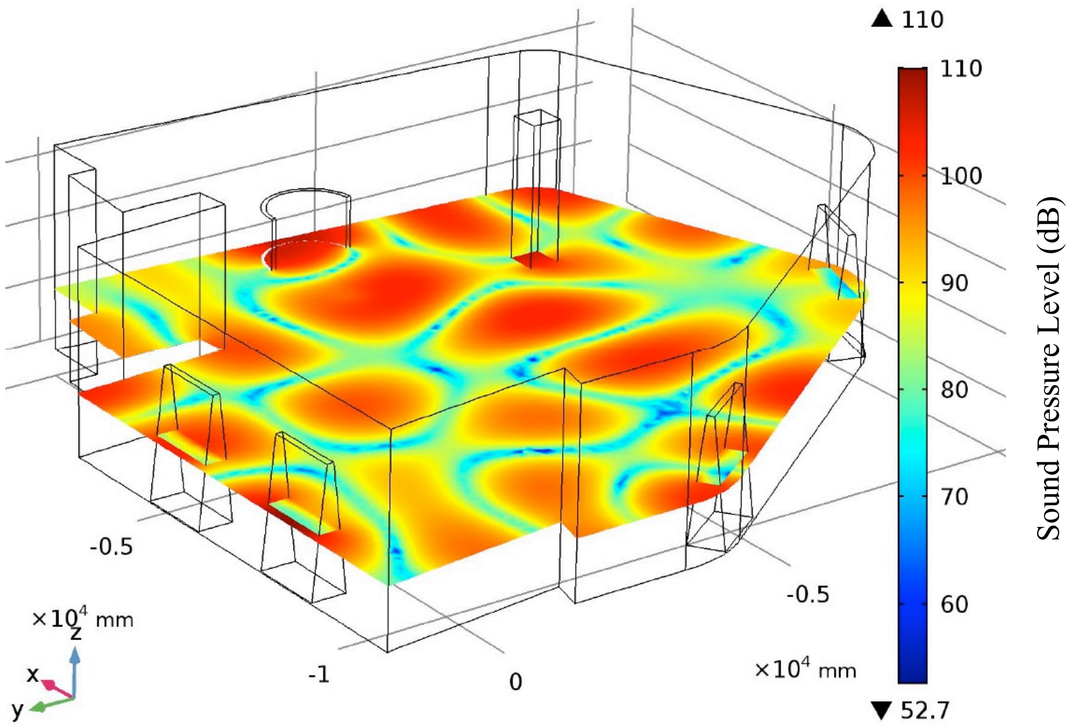


Figure 48: Gallery with Curve - Source outside curve 100 Hz

When there are multiple modes in a room, such is the case in higher frequencies, the modes will compensate for one another and the overall sound in the room will be good and equally distributed. It can also be noted that whether the source is within the curve or outside it, the amount of room modes is similar. Figures 49 through 51 show similar modal density with the source inside the curve.

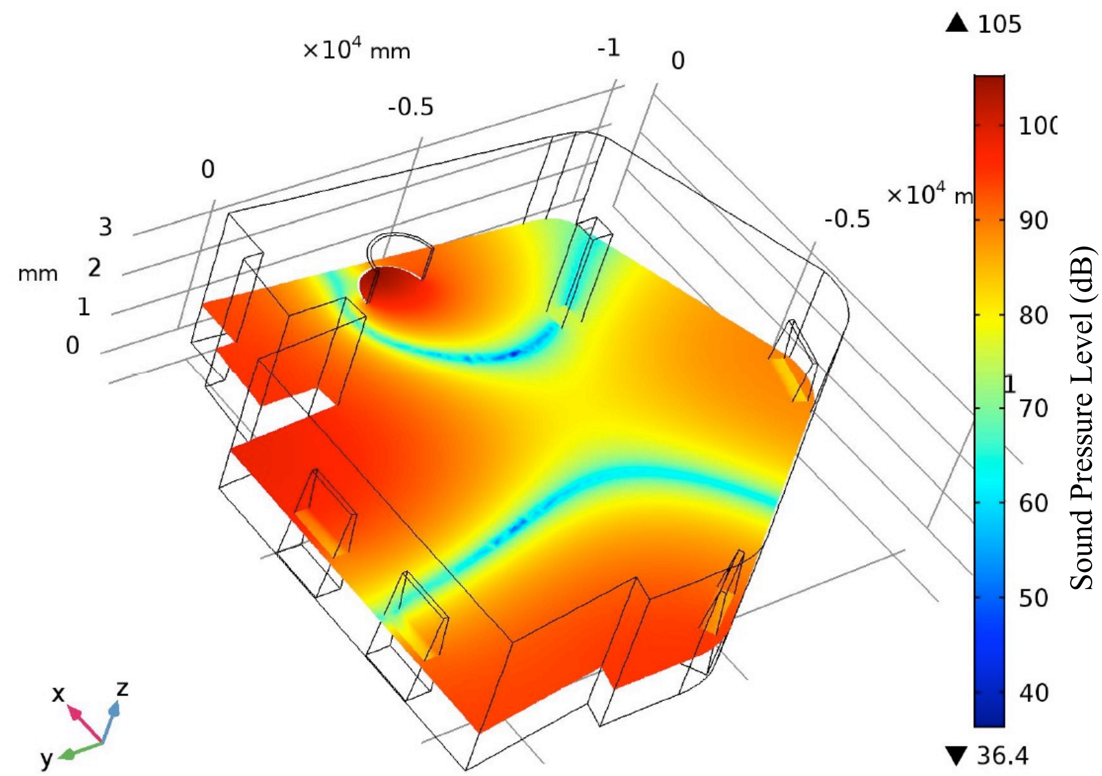


Figure 49: Gallery with Curve - Source inside curve 25 Hz

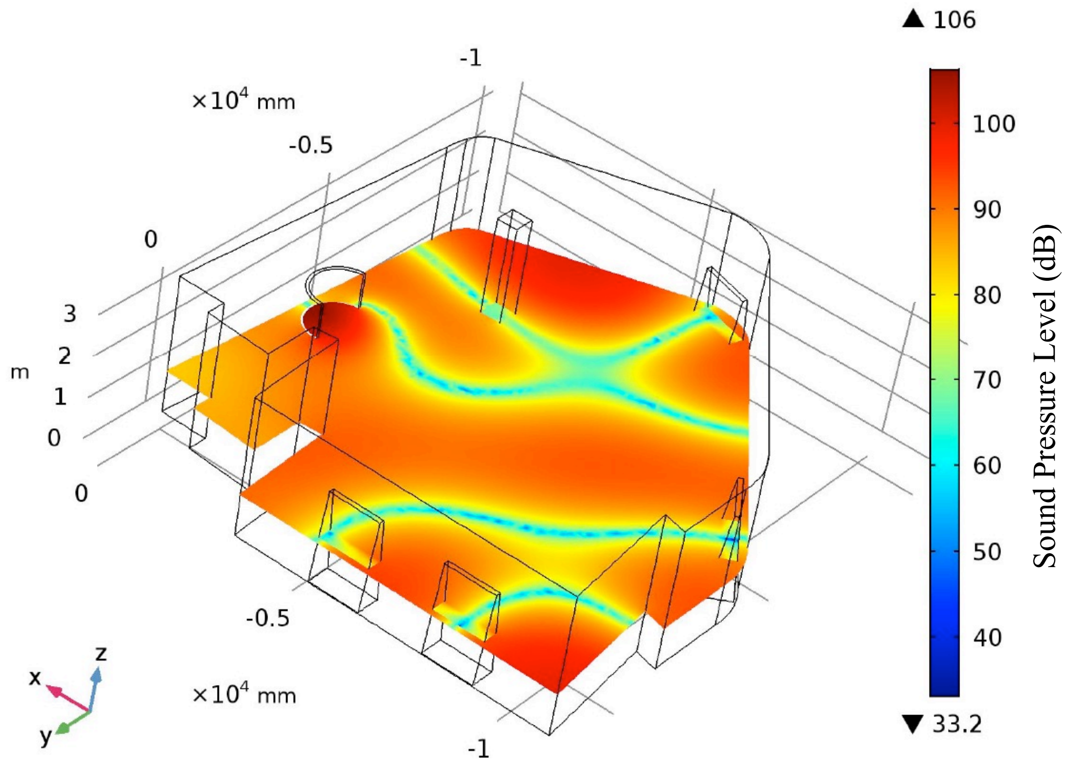


Figure 50: Gallery with Curve - Source inside curve 50 Hz

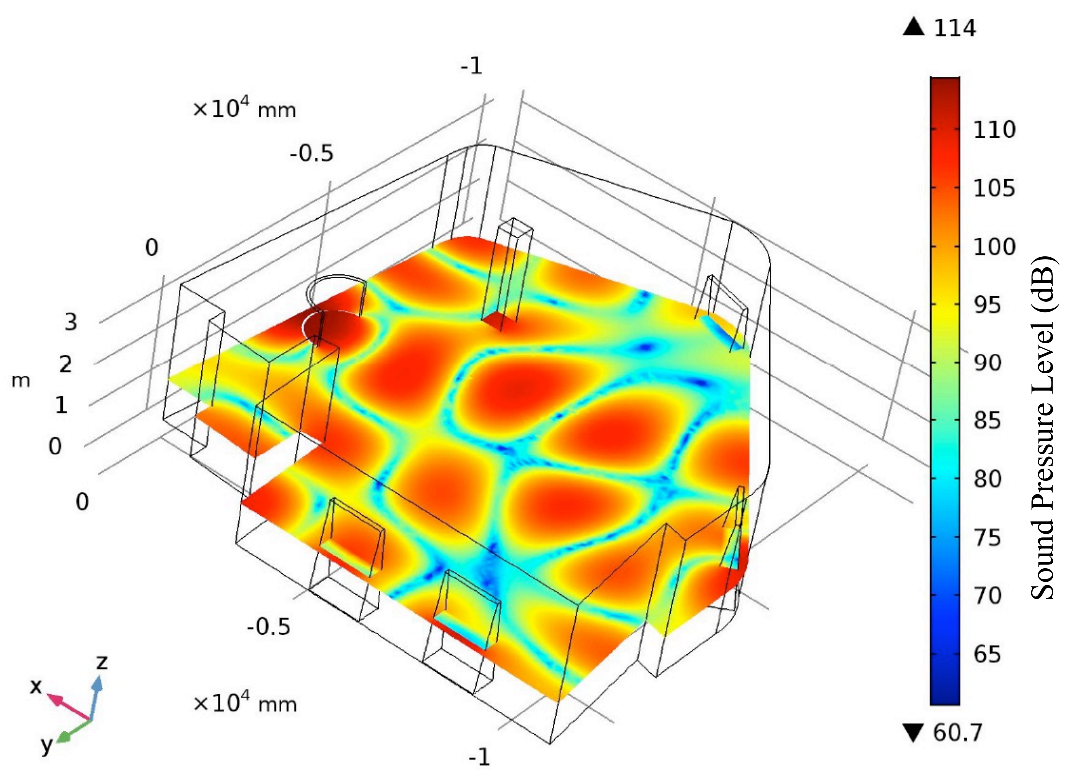


Figure 51: Gallery with Curve - Source inside curve 100 Hz

Though SPL distribution is dominated by room modes, with peaks and valleys, the main conclusion from the wave theory analysis simulation is that the curved surface has no negative impact on the sound level distribution across the Gallery.

6.1.3 Gallery - XL Curve Simulation – Ray Theory

Proceeding the validation, a larger curve ("Curve XL") was placed inside the Gallery simulation to analyze its impact. The Curve in the on-site measurements did not alter the SPL distribution throughout the audience space to any noticeable extent. Due to size constraints, it was not possible to build a larger curve for on-site testing, therefore XL Curve was tested through acoustic simulations. The original Curve was not tested in ray theory simulations as the measured data was already available.

Curve XL was tested with four source locations. The first source location was at OS1 ("XL-OS1"). The second source location was within the focal plane (L-A). The third source location was within the extended circle of the radius (L-B). The final location was outside the extended circle (L-C). The fourth simulation was important to confirm Barron's statement: acceptable reflection can occur if the source and receiver are outside the extended circle of the concave surface as the concave surface acts to disperse the sound (2).

The XL Curve and source locations can be seen in Figure 52.

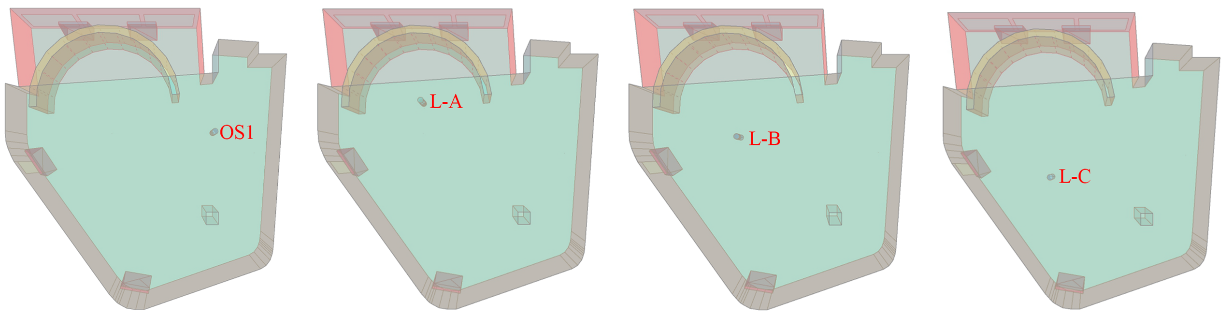


Figure 52: Paul Crocker Gallery with XL Curve and Source Locations

The ratio of curve to room size for Curve XL was more comparable to the curves at St. Martin's and Wigmore Hall; therefore, simulations were created to analyze the impact of an increased curve to room ratio, as shown in Figure 53.

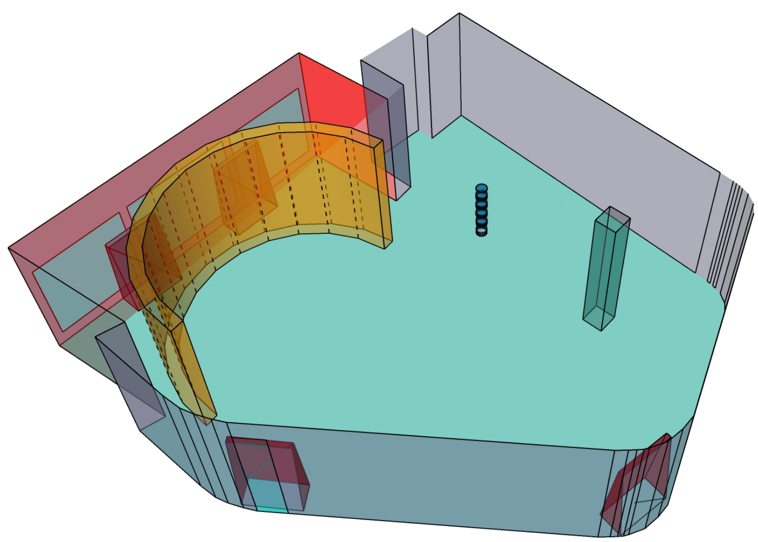


Figure 53: XL Curve with Source Location OS1

The hybrid-ray theory simulation results are shown in Figures 54 through 56 for XL Curve with Source Location OS1. The figures show three octave band frequencies of 125Hz, 500Hz, and 2000Hz respectively.

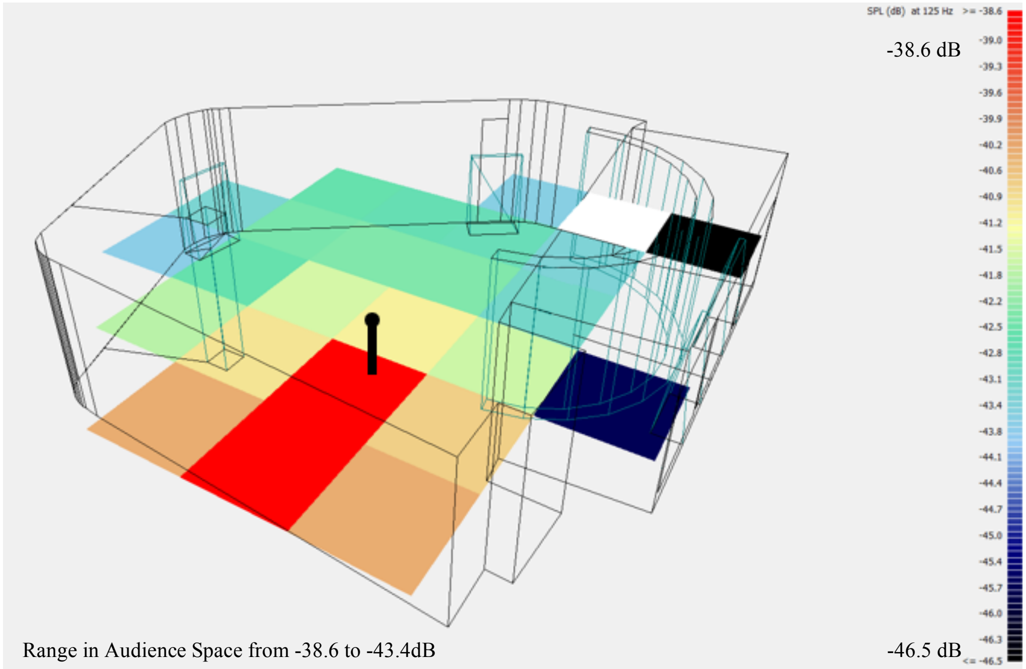


Figure 54: Gallery - XL Curve with Source Location OS1 - SPL distribution at 125Hz

As can be seen by Figure 54, the SPL at 125Hz is equally diffused with the introduction of the XL Curve, with only a 4.8dB difference in SPL throughout the occupiable part of the room. The XL Curve had no negative impact on the audience space. Following the 500 Hz test, the XL Curve OS1 was simulated at 500 Hz.

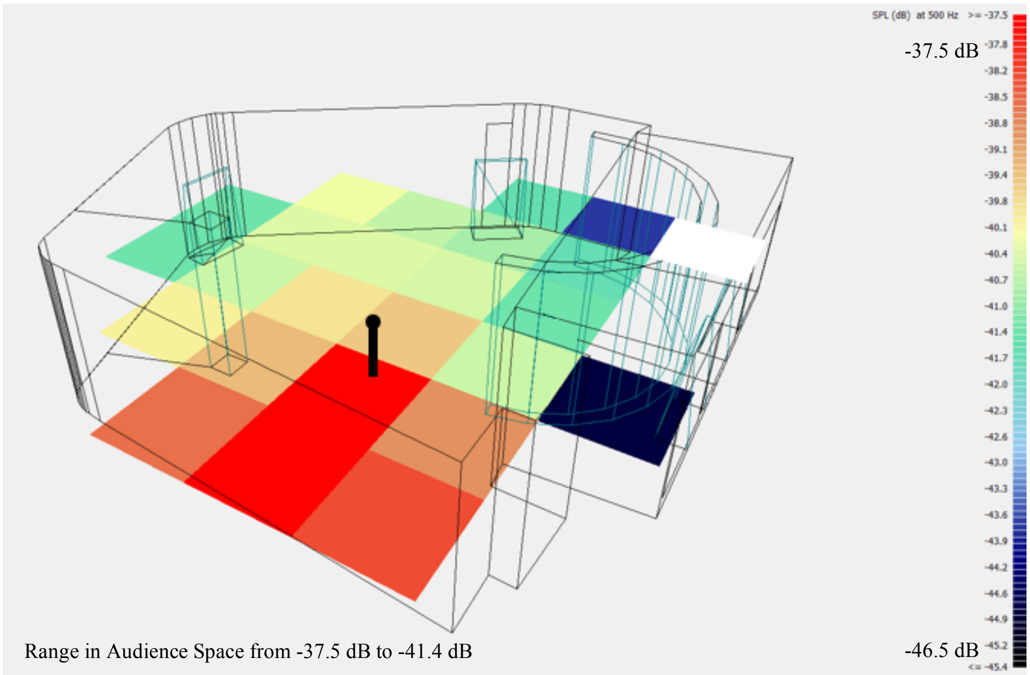


Figure 55: Gallery - XL Curve with Source Location OS1 - SPL distribution at 500Hz

The 500 Hz test, as seen in Figure 55, shows SPL level distribution throughout the room to have a range of 7.9 dB, but when excluding the area behind the curve, the SPL range in the audience / occupied space is only 3.9dB. Following the 500 Hz test, the XL- OS1 was simulated at 2000 Hz.

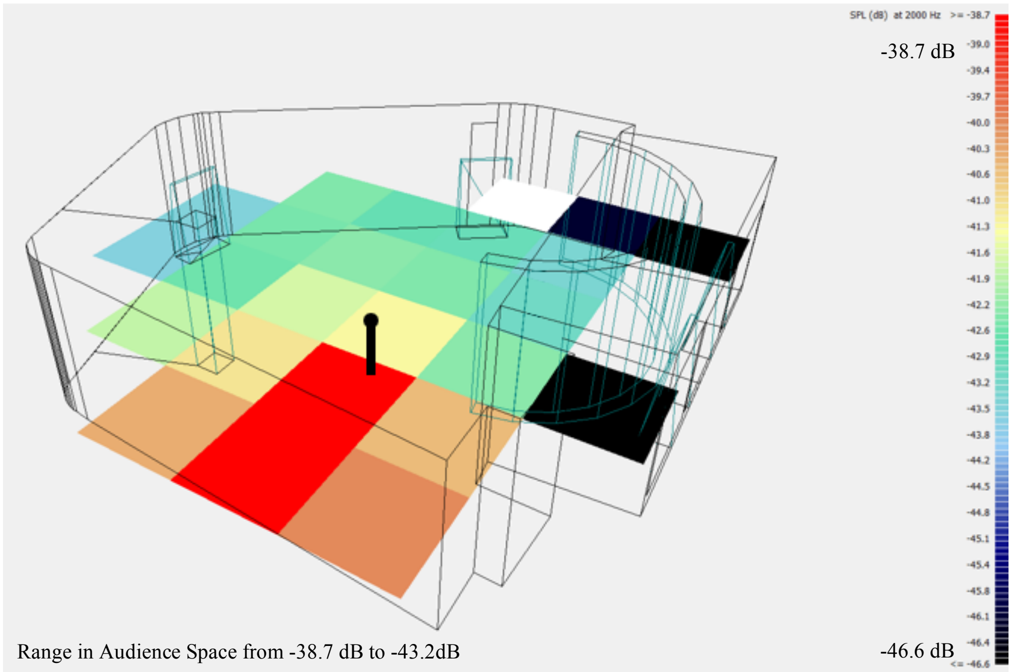


Figure 56: Gallery - XL Curve with Source Location OS1 - SPL distribution at 2000Hz

At 2000Hz, there was a difference of only 4.5dB throughout the audience space, Figure 56. Therefore, all three frequencies had equal sound pressure distribution in the audience space with Curve XL and source location OS1. Following Simulation 1, the source was then moved to location L-A, source within the curve, shown in Figure 57.

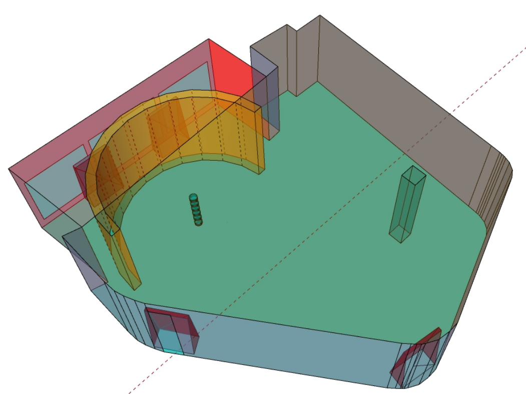


Figure 57: Gallery XL Curve Source Inside Curve (L-A)

The hybrid ray theory simulation results are shown in Figures 58 through 60 for XL Curve with source inside curve (L-A). The figures show three octave band frequencies of 125Hz, 500Hz, and 2000Hz respectively.

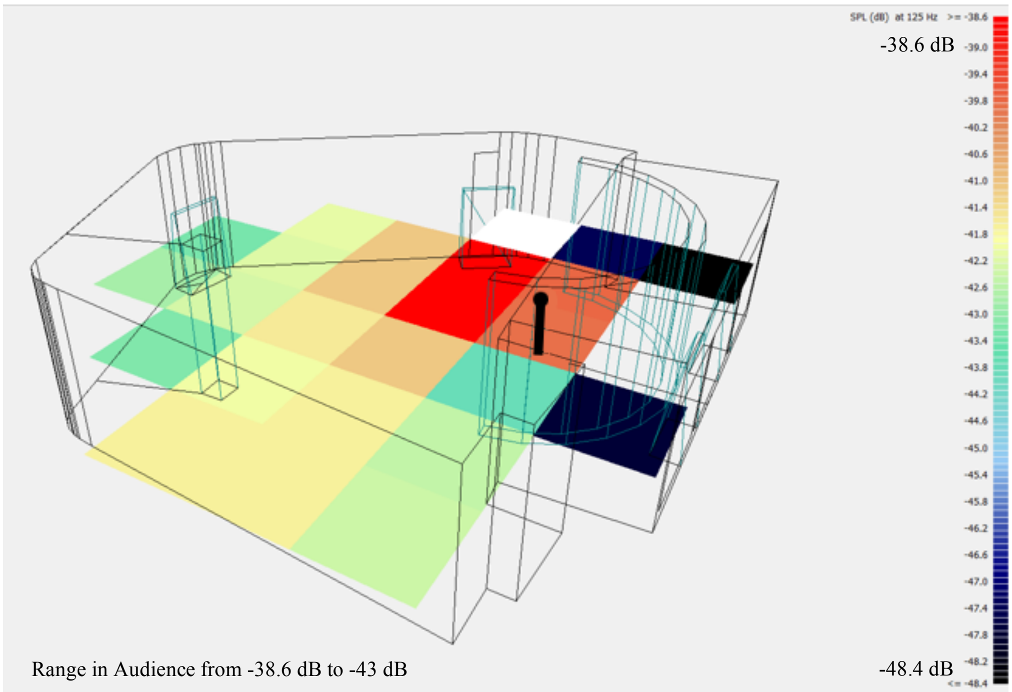


Figure 58: Gallery - XL Curve source inside curve (L-A) - SPL distribution at 125Hz

Following the 125 Hz test, the XL Curve L-A was simulated at 500 Hz.

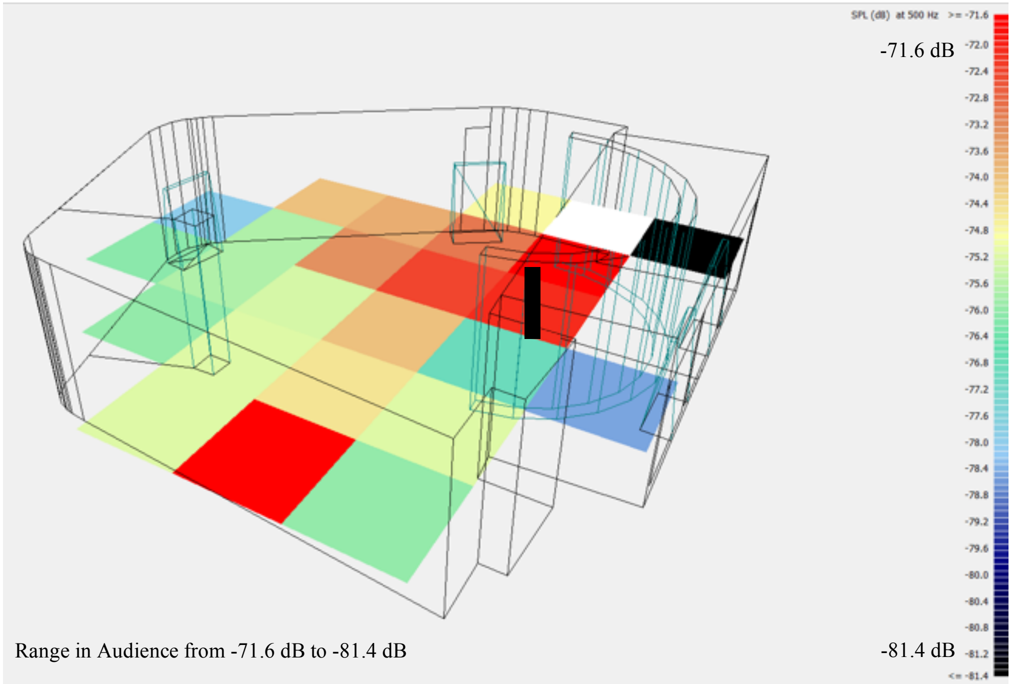


Figure 59: Gallery - XL Curve source inside curve (L-A) – SPL distribution at 500Hz

Following the 500 Hz test, the XL Curve L-A was simulated at 2000 Hz.

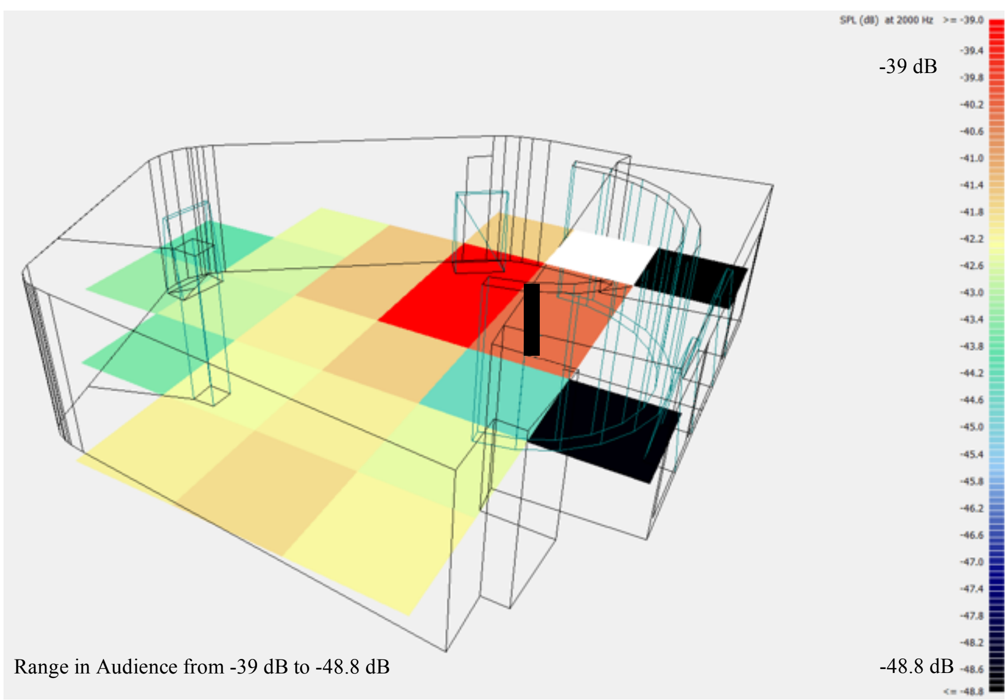


Figure 60: Gallery - XL Curve source inside curve (L-A) – SPL distribution at 2000Hz

In all locations, the SPL was equally diffused throughout the Gallery. The difference in SPL throughout the occupied audience space was 4.8dB at 125Hz and 500Hz, and 4.4dB at 2000Hz; all are still under the 5 dB threshold for equal diffusion of SPL. With the source inside the XL Curve, there was no negative impact to the audience space, see Figures 58 through 60.

The source was then moved to location L-B, with the source in the centre of the curve, as shown in Figure 61.

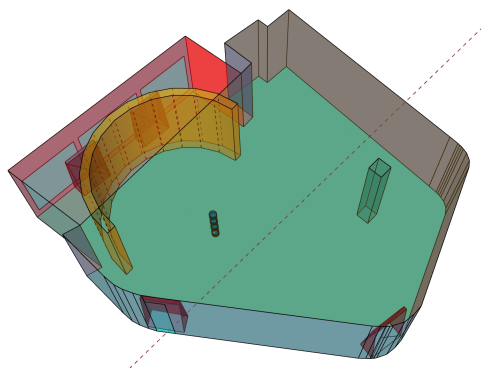


Figure 61: XL Curve with Source in Centre of the Curve (L-B)

The hybrid-ray theory simulation results are shown in Figures 62 through 64 for XL Curve with source in centre of the curve (L-B). The figures show three octave band frequencies of 125Hz, 500Hz and 2000Hz respectively.

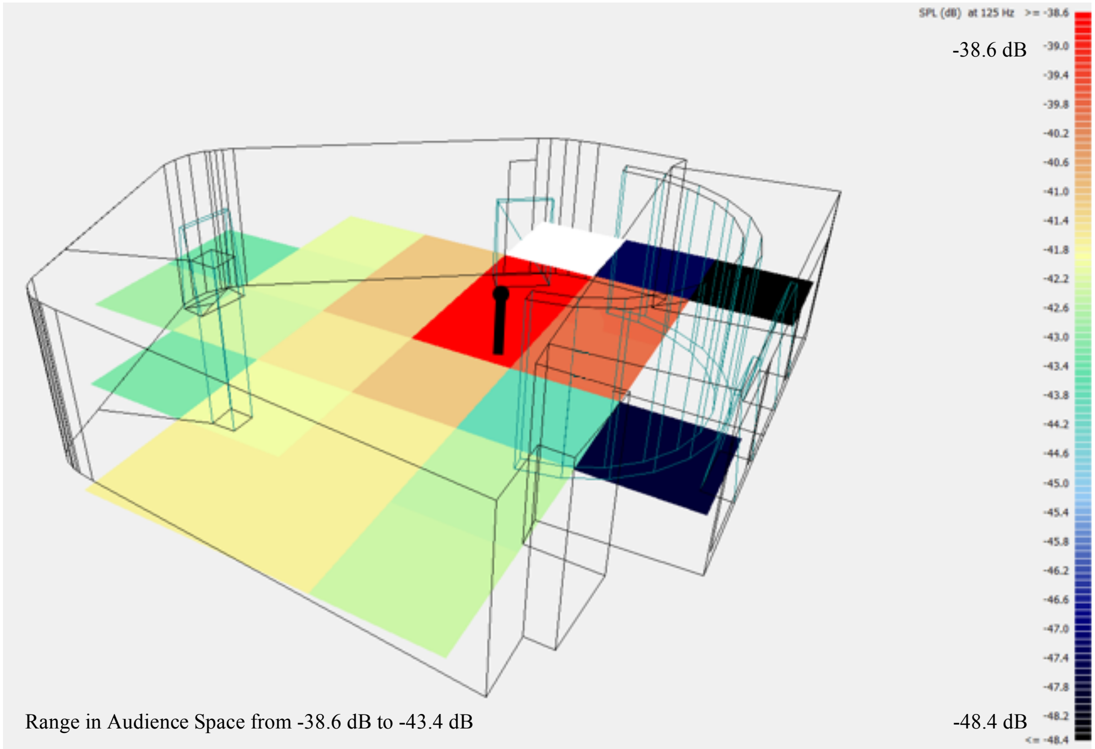


Figure 62: Gallery - XL Curve source in centre of curve (L-B) – SPL distribution at 125Hz

Following the 125 Hz test, the XL Curve L-A was simulated at 500 Hz.

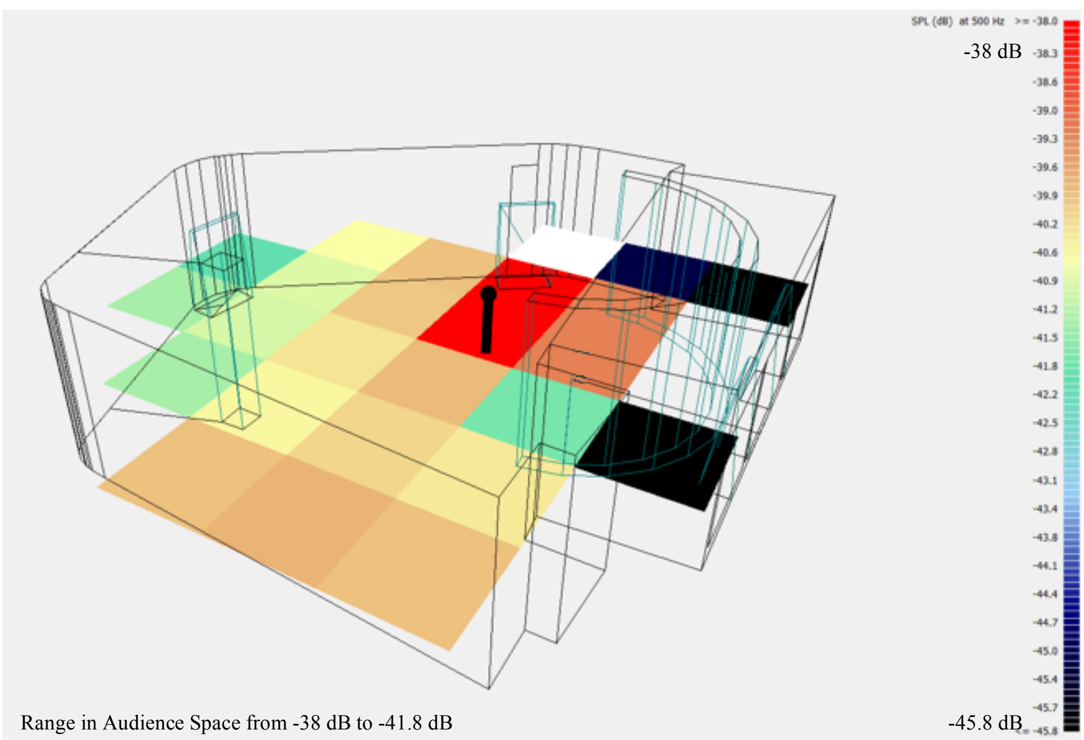


Figure 63: Gallery - XL Curve source in centre of curve (L-B) – SPL distribution at 500Hz

Following the 500 Hz test, the XL Curve L-A was simulated at 2000 Hz.

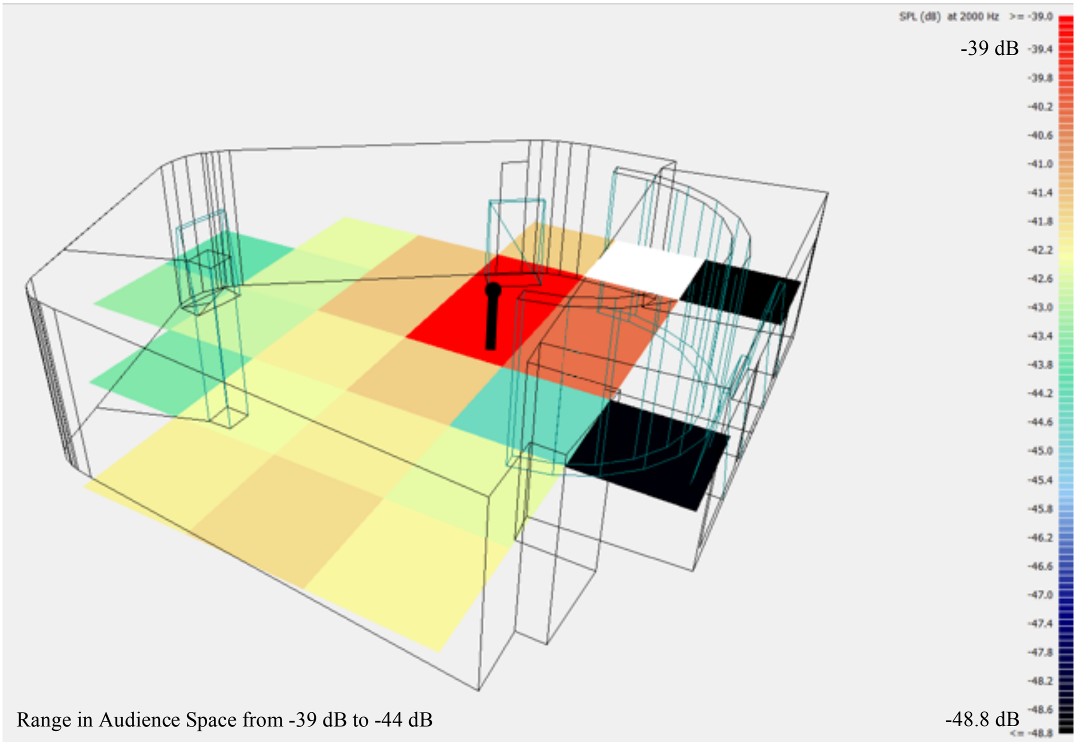


Figure 64: Gallery - XL Curve source in centre of curve (L-B) - SPL distribution at 2000Hz

The source was then moved to location L-C, with the source outside the extended circle, as shown in Figure 65.

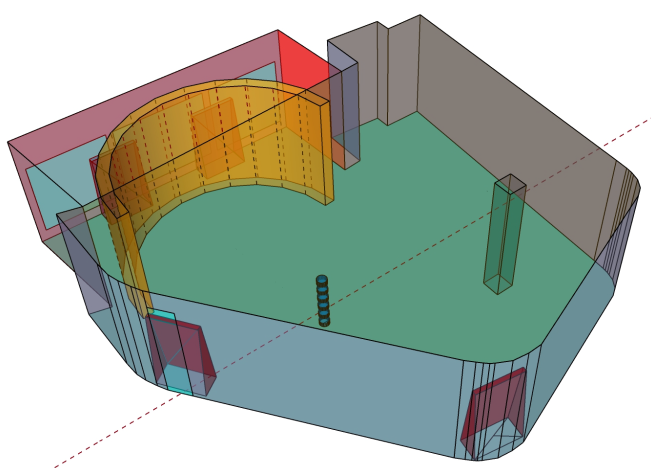


Figure 65: XL Curve with Source Outside the Extended Circle (L-C)

The test was conducted at 125Hz, for XL-L-A.

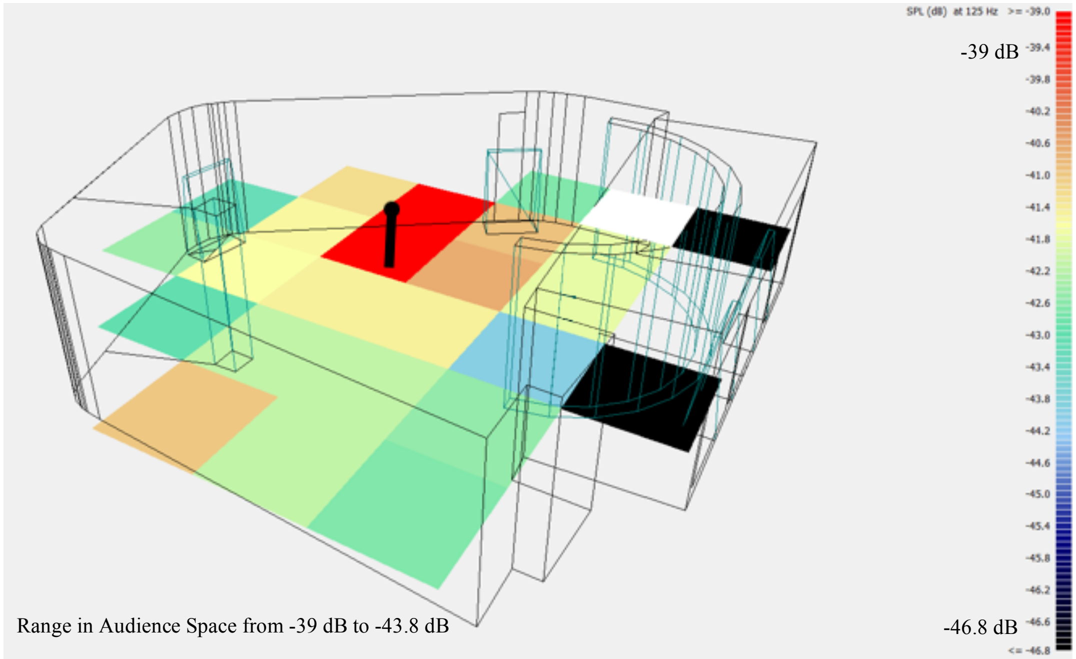


Figure 66: Gallery - XL Curve source outside extended circle (L-C) – SPL distribution at 125Hz

Following the 125 Hz test, the XL Curve L-A was simulated at 500 Hz.

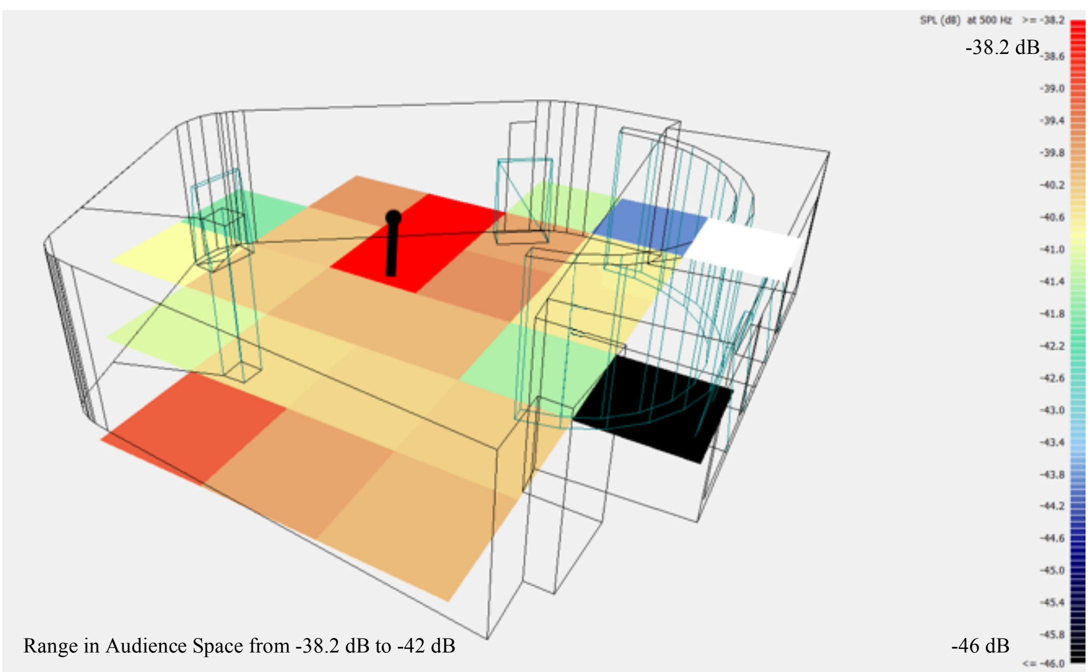


Figure 67: Gallery - XL Curve source outside extended circle (L-C) – SPL distribution at 500Hz

Following the 500 Hz test, the XL Curve L-A was simulated at 2000 Hz.

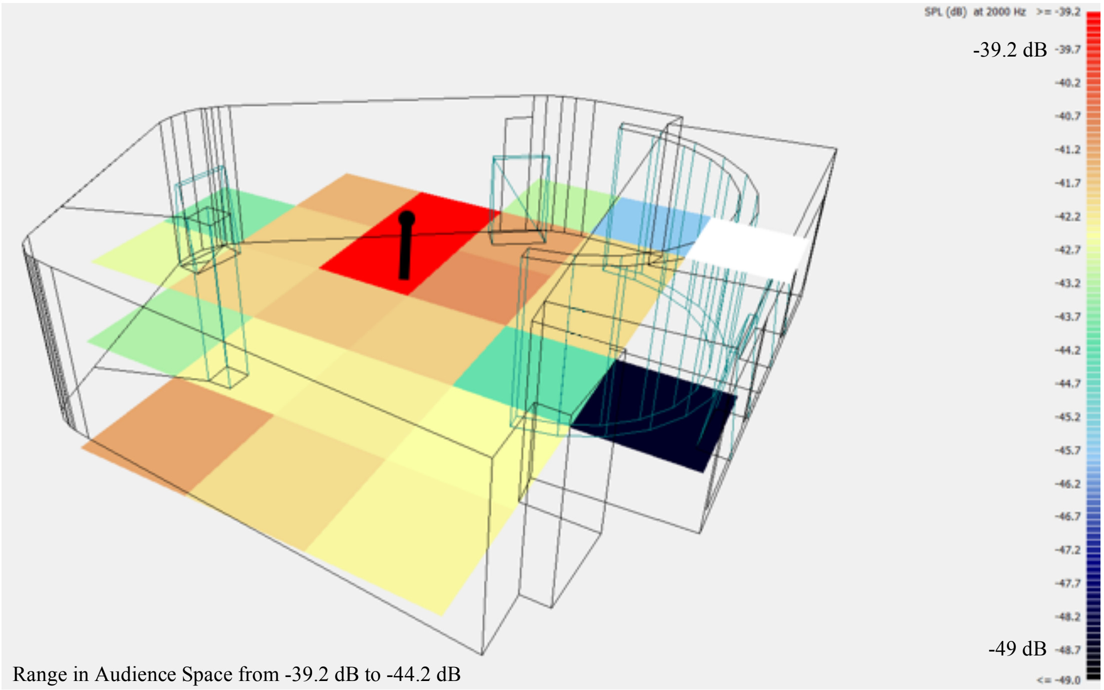


Figure 68: Gallery - XL Curve source outside extended circle (L-C) – SPL distribution at 2000Hz

Source location L-B and L-C also provided equally diffused SPL throughout the occupied space, see Figures 62-64 and 66-68 respectively. Source location L-B had a SPL distribution range of 4.8dB at 125Hz, 3.8 dB at 500Hz and 5dB at 2000Hz; L-C had the exact same SPL distribution ranges as L-B. Thus, it can be stated that the XL curve did not have a negative impact on the audience space at any of the tested source locations. Location L-C was outside the extended circle of the curve and did not impact the room negatively affirming Barron's hypothesis, that concave surfaces disperse the sound when outside the extended circle.

6.1.4 Gallery - XL Curve Simulation – Wave Theory

COMSOL Multiphysics uses geometries for wave theory analysis. The Gallery was simulated with the XL Curve, with the source outside the curve as well as source inside the curve, as shown in Figures 69 and 70.

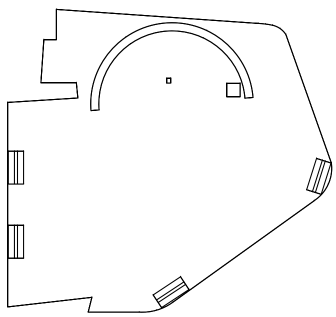
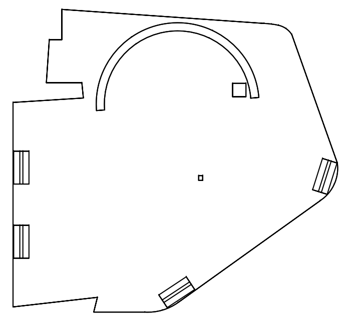
	

Figure 69: Gallery XL Curve, Source inside curve	*Figure 70: Gallery XL Curve, Source outside curve*

Wave theory simulations tested the XL Curve at 25Hz, 50Hz and 100Hz, as shown in Figures 71 through 76 for horizontal distribution of SPL, with the source inside and outside the XL Curve. Vertical distribution is shown in Appendix C.

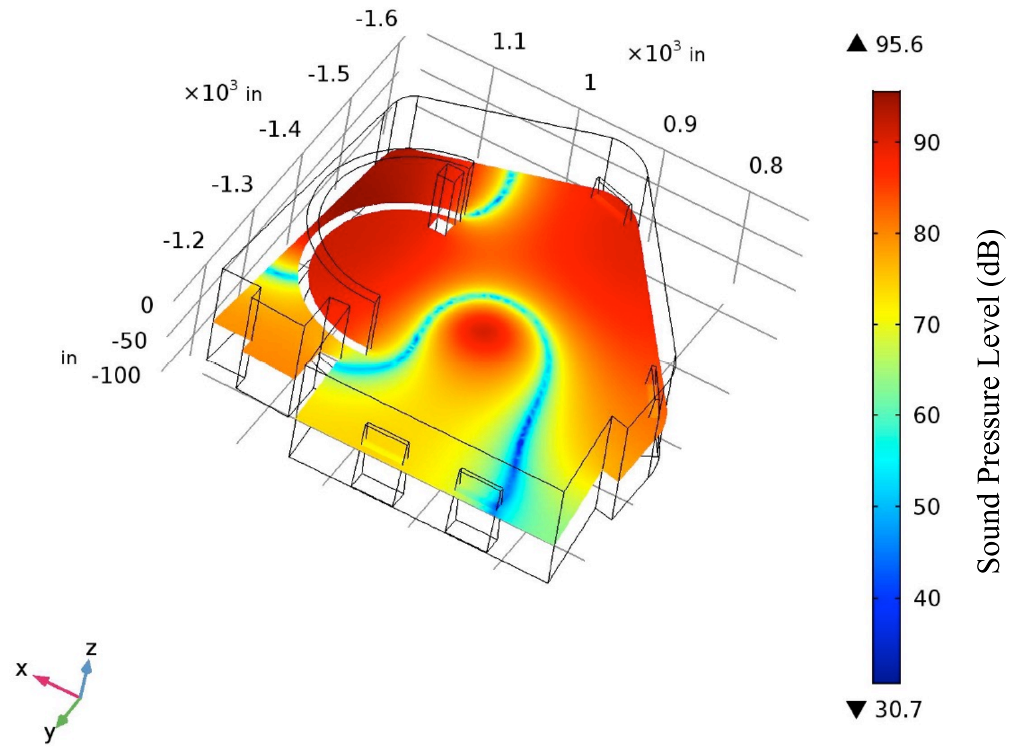


Figure 71: Gallery with XL Curve - Source outside curve 25 Hz

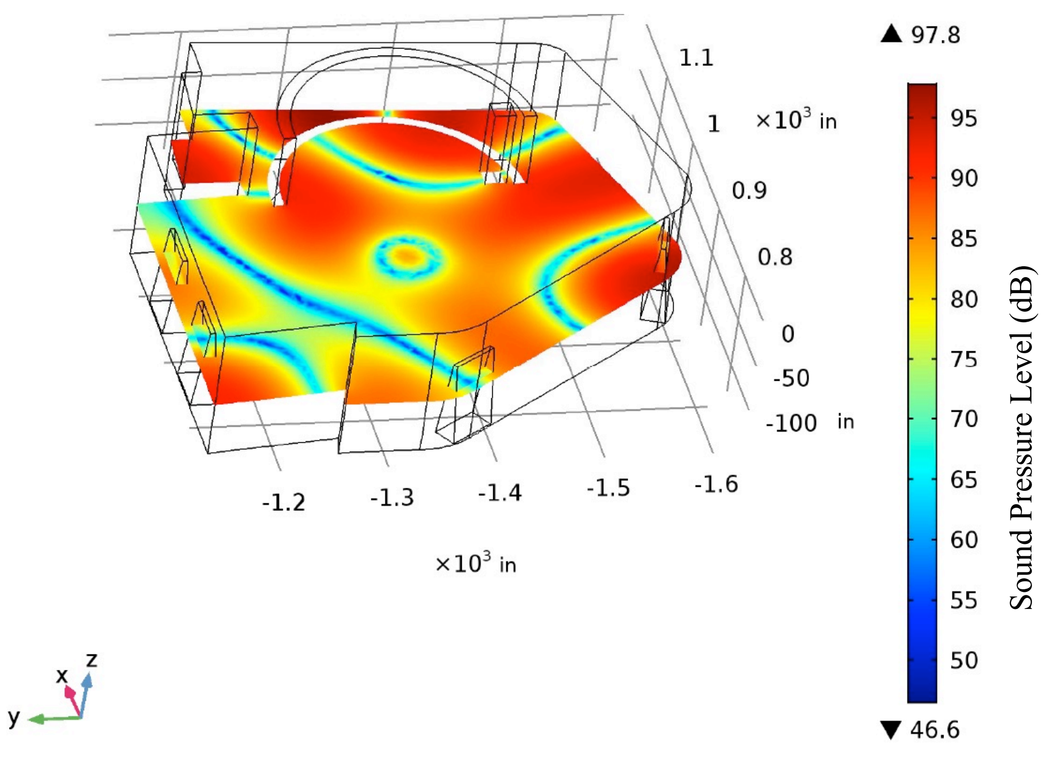


Figure 72: Gallery with XL Curve - Source outside curve 50 Hz

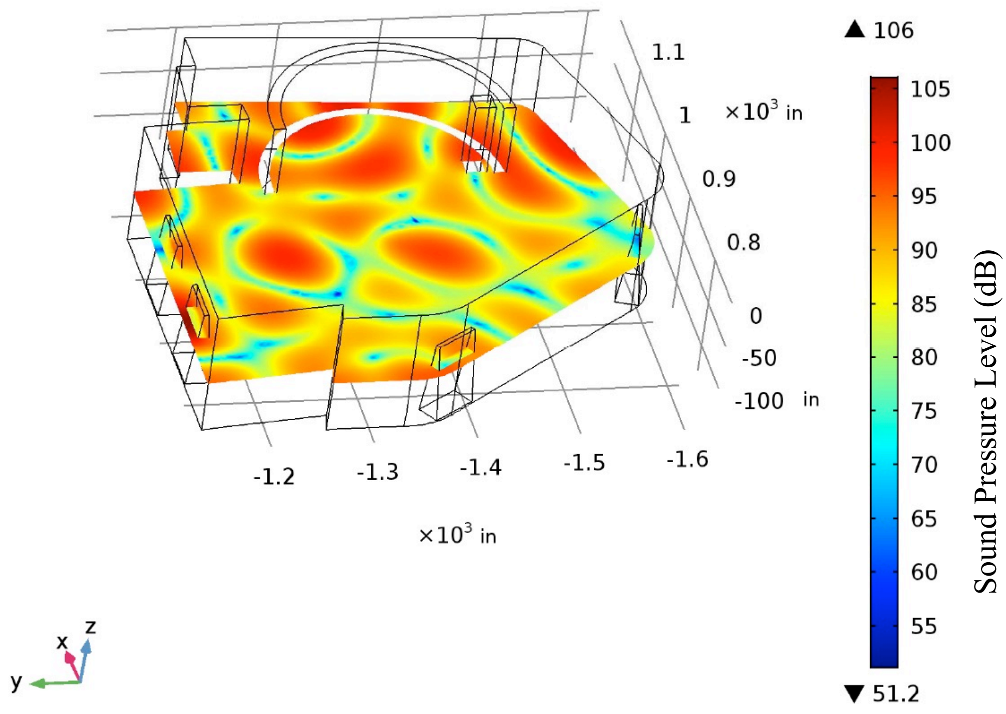


Figure 73: Gallery with XL Curve - Source outside curve 100 Hz

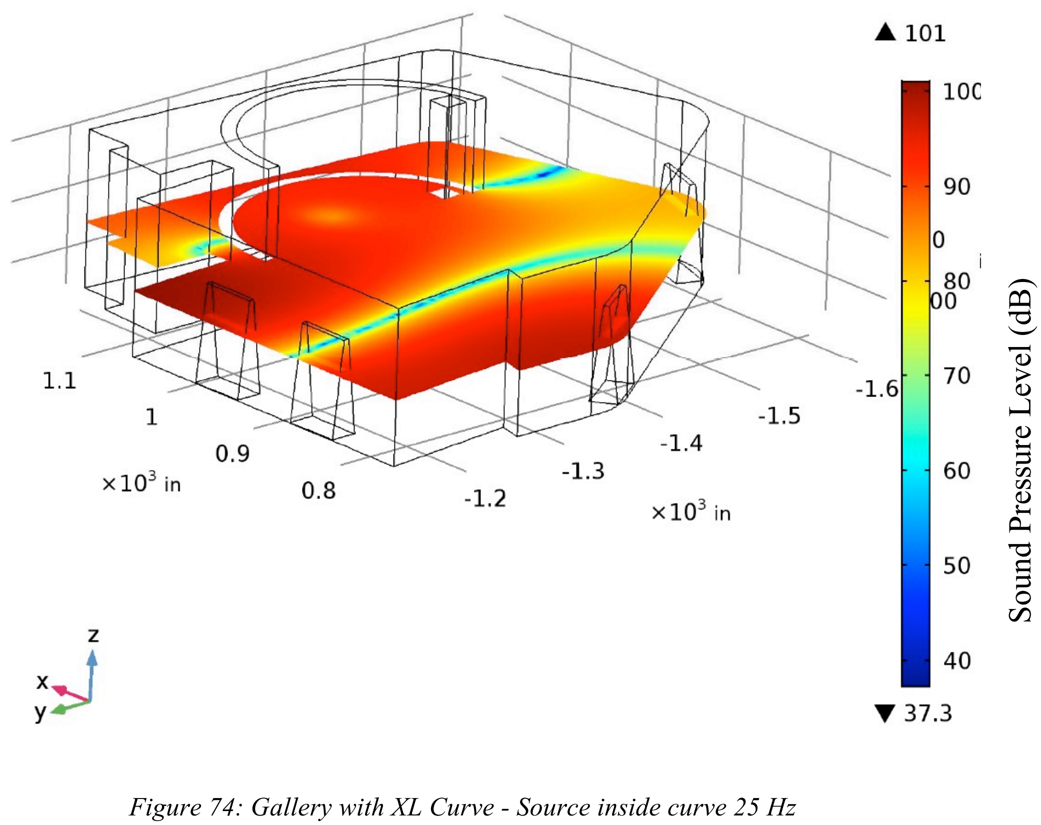


Figure 74: Gallery with XL Curve - Source inside curve 25 Hz

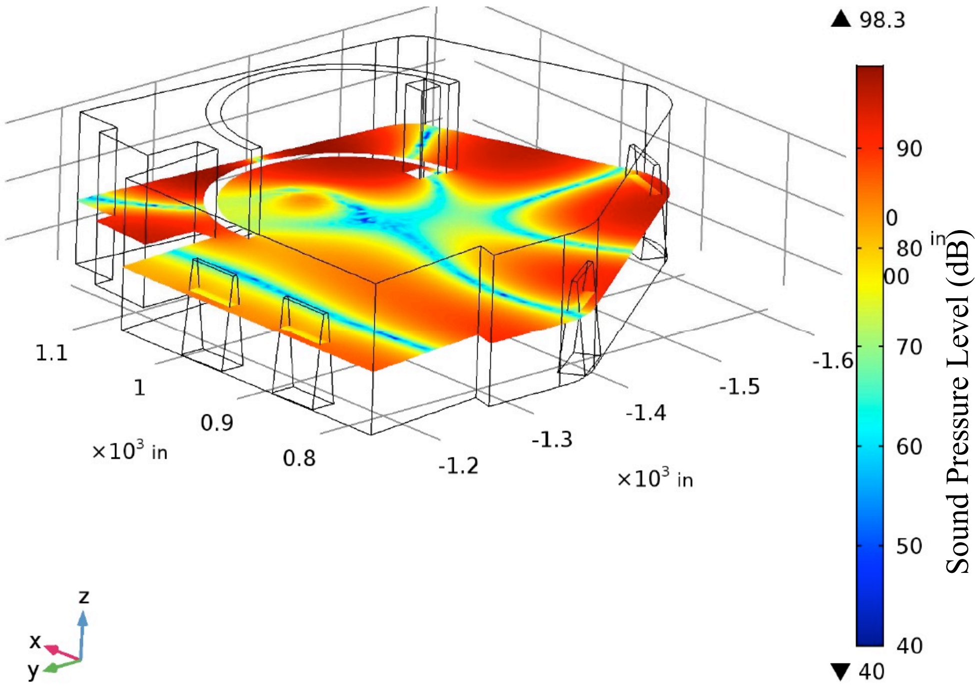


Figure 75: Gallery with XL Curve - Source inside curve 50 Hz

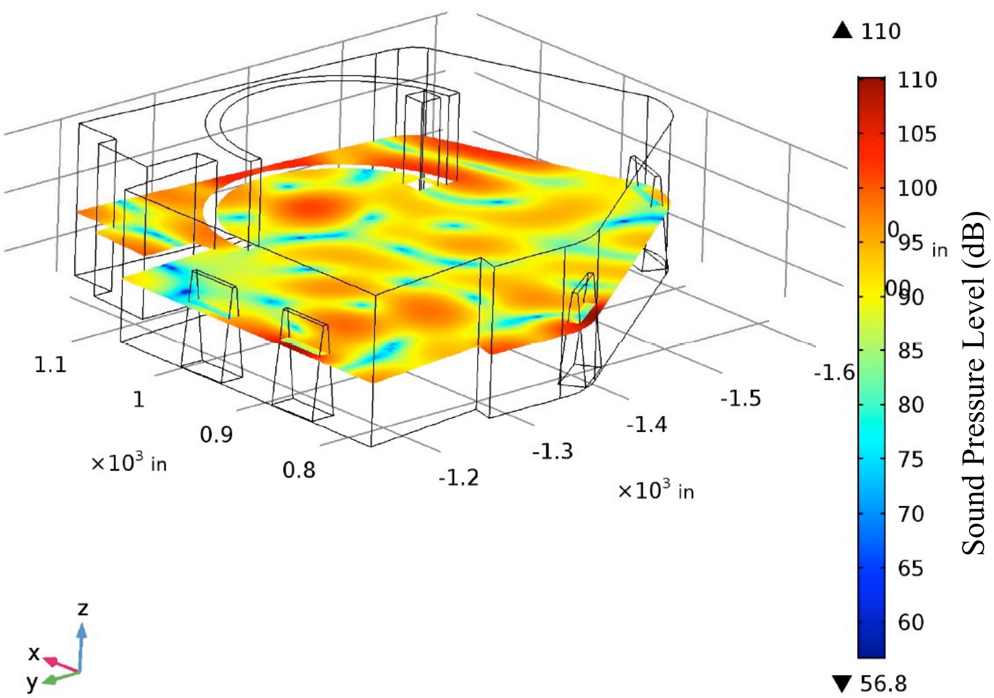


Figure 76:Gallery with XL Curve - Source inside curve 100 Hz

In comparing the simulations of the Curve in the Gallery to the XL Curve, the SPL distribution show strong influence of room modes due to small modal density. The main difference between the Curve wave analysis and the XL-curve wave analysis is the location of the modes within the room. Though the SPL distribution is dominated by room modes, wave analysis shows that curved surfaces have no negative impact on SPL distribution within the Gallery. As noted previously, though room modes are more distinct at lower frequencies, such as 25Hz, musicians tend not to play this note alone, as it is nearly three octaves below middle C. Therefore, when accompanied by other notes and / or musicians, the deconstructive waves will disappear due to frequencies superimposing on one another, creating good sound.

6.2 St. Martin-in-the-fields Anglican Church

6.2.1 Ray Theory Validation

A schematic detail for the layout of the St. Martin's showing the existing PA system with four speaker locations ("Speakers") is shown in Figure 77 and 78.

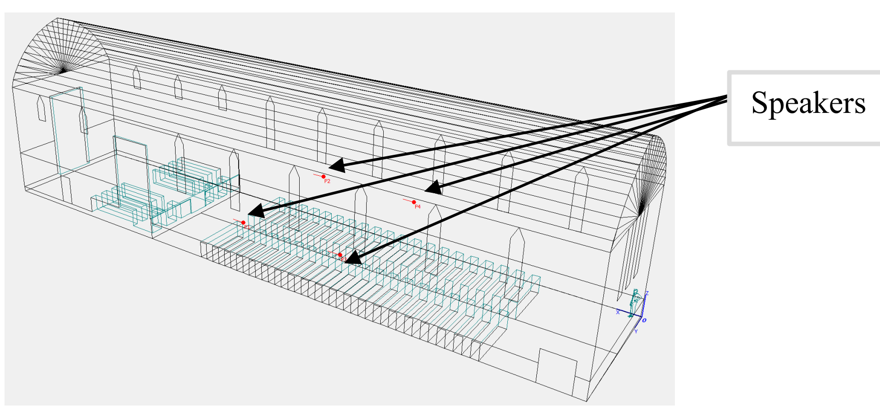


Figure 77: St. Martin-in-the-fields Speaker Source Location (A)

On-site sine-sweep measurements determined the RT for St. Martin's and were used to validate the simulation. The acoustic absorption coefficients of the materials were selected from the computer database materials, as seen in Table 9. The measured RT and simulated pre-adjusted

RT are shown in Tables 9 and 10. These were further adjusted, to match the existing RT of St. Martin's, by combining the database numbers with Reynold's textbook (16). The adjusted materials are shown in Table 11, with the validated RT in Table 12.

Table 9: St. Martin's – Pre-adjusted materials absorption coefficients - ODEON Database – Simulation 1

Materials (a)	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Roof	0.28	0.28	0.14	0.09	0.06	0.05	0.05	0.05
Wood Type 1	0.25	0.25	0.15	0.1	0.09	0.08	0.07	0.07
Glazing	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02
Wall / Gypsum	0.28	0.28	0.12	0.1	0.17	0.13	0.09	0.09
Brick	0.02	0.02	0.03	0.03	0.04	0.05	0.07	0.07
Wood Type 2	0.25	0.25	0.15	0.1	0.09	0.08	0.07	0.07
Floor Plate	0.15	0.15	0.11	0.1	0.07	0.06	0.07	0.07

Table 10: Measured and pre-adjusted RT for St. Martin's

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
RT measured (s)	-	3.11	2.88	3.27	2.99	2.71	2	1.01
RT pre-adjusted (s)	-	1.18	1.18	2.21	2.88	2.56	2.78	2.32

Table 11: St. Martins - Adjusted materials absorption coefficients – Simulation 2

Materials (a)	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Roof	0.28	0.28	0.14	0.09	0.06	0.05	0.05	0.05
Wood Type 1	0.2	0.18	0.13	0.08	0.07	0.09	0.09	0.08
Glazing	0.04	0.04	0.04	0.03	0.02	0.02	0.03	0.03
Wall / Gypsum	0.28	0.2	0.09	0.08	0.15	0.13	0.12	0.12
Brick	0.25	0.25	0.15	0.1	0.09	0.08	0.07	0.07
Wood Type 2	0.15	0.15	0.11	0.1	0.07	0.06	0.07	0.07
Floor Plate	0.28	0.28	0.14	0.09	0.06	0.05	0.05	0.05

Table 12: Measured and adjusted RT for St. Martin's

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
RT measured (s)	-	3.11	2.88	3.27	2.99	2.71	2	1.01
RT adjusted (s)	1.24	1.43	2.5	3.28	2.9	2.73	2.07	1.21

St. Martin's has a PA speaker system, which was used as a source for on-site testing purposes. As can be seen from Table 11, the RT in most frequencies were matched within engineering accuracy excluding 63Hz as the measured data was unavailable, and 125 Hz, where the assumed difference is likely due to background noise.

The project investigated the acoustical impact of the performance area on the audience space. Thus, when determining new source locations, there were two additional situations simulated.

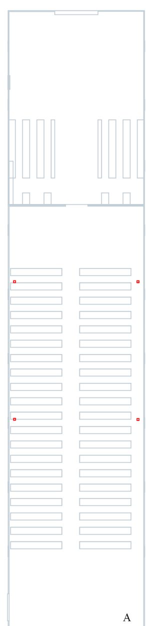
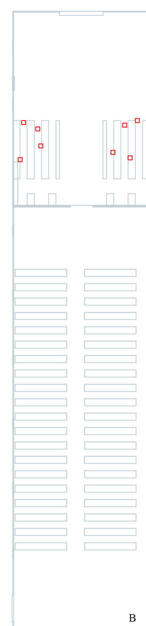
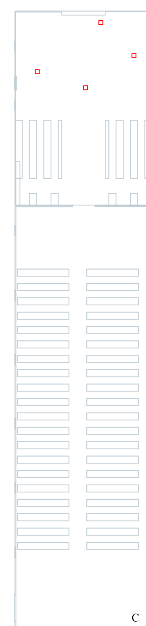
		

Figure 78: St. Martin's - Existing Speakers as Source (A)	*Figure 79: St. Martin's - Choir as Source (B)*	*Figure 80: St. Martin's - Musical Ensemble as Source (C)*

After the validation was complete, additional simulations were run for new source locations in Figures 79 and 80. These included sources tested as a choir in the quire[1], as well as a musical ensemble, which was tested between the quire and sanctuary[2], as shown in Figures 81 and 82. These locations were chosen to validate whether a performance by a choir or a musical ensemble would be able to provide equal SPL distribution throughout the enclosed room without additional

[1] The quire is the area between the nave and the sanctuary.
[2] The sanctuary is where the altar is located.

technical amplification. The choir and musical ensemble source locations are shown in Figures 81 and 82 respectively.

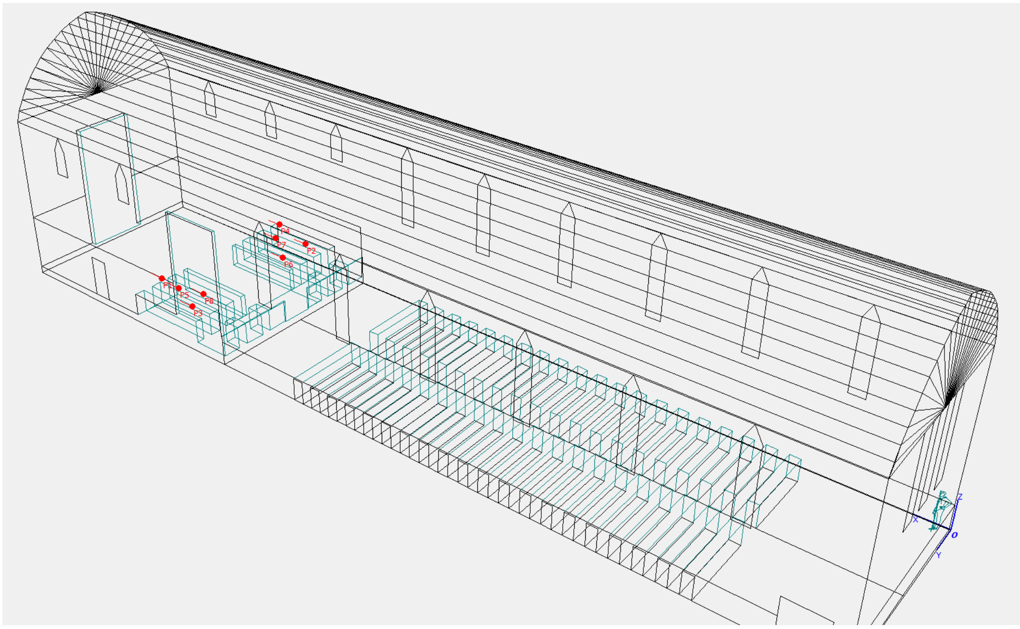


Figure 81: St. Martin-in-the-fields Choir Source Location (B)

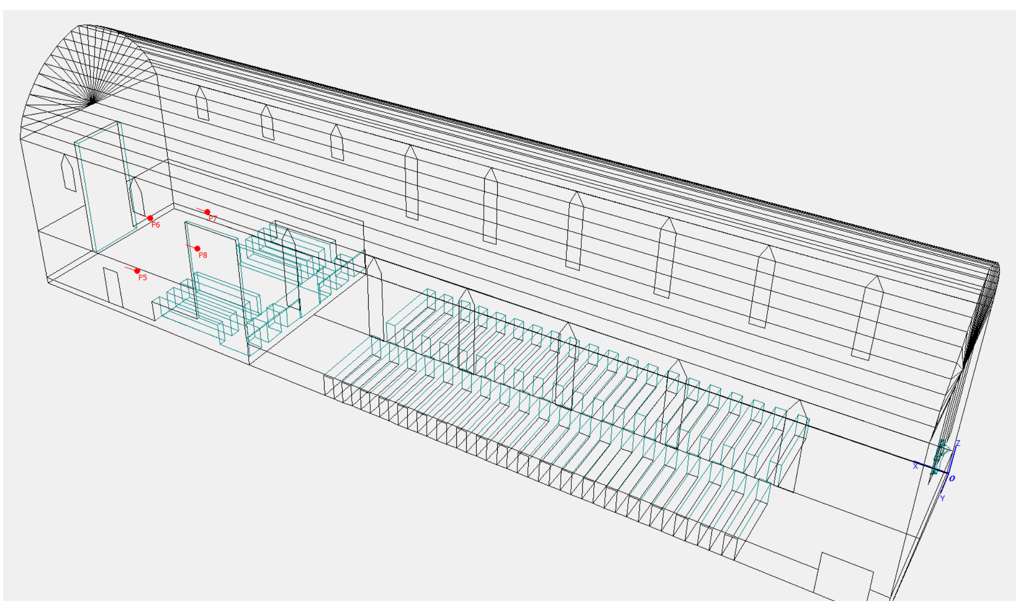


Figure 82: St. Martin-in-the-fields Musical Ensemble Source Location (C)

The RT times were used to validate the computer model of St. Martin's; SPL distribution can be seen in Figures 83 through 85 for location A, Speakers. The SPL distribution was evaluated for sound diffusion within the enclosed room. Results are shown in Figures 83 through 85 for three octave band frequencies.

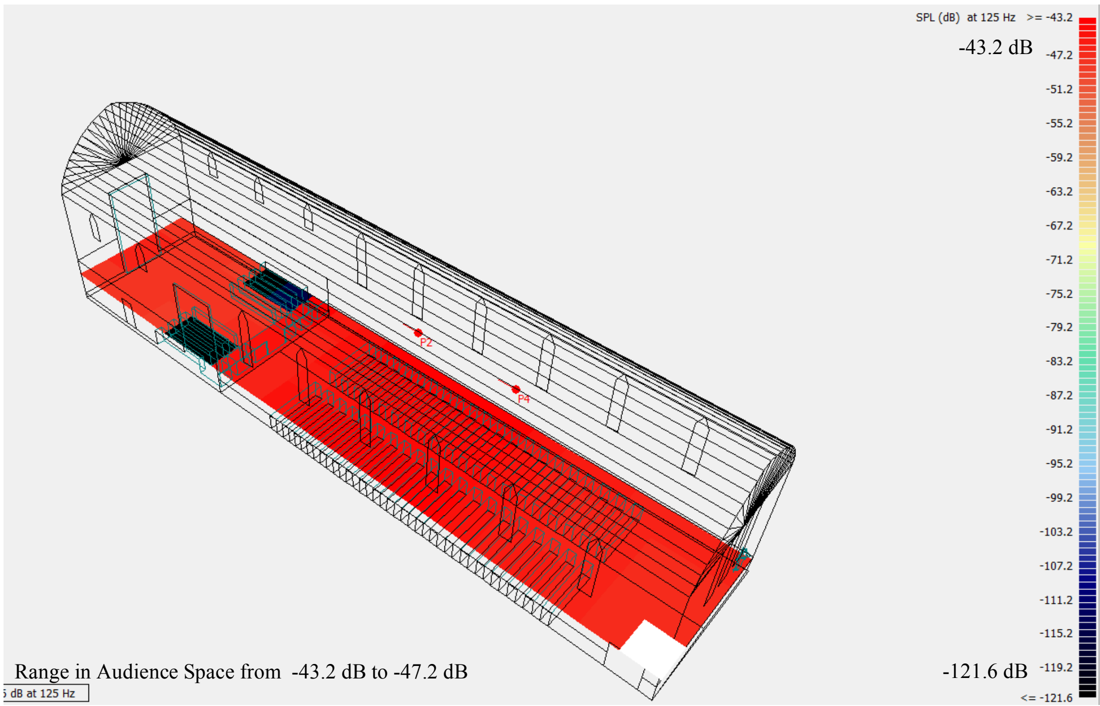


Figure 83: SPL distribution at 125 Hz for existing Speakers (Location A)

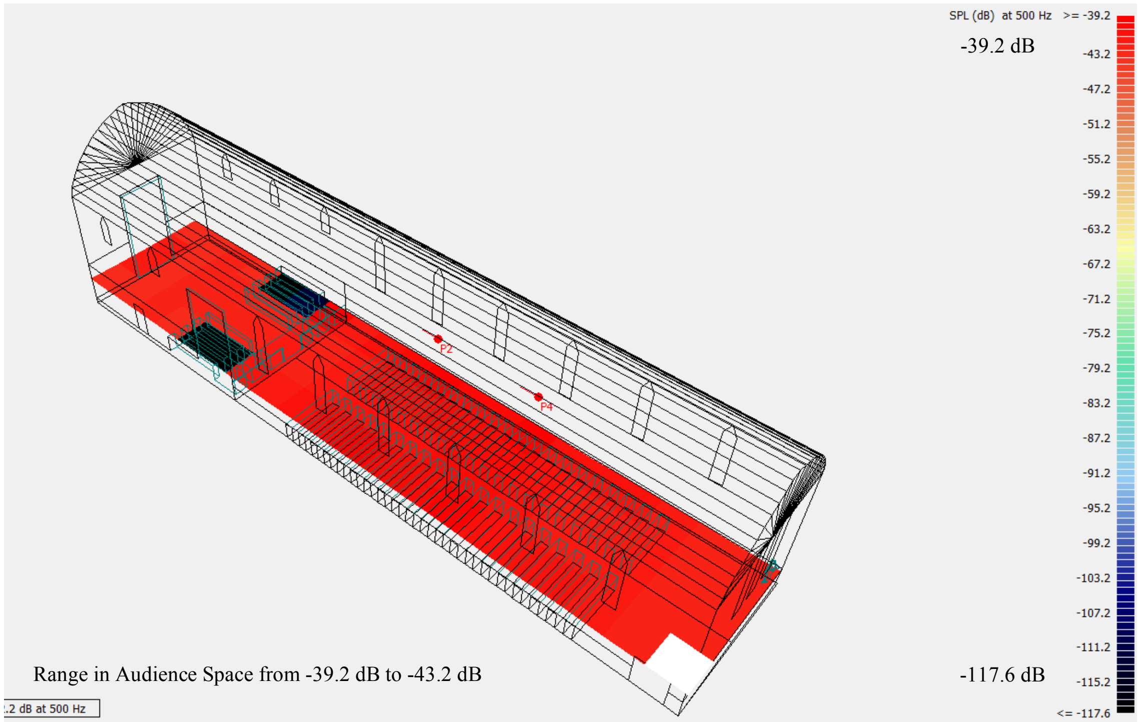


Figure 84: SPL distribution at 500 Hz for existing Speakers (Location A)

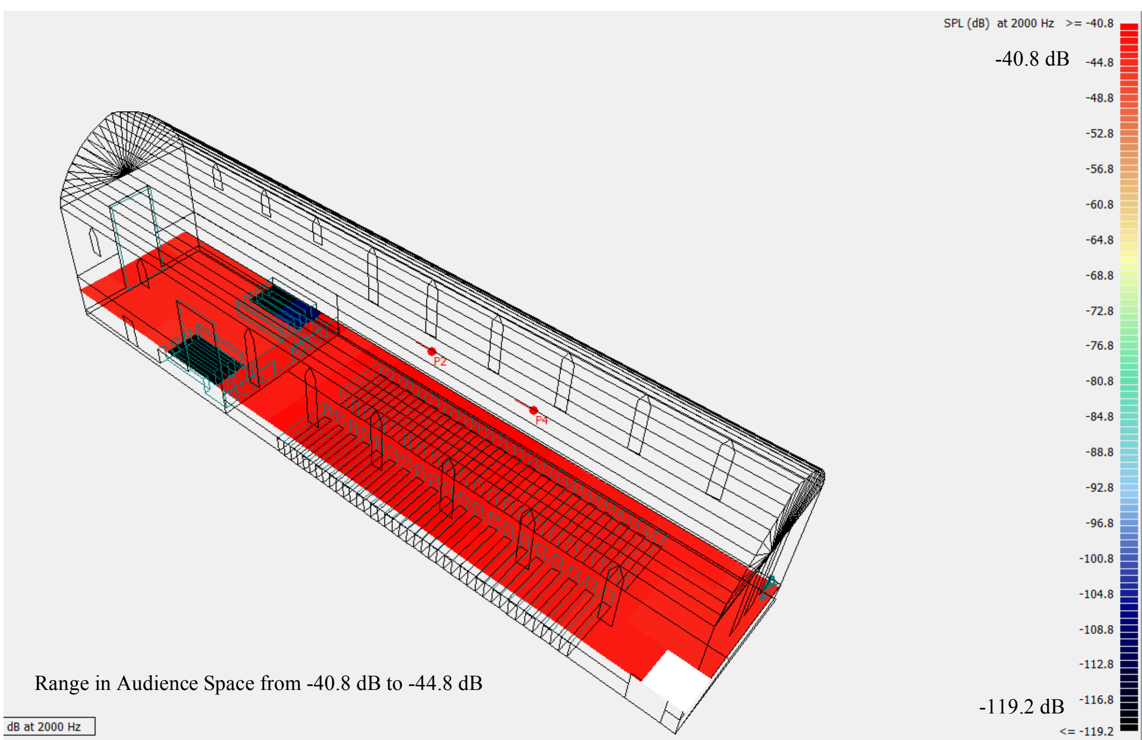


Figure 85: SPL distribution at 2000 Hz for existing Speakers (Location A)

The SPL grid responses for the existing speakers at 125 Hz, 500 Hz, and 2000Hz are shown in Figures 83 through 85 for all simulated source locations; additional SPL grid responses for one-third octave band frequencies can be found in the Appendix C. As can be noted from the above figures, the Speaker source location produced equal SPL distribution throughout the room, therefore the barrel-vaulted ceiling had no negative impact on the room.

Following the validation of St. Martin's by using the Speakers as the source, which gave unoccupied RT, computer database materials, and the geometries from as-builts, further simulations were completed for the choir and musical ensemble situations.

6.2.2 Additional Mid- to High-Frequency Simulations

As RT was validated for the Speaker simulation, additional simulations were conducted using the source locations shown in Figures 79 through 82. The SPL was analyzed to discover if it diffused equally throughout the room. This can be seen through the following SPL distribution grids which were created using hybrid-ray theory simulations.

The grid response below shows the SPL distribution for St. Martin's with the source location B at 125 Hz.

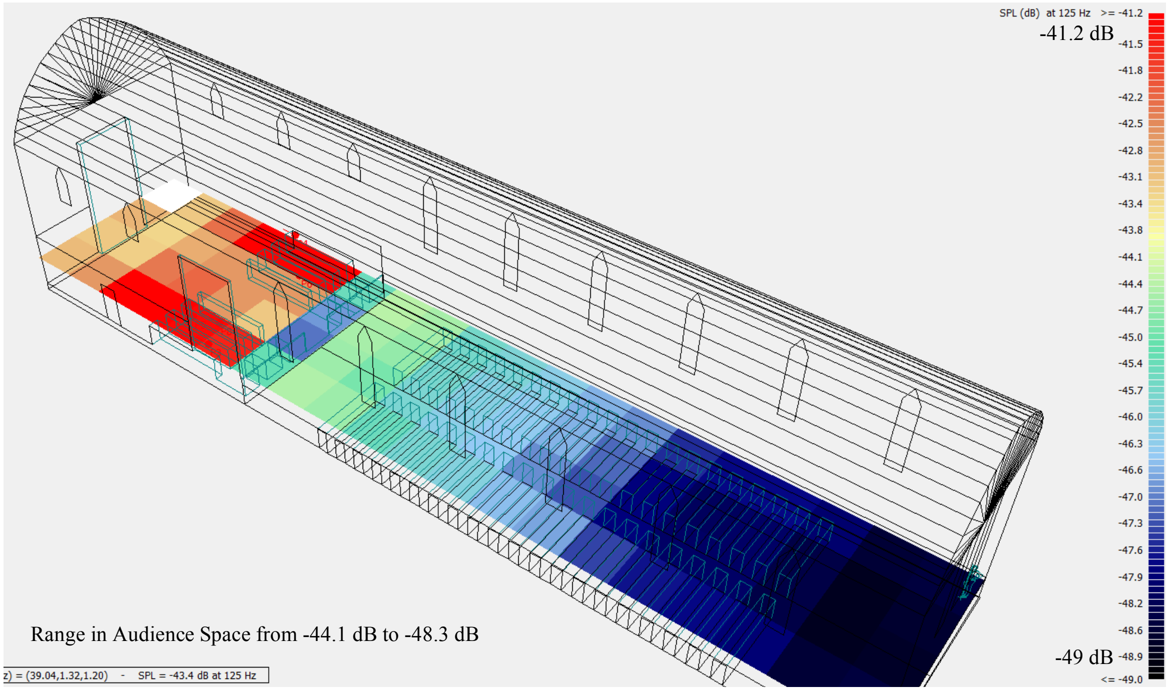


Figure 86: SPL distribution at 125 Hz for Choir (Location B)

Following this, the room was simulated at a mid-range frequency, 500Hz, with the source location B.

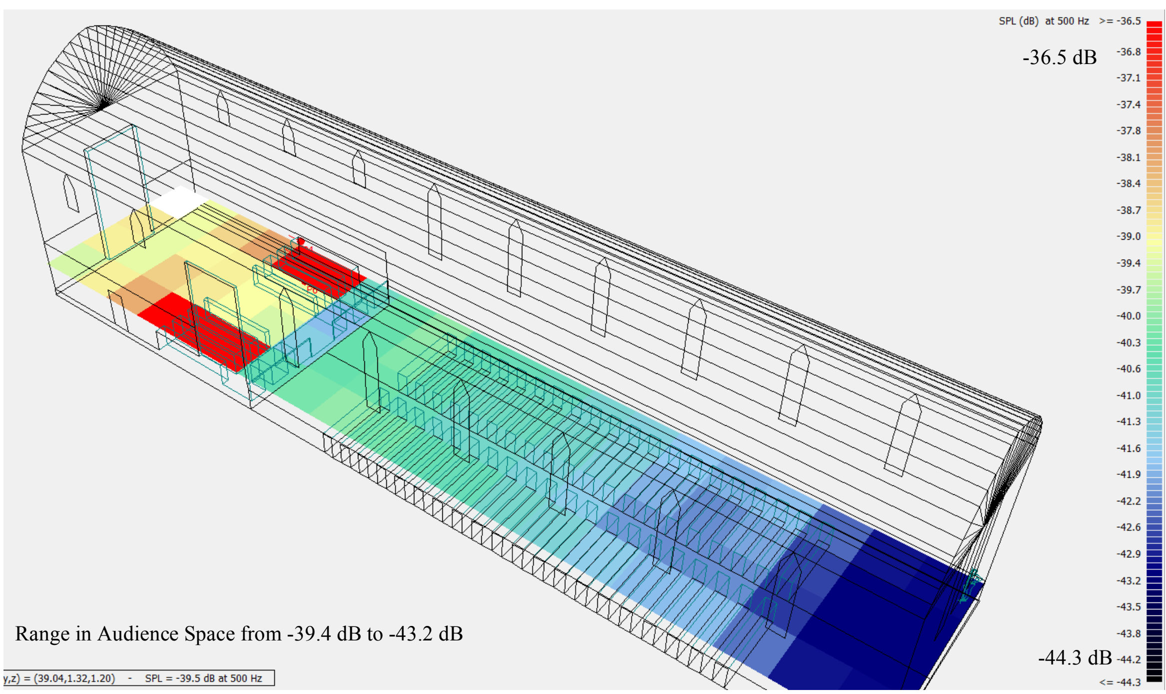


Figure 87: SPL distribution at 500 Hz for Choir (Location B)

The final simulation for Location B was at 2000Hz.

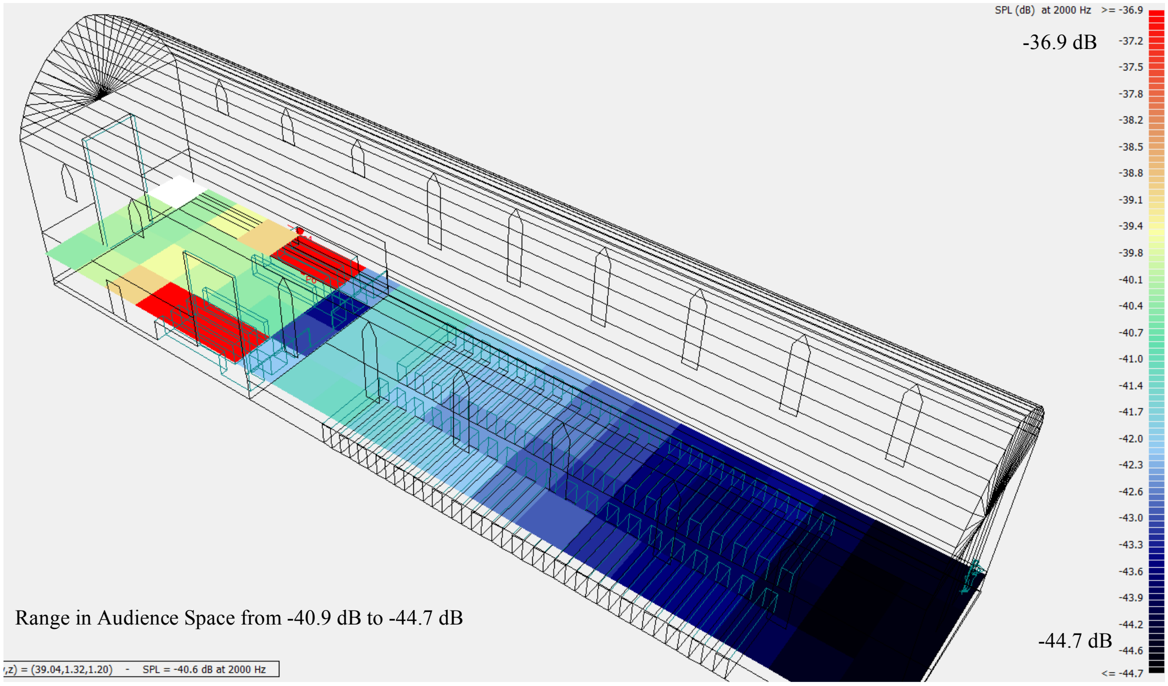


Figure 88: SPL distribution at 2000 Hz for Choir (Location B)

The choir set-up had an equal SPL distribution with a range of 3.8dB at 500Hz and 2000 Hz throughout the room excluding a 2m radius around the sources, as shown in Figure 87 and 88. The grid response showed higher SPL in the quire which is due to multiple sources in one location. It can be noted that the SPL decreased as the receiver moved further away from the source. This was highly notable at 125Hz, Figure 86, where the front half of the room had SPL values of -41.2dB to -45.0dB, and the back half of the room ranged from -45dB to -49dB. Overall, the barrel-vaulted ceiling did not negatively impact the SPL distribution within the church.

The grid response below shows the SPL distribution for St. Martin's with the source location C at 125 Hz.

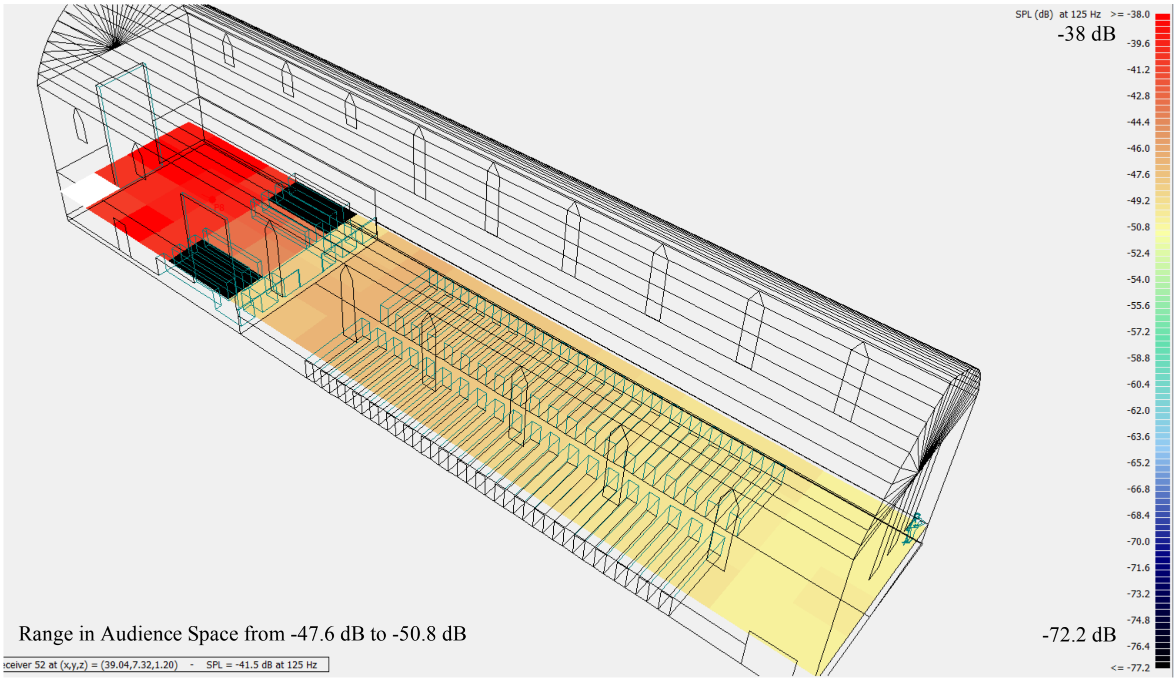


Figure 89: SPL distribution at 125 Hz for Musical Ensemble (Location C)

Following this, the room was simulated at a mid-range frequency, 500Hz, with the source location C.

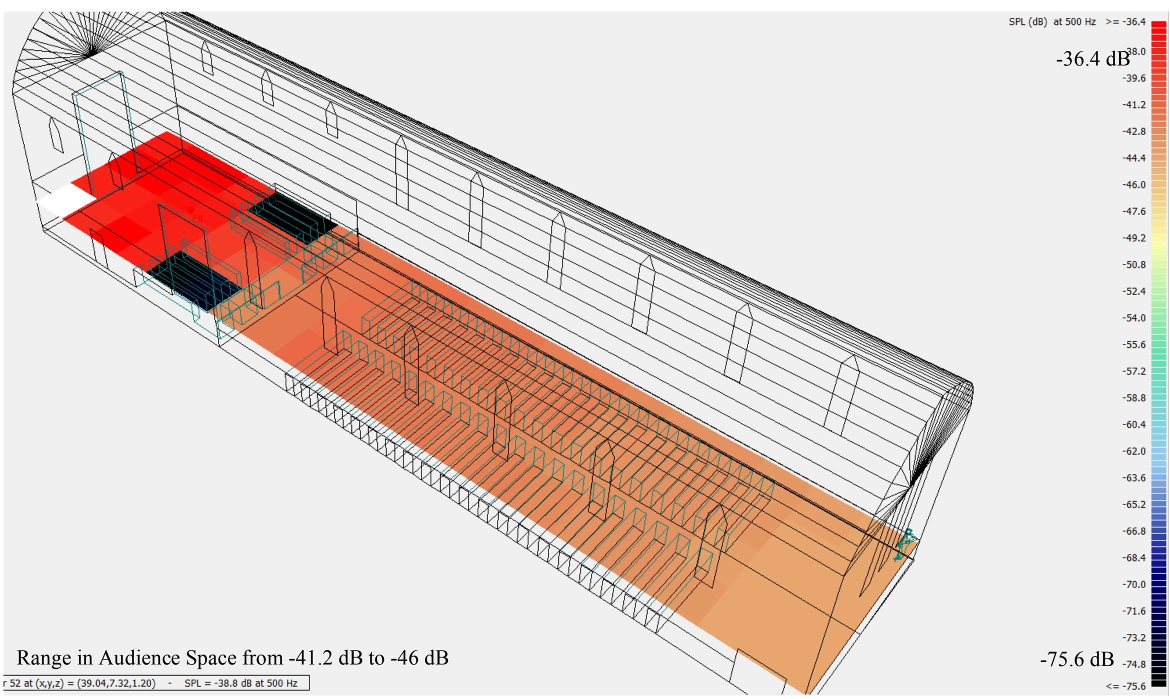


Figure 90: SPL distribution at 500 Hz for Musical Ensemble (Location C)

The final simulation for Location C was at 2000Hz.

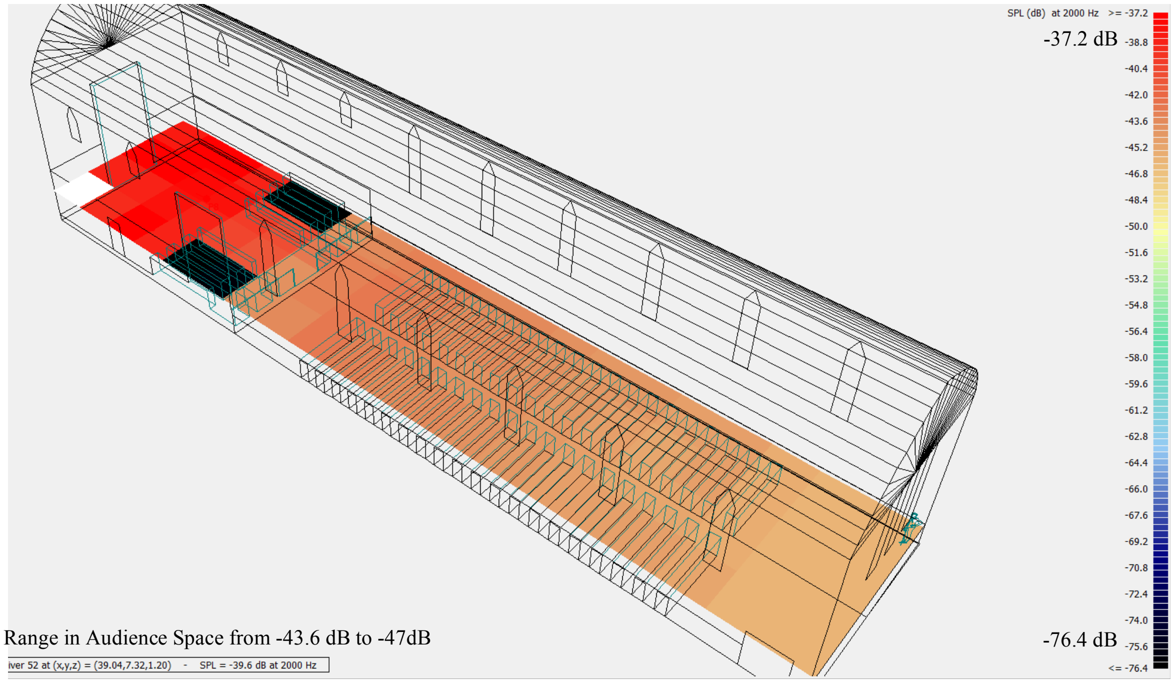


Figure 91: SPL distribution at 2000 Hz for Musical Ensemble (Location C)

As expected, the SPL distribution is louder near the source but quite uniform in the audience space for the musical ensemble simulation as shown in Figures 89-91. At 125Hz the sources had approximately a 3.4dB range for distribution within the audience space. The SPL range throughout the audience area at 500Hz was 4.8dB. Similarly to the choir results, the SPL decreased as a function of receiver to source distance. There was a 3.4dB range at 2000Hz in the audience space. Though SPL decreased with distance, overall, the SPL within the audience area was equal, concluding in no negative impact from the barrel-vaulted ceiling.

6.2.3 Low Frequency Analysis of St. Martins

The computer model of St. Martin's for COMSOL was based on as-built drawings. St. Martin's was simulated first with one source and then with three sources. The sources for wave theory simulation were in the same location as the musical ensemble situation from the hybrid-ray theory analysis, which was in the sanctuary. Wave theory analysis showing modal density can be seen in Figures 92 through 97. Simulations were completed for low frequencies which included 25Hz, 50Hz and 100Hz. The first three images show the modal density of one source within the room.

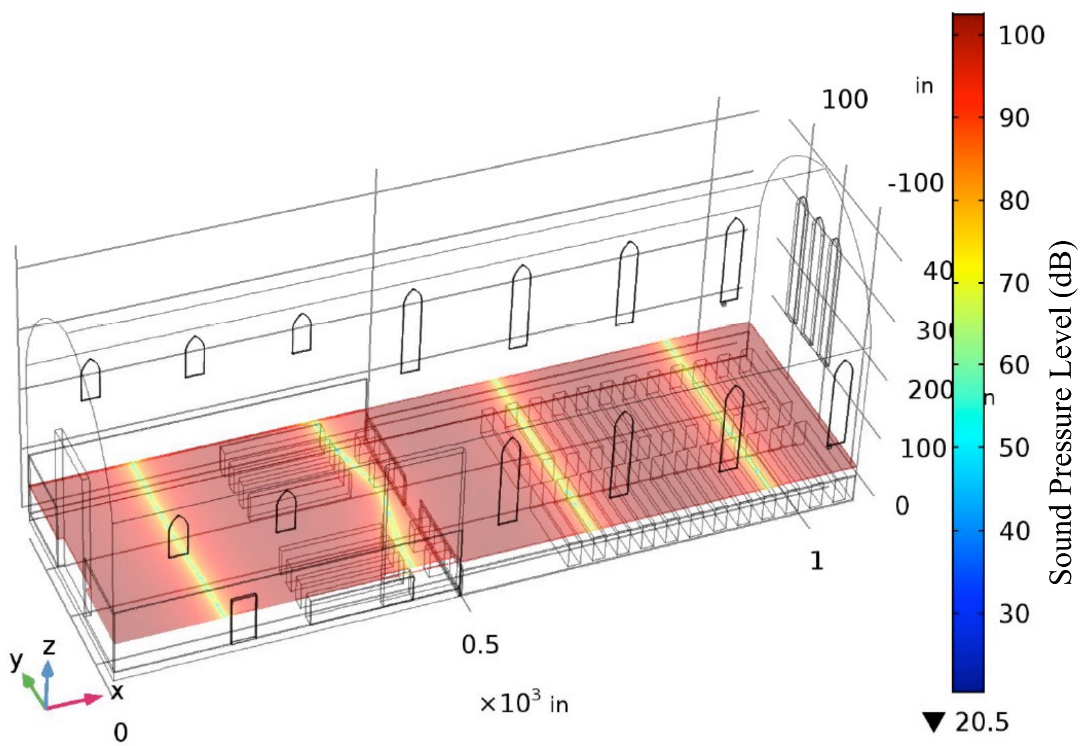


Figure 92: St. Martin's – One source 25 Hz

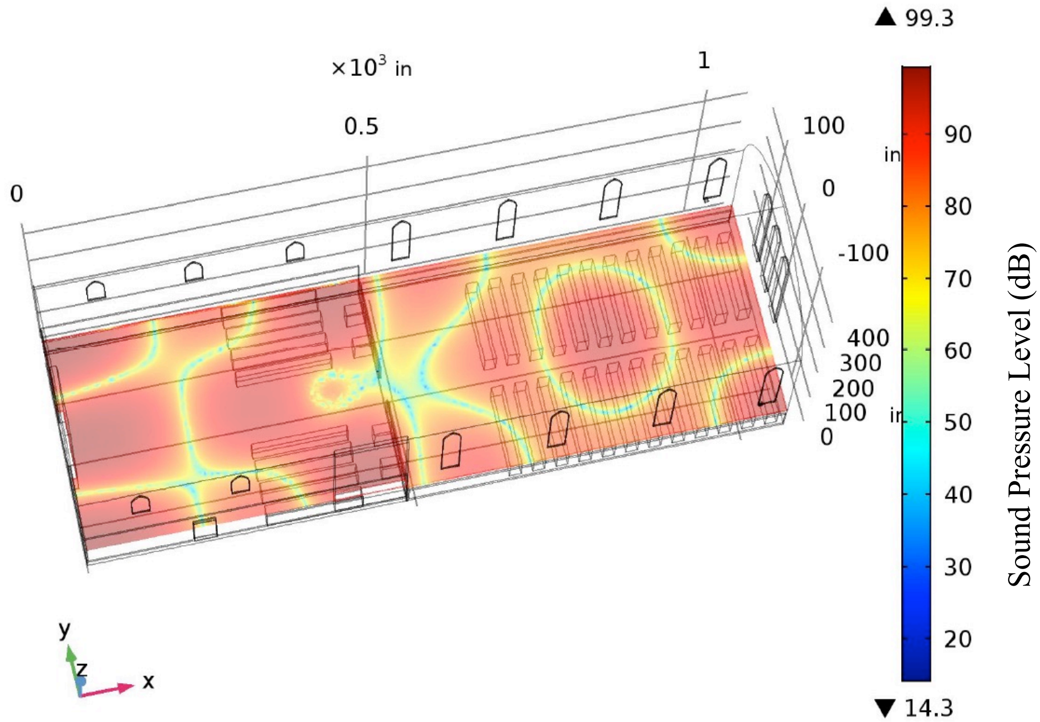


Figure 93: St. Martin's – One source 50 Hz

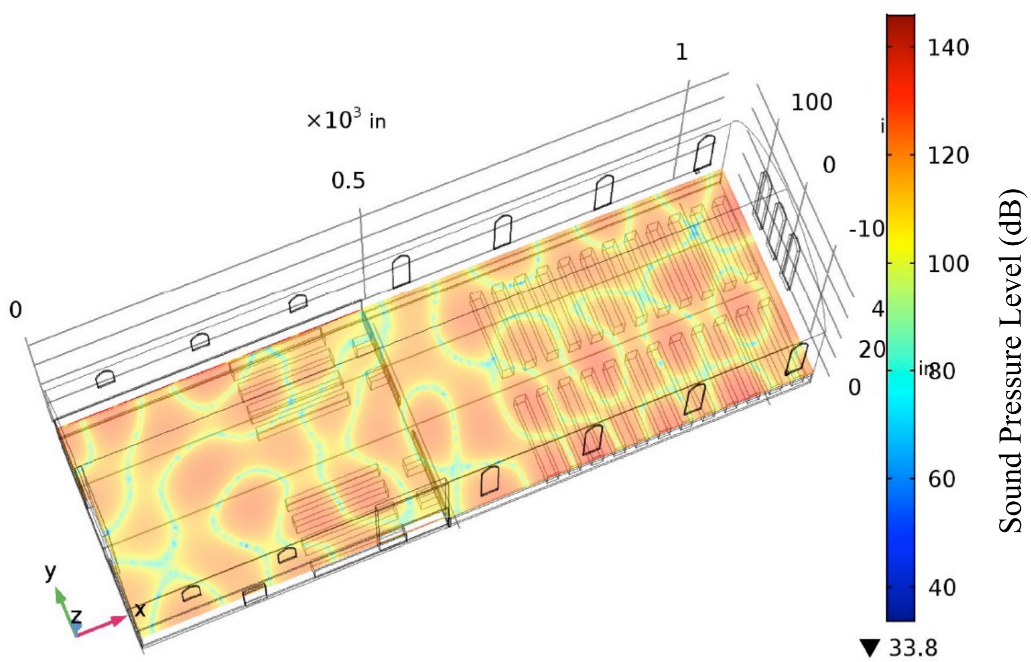


Figure 94: St. Martin's – One source 100 Hz

The next three images show the modal density of St. Martin's with three sources.

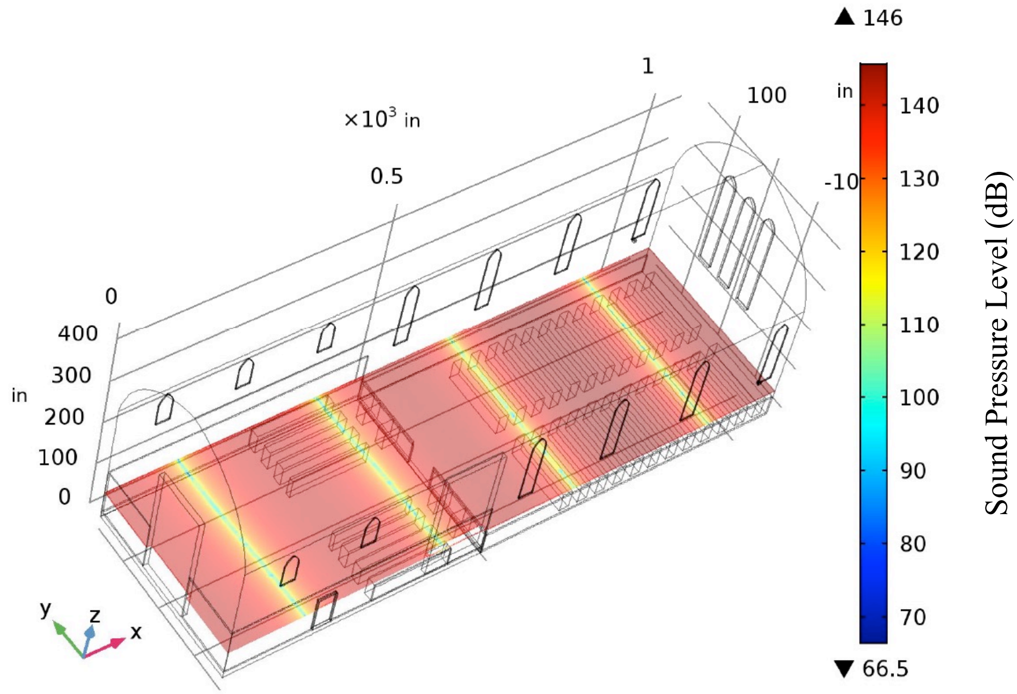


Figure 95: St. Martin's – Three sources 25 Hz

The low frequency simulations of St. Martin's show that there is one strong mode in the X direction for 25Hz for both one and three sources, as seen in Figure 88 and 91.

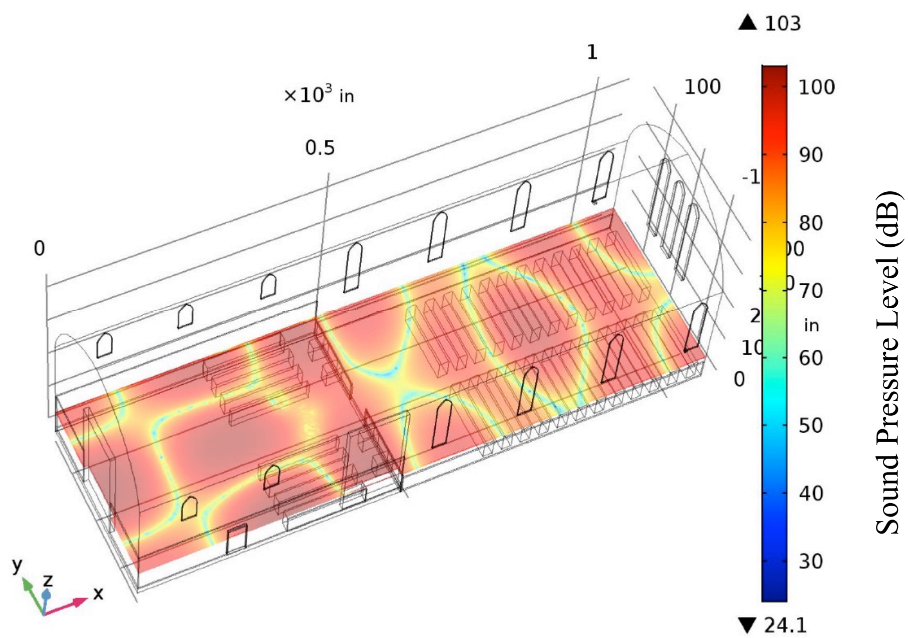


Figure 96: St. Martin's – Three sources 50 Hz

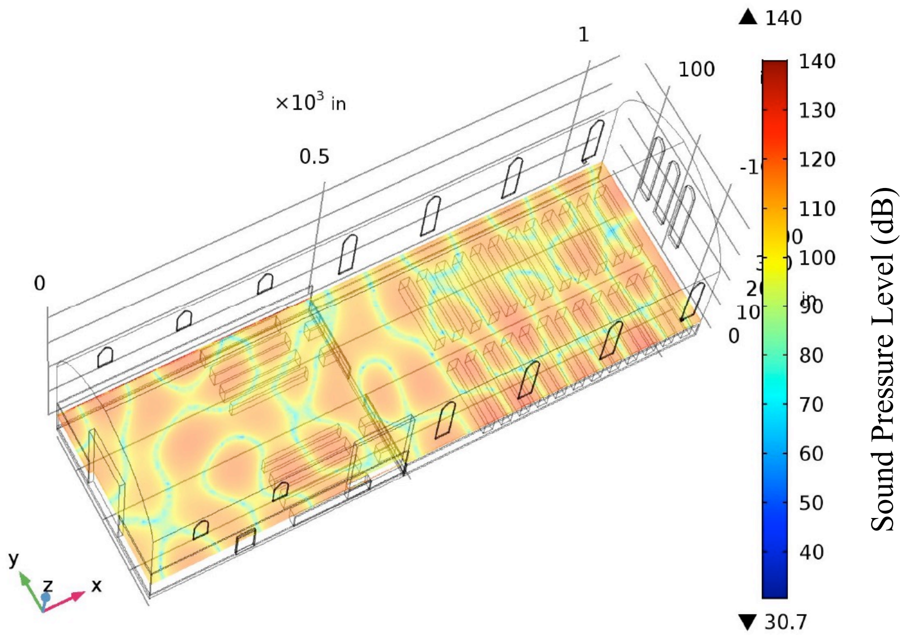


Figure 97: St. Martin's - Three sources 100 Hz

As the frequency increases to a higher band, more modes appear, as can be seen by comparing Figure 92 and 95 against Figure 93, 94, 96 and 97. The multitude of modes close together compensates for one another and produces good sound within a room. The modal density result of simulations for one source versus three sources, Figure 92 through 97, are nearly identical. Even though the SPL distribution has many peaks and valleys, all wave theory simulations of St. Martin's prove that the barrel-vaulted ceiling did not negatively impact the acoustical performance of St. Martin's negatively. This is shown by high modal density in the audience area.

6.3 Wigmore Hall

Wigmore Hall is located in the United Kingdom; therefore, it was not feasible to complete site measurements. Literature was used to validate the simulation experiments.

6.3.1 Ray Theory Validation

Similar to the other two locations, Wigmore Hall was evaluated using hybrid-ray theory analysis. To validate the 3D model for the hybrid-ray analysis, materials were chosen from the computer database to match the material composition of the room, as shown in Table 13. There was no need for absorption coefficients of materials to be further adjusted as the RT values were within engineering accuracy. The RT listed in multiple papers was used to validate the room (5) (10). The simulation was validated using RT of the unoccupied room at 1.63s at 500Hz, 1000Hz and 2000Hz, and an occupied room RT of 1.5s (10) (5).

The materials below provided the RT values listed in Table 14, which match the aforementioned papers.

Table 13: Wigmore Hall - AbsorptionW coefficients of materials

Materials (a)	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
Other	0.28	0.28	0.12	1	0.17	0.13	0.09	0.09
Roof	0.14	0.14	0.1	0.06	0.05	0.04	0.03	0.03
Auditorium Seats	0.33	0.36	0.47	0.57	0.62	0.62	0.6	0.58
Front Wall	0.02	0.02	0.03	0.04	0.05	0.07	0.08	0.08
Back Wall of stage	0.14	0.14	0.1	0.06	0.04	0.04	0.03	0.03
Floor	0.09	0.09	0.08	0.21	0.26	0.27	0.37	0.25
Walls	0.3	0.3	0.12	0.08	0.06	0.06	0.05	0.05
Stage Floor	0.17	0.17	0.32	0.12	0.06	0.03	0.02	0.02
Balcony	0.14	0.14	0.1	0.06	0.04	0.04	0.03	0.03
Dome	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Glazing on Ceiling	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02

Table 14: Wigmore Hall RT values – Unoccupied

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
RT Barron's measured data (s)	-	-	-	1.63	1.63	1.63	-	-
RT Simulation Unoccupied (s)	1.36	1.33	1.63	1.69	1.65	1.62	1.39	0.88

Table 15: Wigmore Hall RT values - Occupied

	63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz
RT Wulfrank & Orlowski's measured data (s)	-	-	-	1.5	1.5	1.5	-	-
RT Simulation Occupied (s)	1.14	1.17	1.39	1.45	1.47	1.42	1.23	0.78

As can be seen from Tables 14 and 15, both unoccupied and occupied RT were matched. Once validated, simulations were run for four different situations. Situation 1 was with a source location at the back of the stage under the dome ("P1"), situation 2 was near the middle of the stage ("P2"), the third situation was near the front of the stage ("P3"), while the fourth situation was that of a musical ensemble with five sources on the stage ("P3, P4, P5, P6, P7"). Source locations can be seen in Figure 98, where the fourth situation is "active" and therefore shown with larger pink dots.

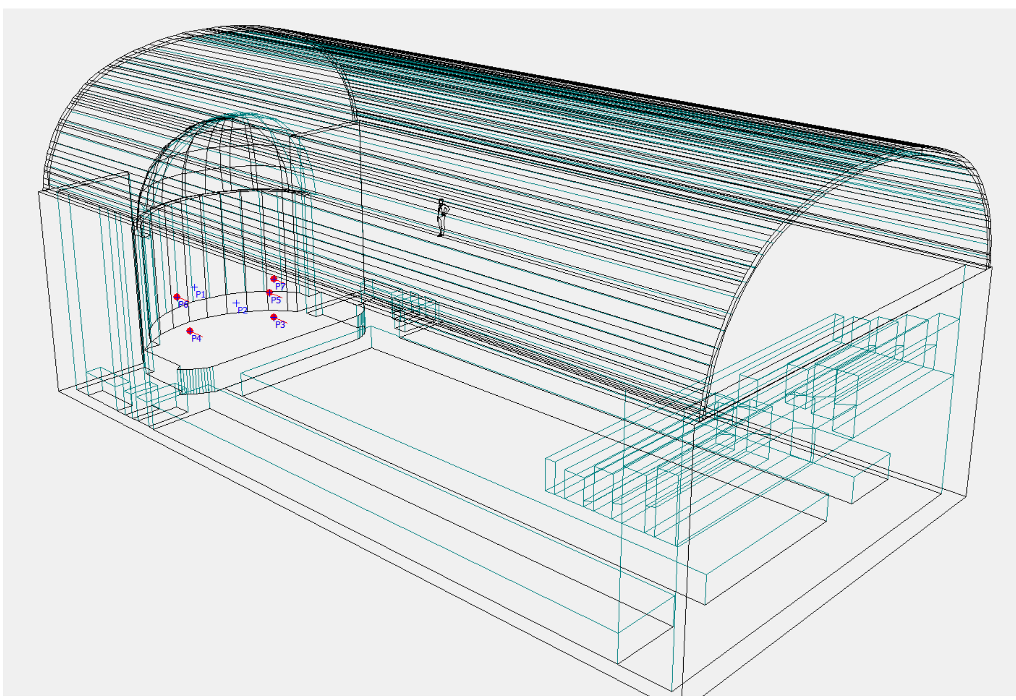


Figure 98: Wigmore Hall - Simulation set-up with source locations

The simulation results are shown for 125 Hz, 500Hz and 2000Hz in figures 99 through 101, while the remaining one-third octave band results can be seen in the Appendix C. Additional simulations were created for Wigmore Hall as an occupied space with the musical ensemble to analyze if SPL distribution changed.

When discussing SPL, for the purpose of the study, the audience area of Wigmore Hall did not include the stage. The grid response below shows the SPL distribution for Wigmore Hall with the source under the dome, at 125 Hz.

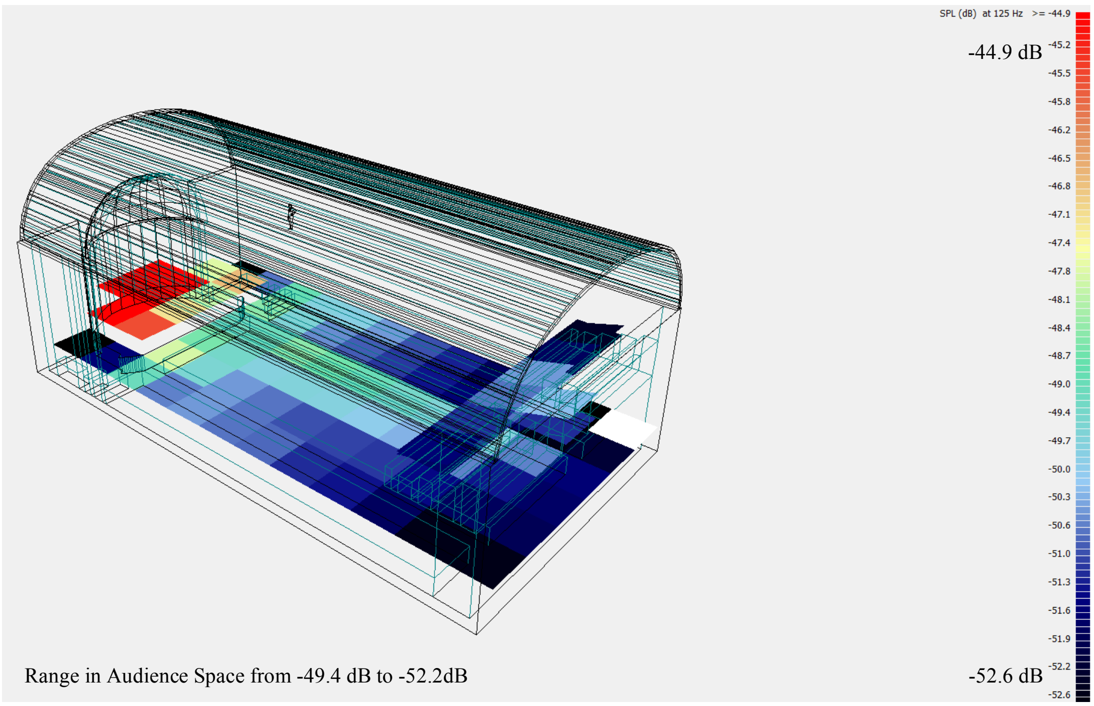


Figure 99: SPL distribution at 125 Hz - Source P1 - Under Dome

Following this, the room was simulated at a mid-range frequency, 500Hz, with the source under the dome.

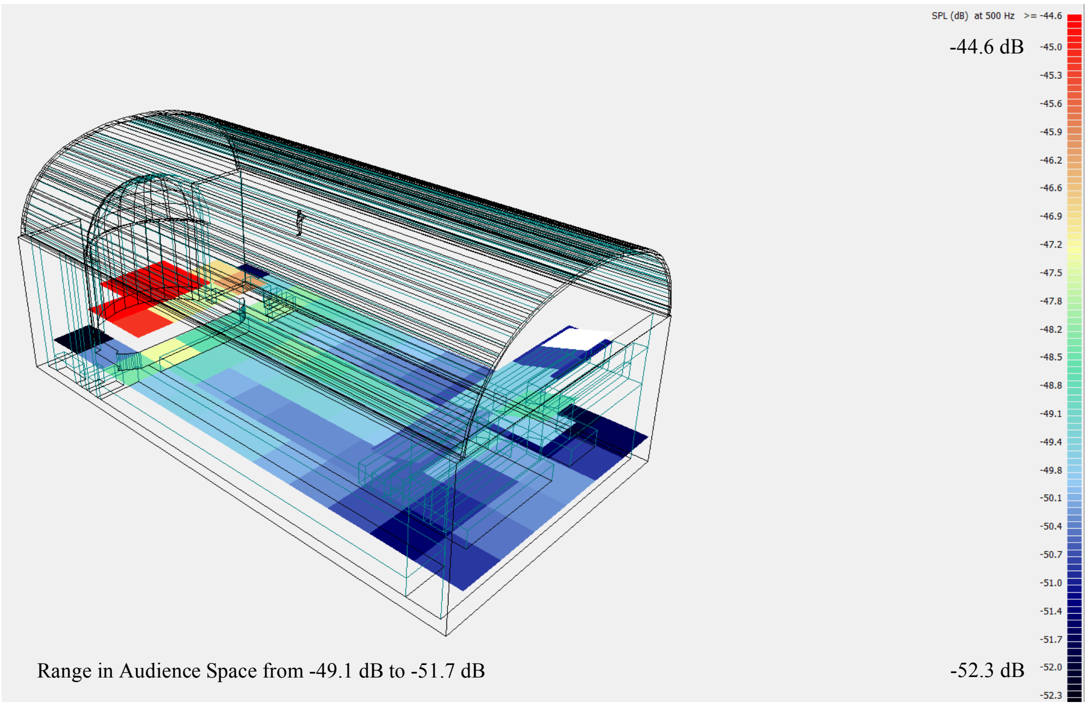


Figure 100: SPL distribution at 500 Hz - Source P1 - Under Dome

The final simulation for the source under the dome was at 2000Hz.

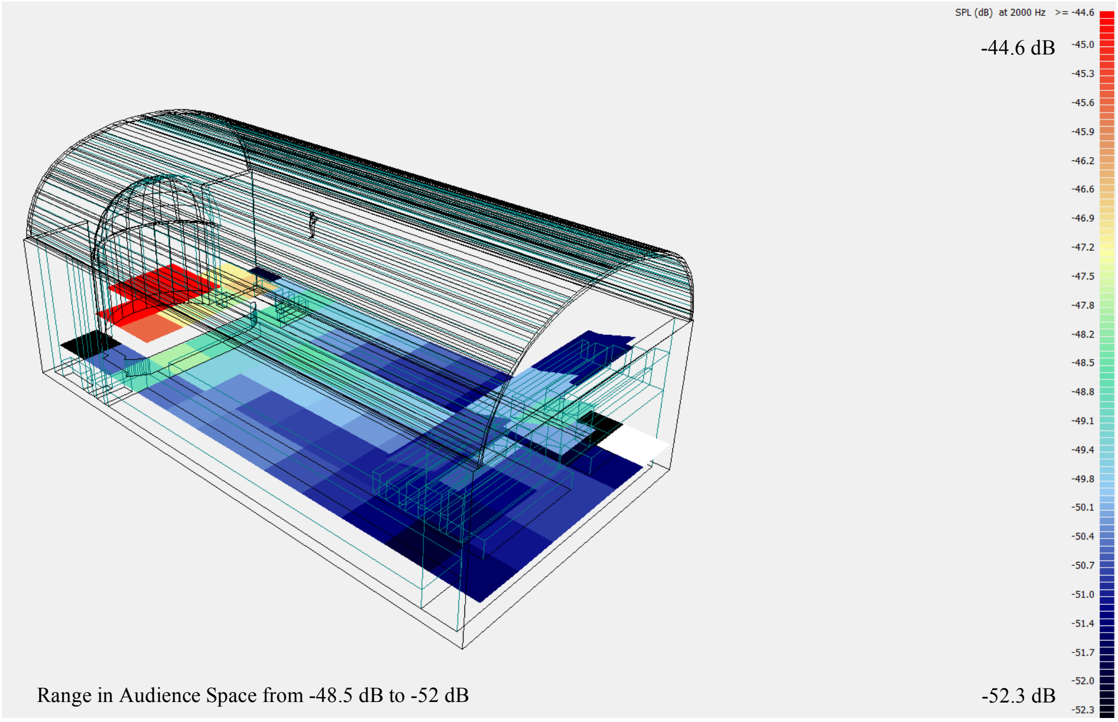


Figure 101: SPL distribution at 2000 Hz - Source P1 - Under Dome

For source P1, the sound pressure distribution within the audience space, and including the balcony, had a range of 2.8dB at 125Hz, 2.6dB at 500Hz and 3.5dB at 2000Hz. As can be noted with other simulated large rooms, SPL decreased as a function of source to receiver distance. With such low changes in SPL throughout the room it confirms the statements that Wigmore Hall is known for its incredible acoustics. Overall, the elliptic vaulted ceiling, cylindrical stage platform, and spherical cupola, did not negatively impact the SPL distribution across the room.

Following the simulation of Situation 1, the source was moved to the middle of the stage for P2. The grid response below shows the SPL distribution for Wigmore Hall with the source in the middle of the stage, at 125 Hz.

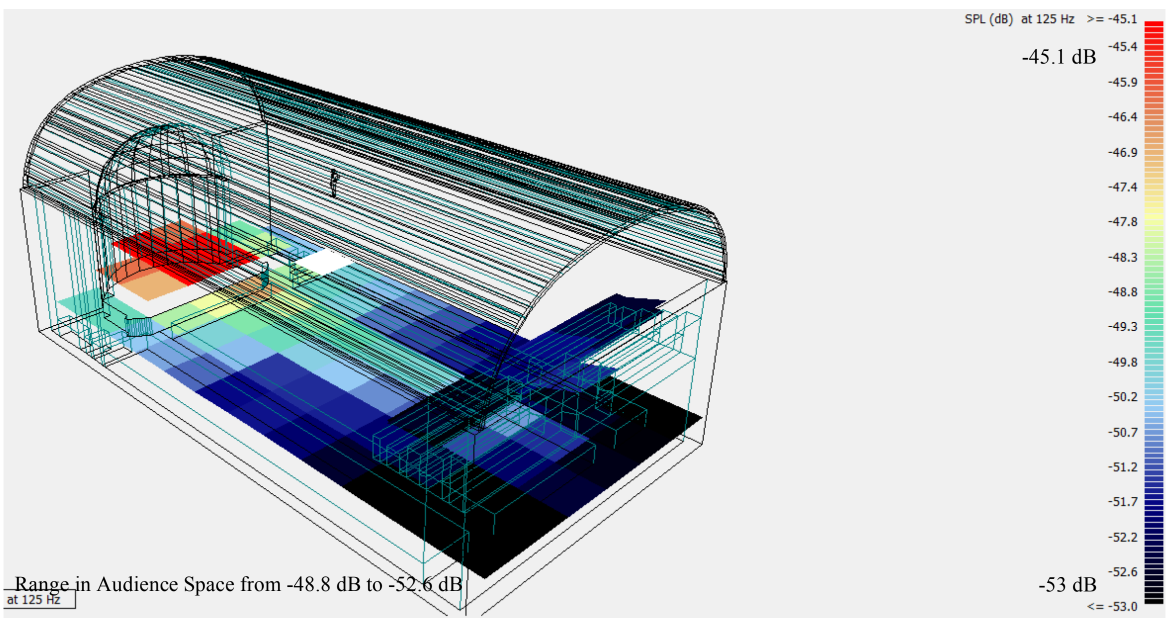


Figure 102: SPL distribution at 125 Hz - Source P2 - Middle of stage

Following this, the room was simulated at a mid-range frequency, 500Hz, with the source in the middle of the stage.

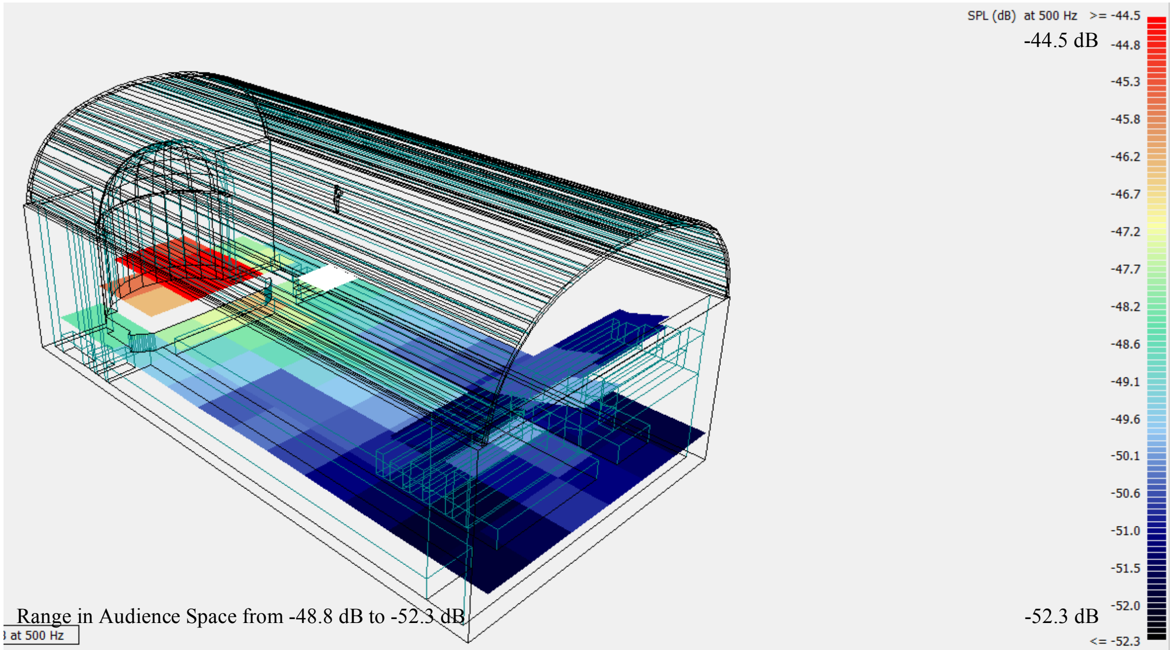


Figure 103: SPL distribution at 500 Hz - Source P2 - Middle of stage

The final simulation for the source in the middle of the stage was at 2000Hz.

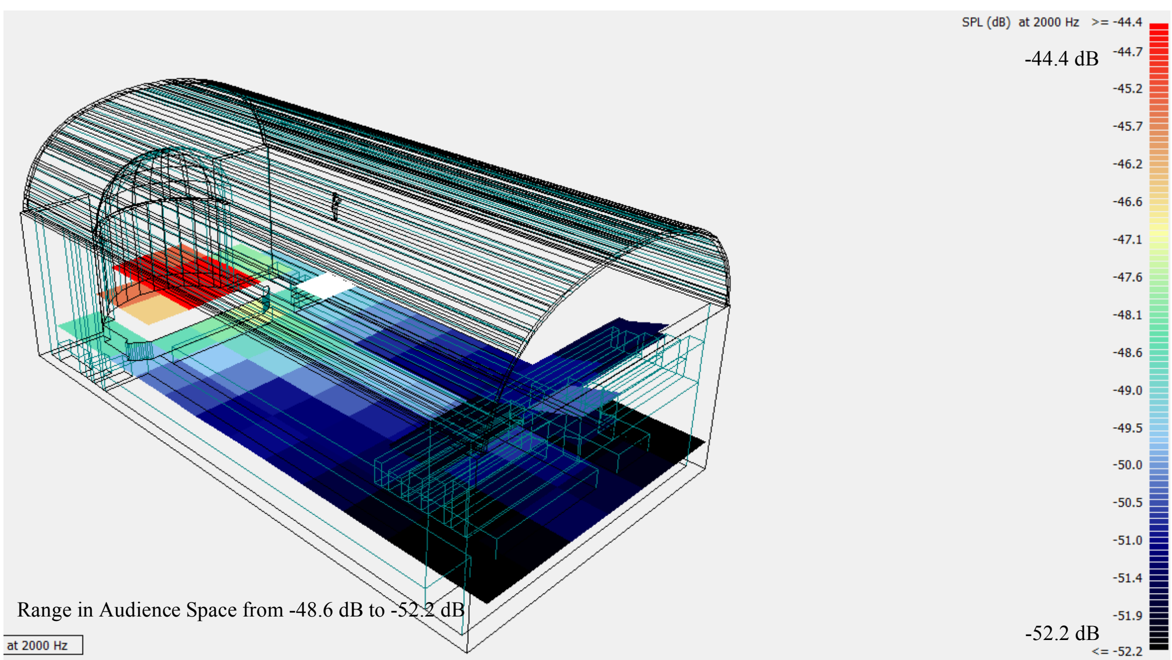


Figure 104: SPL distribution at 2000Hz - Source P2 - Middle of stage

When the source was moved to the middle of the stage at location P2 the SPL distribution in the audience space had a range of 3.8dB for 125Hz, 3.5dB at 500Hz and 3.6dB at 2000Hz. The results, shown in Figures 102 through 104 prove that the SPL distribution throughout the audience space of Wigmore Hall with a source in the centre of the stage is equal, and was not compromised by its curved elements. An issue may arise for the musician due to the intensity of sound on the stage, but this would need to be researched further.

The grid response below shows the SPL distribution for Wigmore Hall with the source at the front of the stage, at 125 Hz.

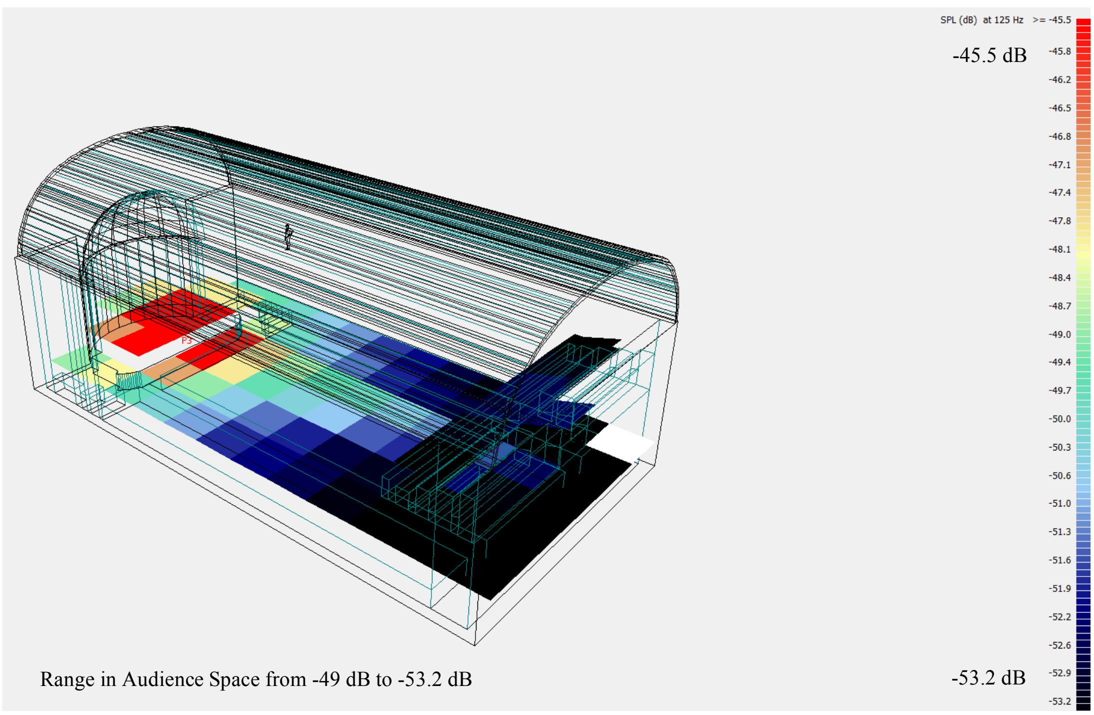


Figure 105: SPL distribution at 125Hz - Source P3 - Front of stage

Following this, the room was simulated at a mid-range frequency, 500Hz, with the source at the front of the stage.

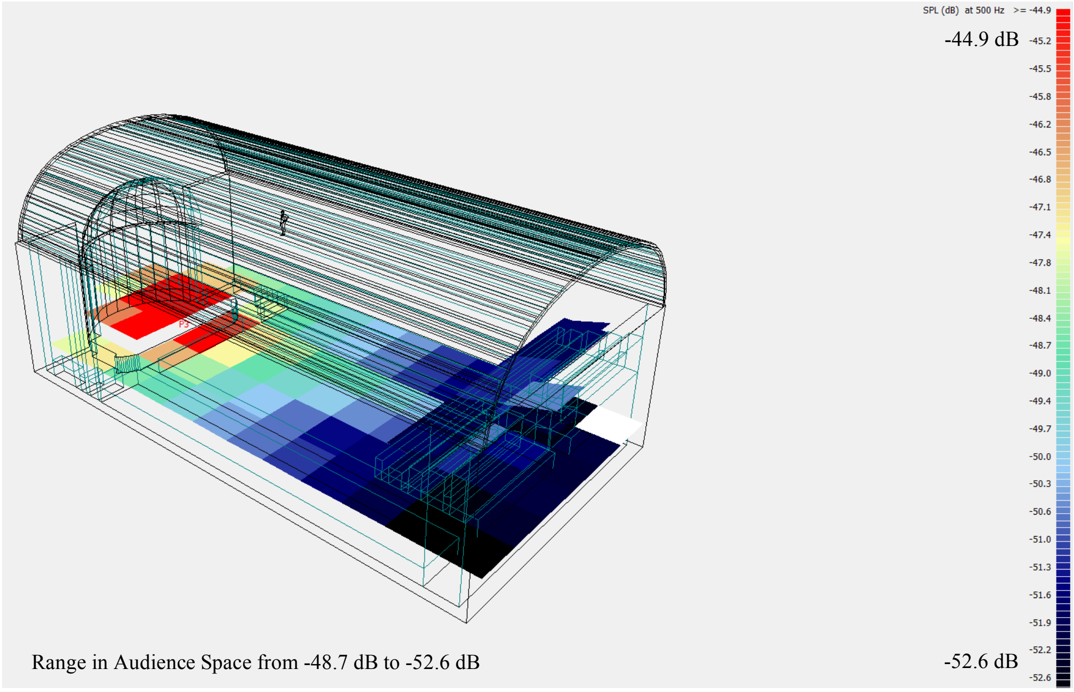


Figure 106: SPL distribution at 500Hz - Source P3 - Front of stage

The final simulation for the source in the source at the front of the stage, was at 2000Hz.

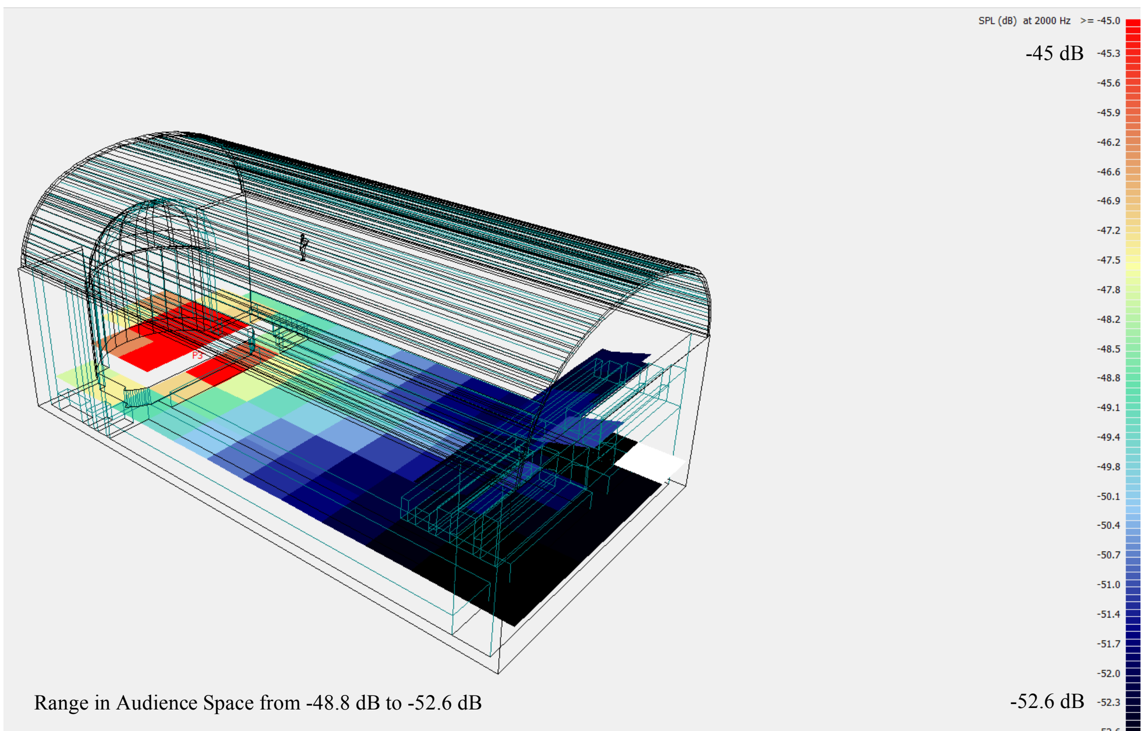


Figure 107: SPL distribution at 2000Hz - Source P3 - Front of stage

When the source was relocated to the front of the stage, location P3, the SPL distribution in the audience space had a range of 4.2dB at 125Hz, 3.9dB at 500 Hz and 3.8dB at 2000Hz; all simulated frequencies showed no negative impact of the curved ceiling, cupola and back of stage area, on the audience space, as shown in Figures 105-107.

The final unoccupied room simulation of Wigmore Hall was completed as a small ensemble (P3, P4, P5, P6, and P7). The grid response below shows the SPL distribution for the unoccupied Wigmore Hall with the source as a small musical ensemble, at 125 Hz.

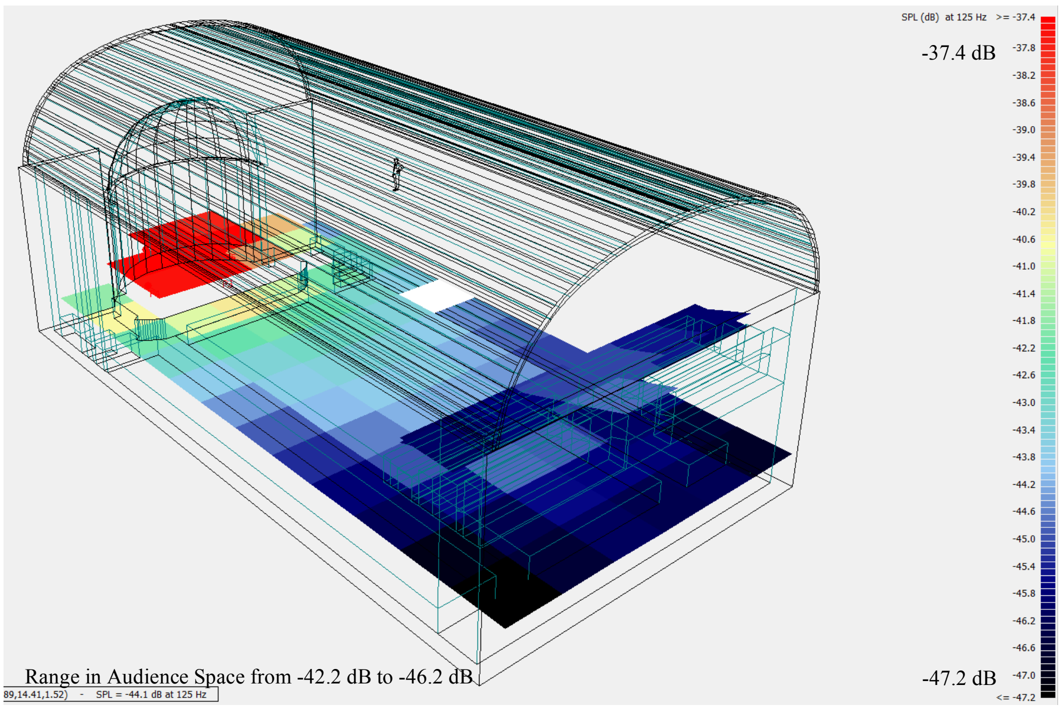


Figure 108: SPL distribution at 125Hz - Source P3, P4, P5, P6 and P7 - Small ensemble

Following this, the room was simulated at a mid-range frequency, 500Hz, with the source as a small ensemble as an unoccupied room.

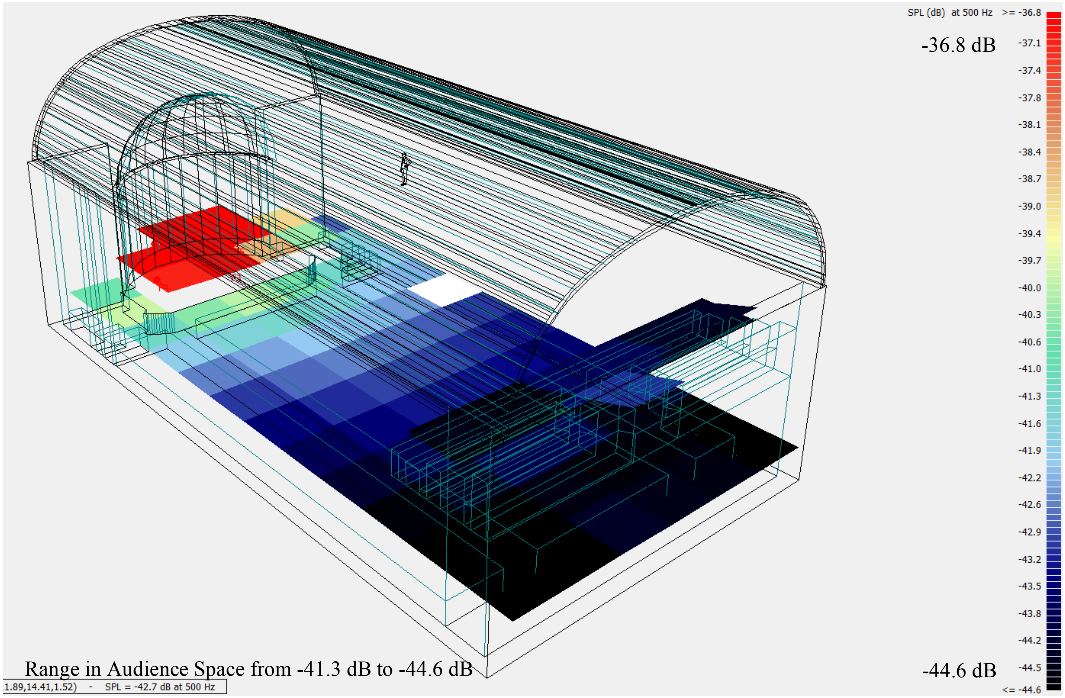


Figure 109: SPL distribution at 500Hz - Source P3, P4, P5, P6 and P7 - Small ensemble

The final simulation for the source in the source as a small ensemble as an unoccupied room, was at 2000Hz.

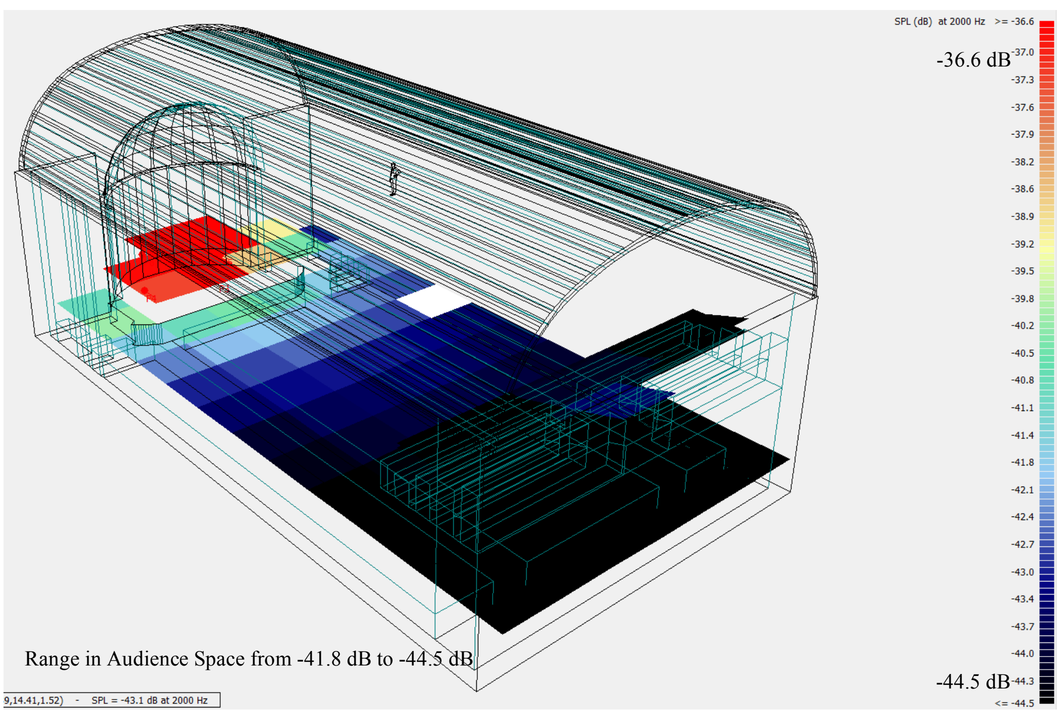


Figure 110: SPL distribution at 2000Hz - Source P3, P4, P5, P6 and P7 - Small ensemble

The range of SPL distribution in the audience space for the unoccupied room with the small ensemble was 4dB at 125Hz, 3.3 dB and 500 Hz and 2.7dB at 2000Hz, Figures 108-110. All ranges were within 5dB difference throughout the room, confirming good SPL distribution with a multitude of performers. Wulfrank and Orlowski stated that the Hall is good for ensembles of eight or less, and this simulated test was for an ensemble of five, indicating their statement to be correct.

Barron noted that the occupied hall had a reverberation time of 1.5s, therefore SPL distribution was analyzed across the simulated Wigmore Hall to see if, as an occupied room, it remained equally distributed.

The grid response below shows the SPL distribution for the occupied Wigmore Hall with the source as a small ensemble, at 125 Hz.

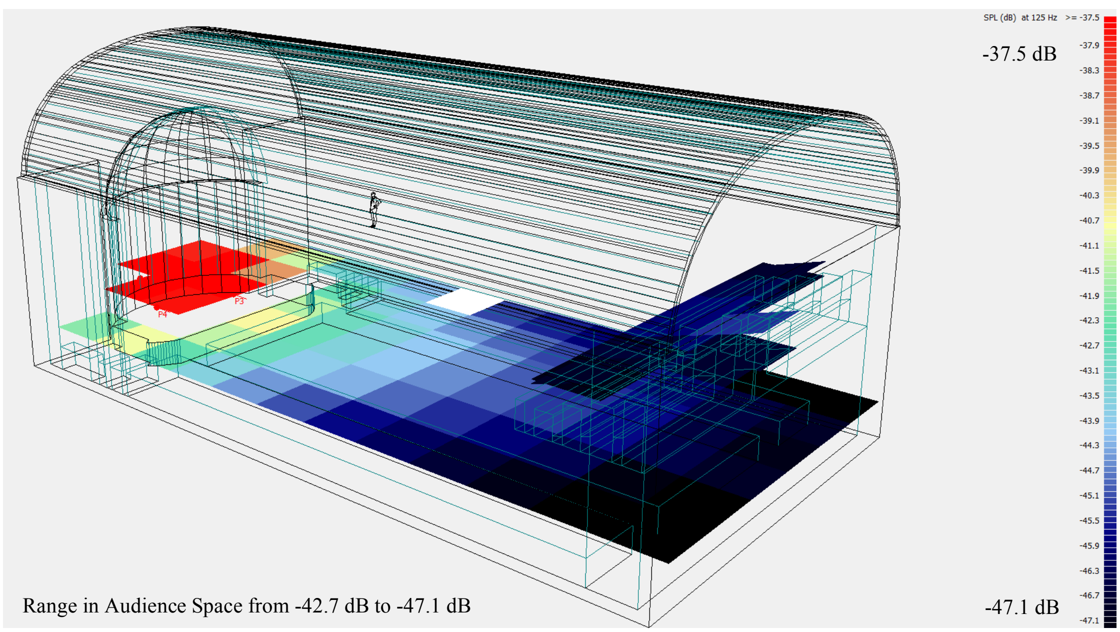


Figure 111: SPL distribution at 125Hz - Source P3, P4, P5, P6 and P7 - Small ensemble (Occupied seating)

Following this, the room was simulated at a mid-range frequency, 500Hz, with the source as a small ensemble as an occupied room.

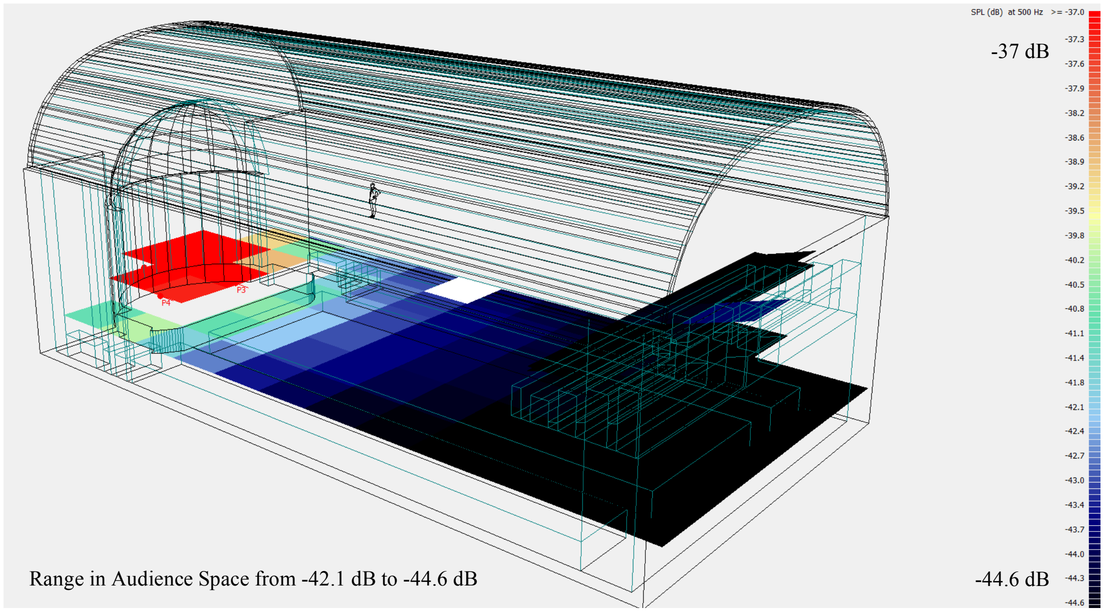


Figure 112: SPL distribution at 500Hz - Source P3, P4, P5, P6 and P7 - Small ensemble (Occupied seating)

The final simulation for the source in the source as a small ensemble as an occupied room, was at 2000Hz.

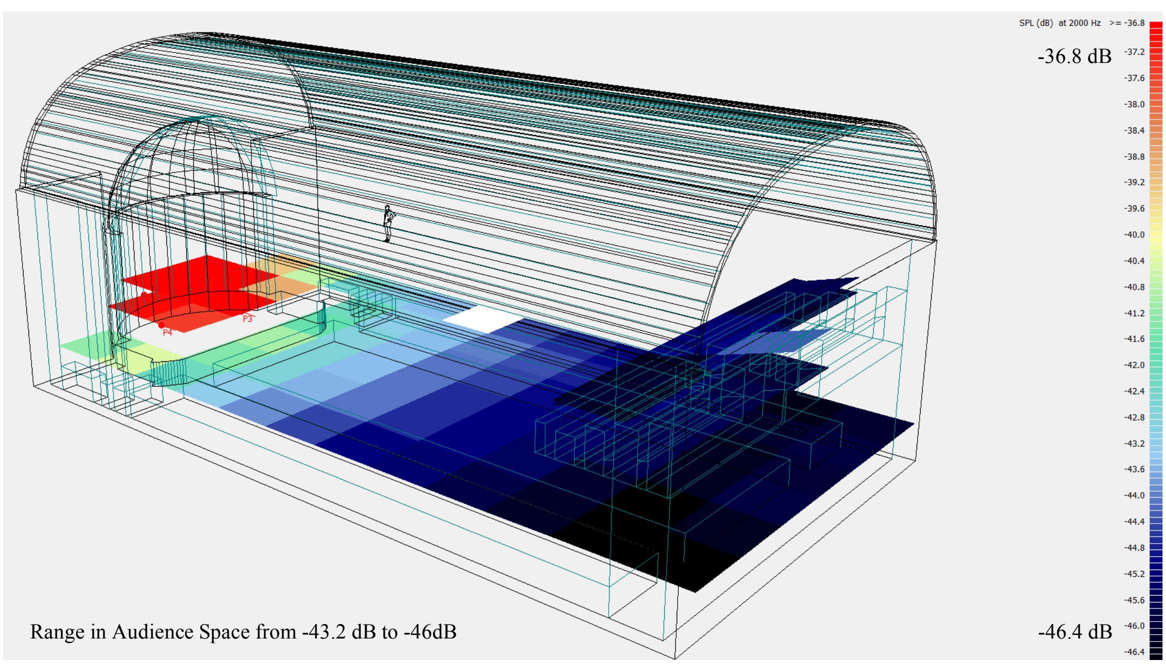


Figure 113: SPL distribution at 2000Hz - Source P3, P4, P5, P6 and P7 - Small ensemble (Occupied seating)

As can be seen from the occupied version of the small ensemble, the SPL distribution remains equal throughout the audience space, see Figures 111 through 113. At 125Hz the range within the audience space is approximately 4.4 dB, at 500Hz it is 2.5 and at 2000 Hz it is 2.8dB. In comparison to the unoccupied seating, the SPL distribution through the room improves with an audience, as seen by smaller differences in SPL distribution across the room, showing that the curved features did not negatively impact the space.

6.3.2 Low Frequency Analysis of Wigmore Hall

Similar to the Gallery and St. Martin's, Wigmore Hall was evaluated using wave theory analysis, which relied on geometries as opposed to materials. Wigmore Hall was simulated with one source and then with three sources. These were tested at low frequencies 25Hz, 50Hz ,and 100Hz. The sources were located on the stage, similarly to the hybrid-ray theory simulation set up for multiple sources as a musical ensemble, as shown in Figure 98. The SPL distributions are plotted in Figures 114 through 119. The first three modal responses were simulated with one source.

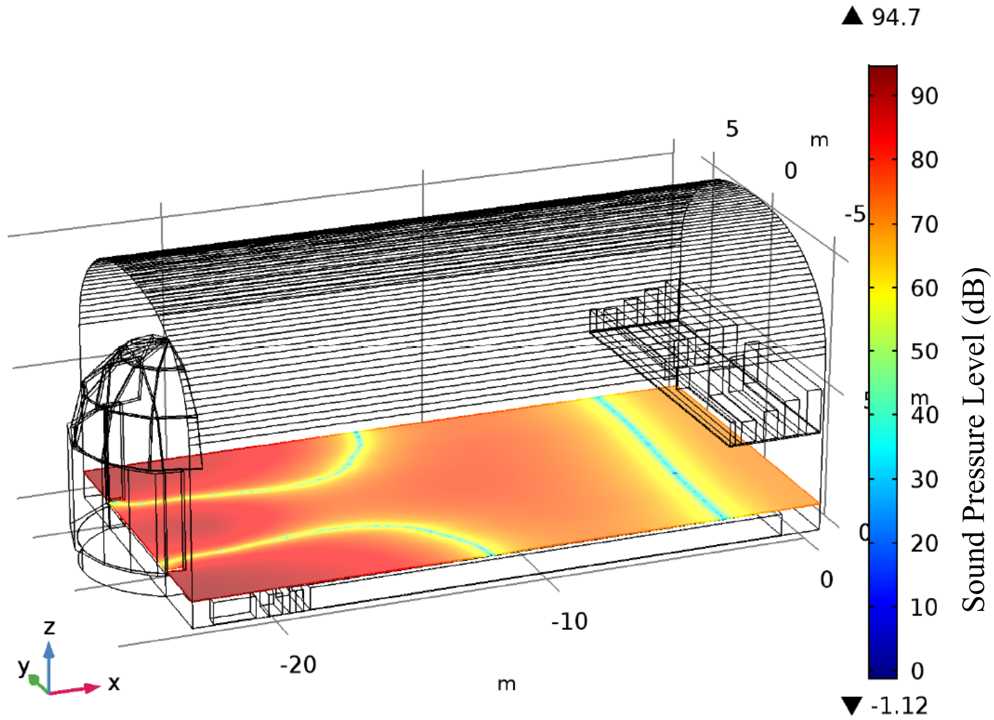


Figure 114: Wigmore Hall - One Source 25Hz

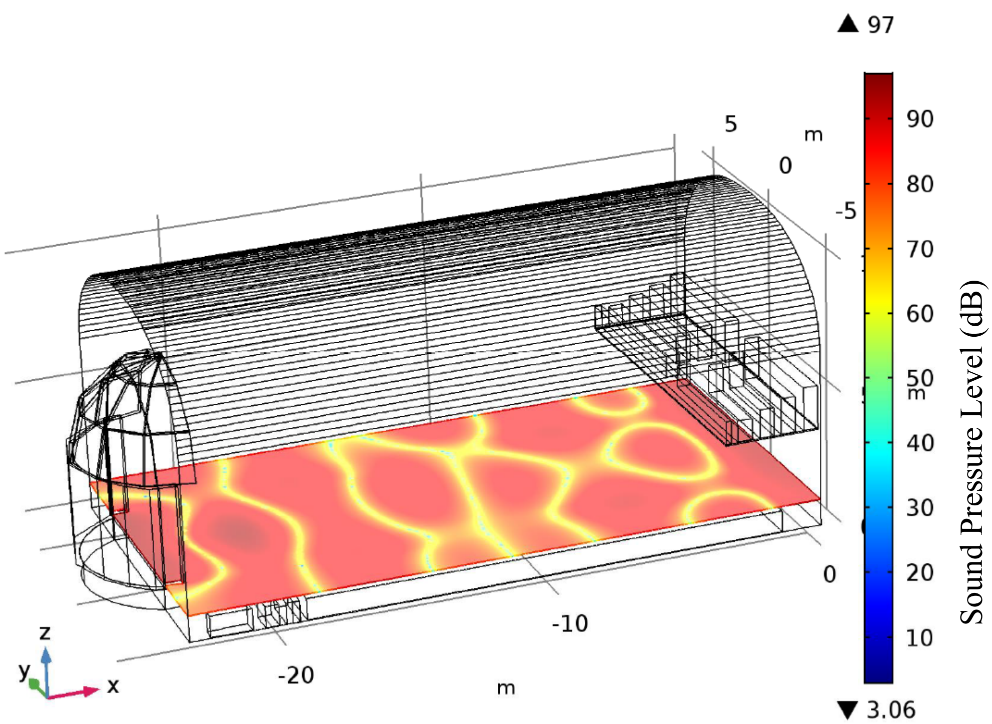


Figure 115: Wigmore Hall - One Source 50Hz

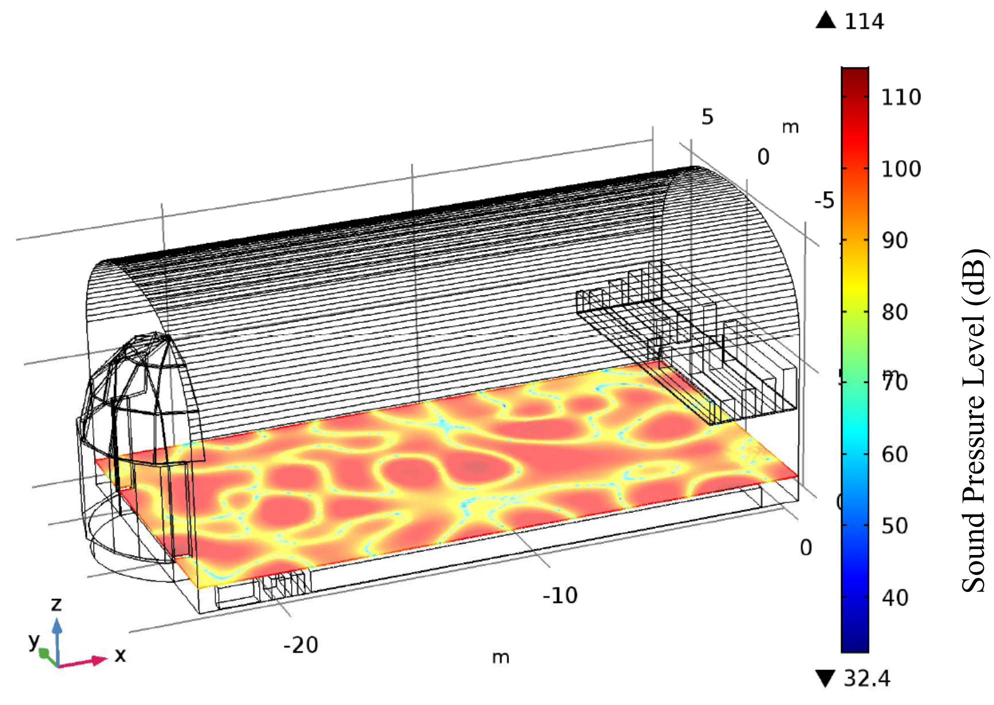


Figure 116: Wigmore Hall - One Source 100Hz

The following three modal responses were simulated with three sources.

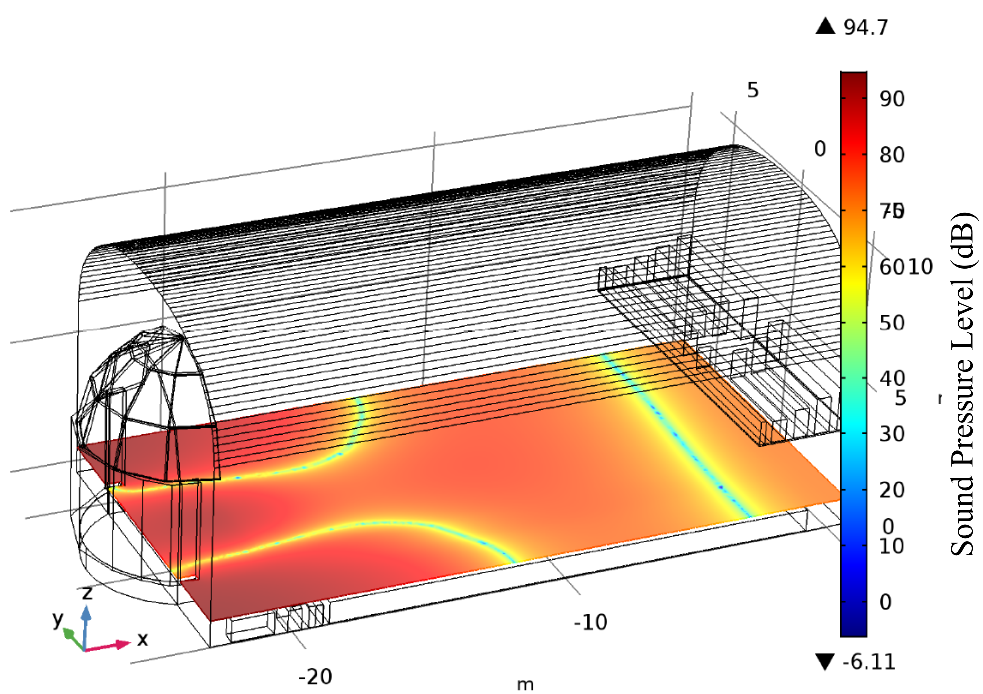


Figure 117: Wigmore Hall - Three Sources 25Hz

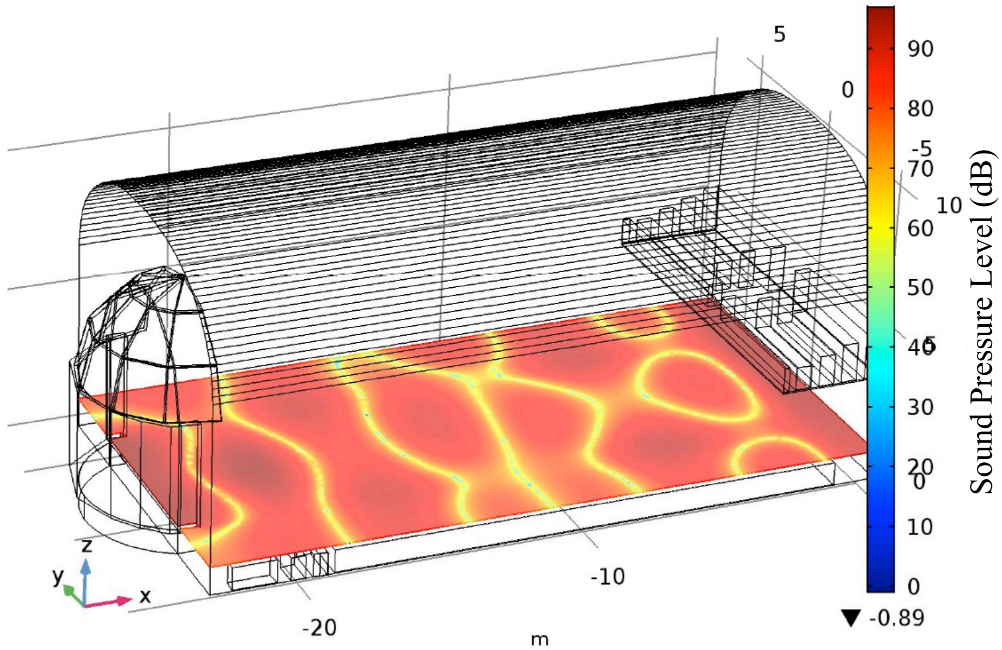


Figure 118: Wigmore Hall - Three Sources 50Hz

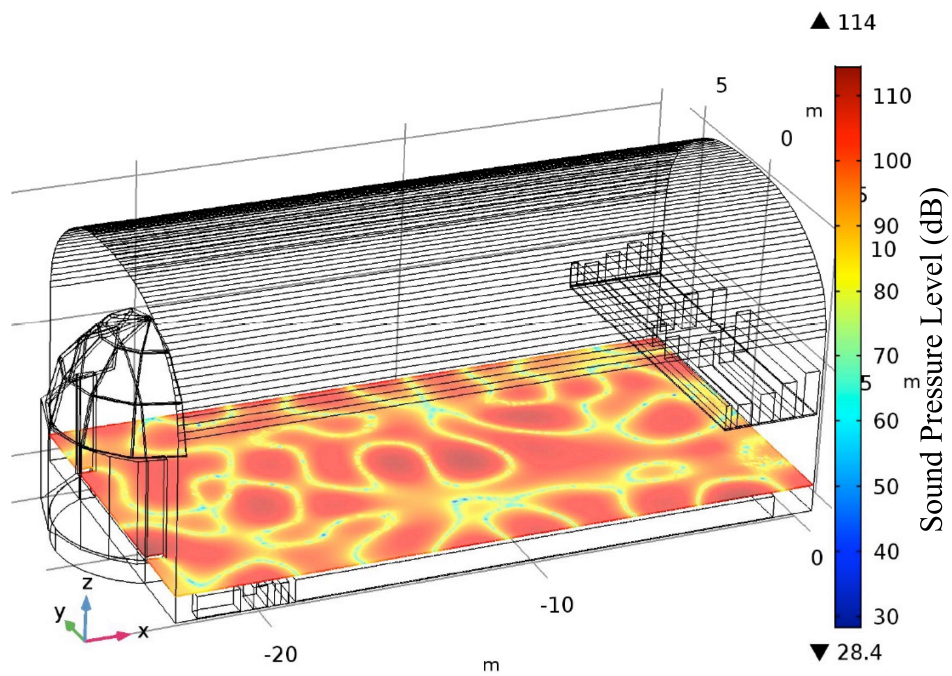


Figure 119: Wigmore Hall - Three Sources 100Hz

The modal density, shown in Figures 114 through 119, for Wigmore Hall increased as frequency increased. Wigmore Hall had a stronger mode in the Y direction closer to the stage and then it changed under the balcony to a mode in the X direction. This occurred with both one source, Figure 114, and with three sources, Figure 117. In the highest frequency simulated, 100Hz, the room modes were evenly dispersed throughout the room as shown in Figures 116 and 119. It should be noted that in a concert a variety of frequencies from multiple instruments would superimpose and the sound in the room would be good. Once again, the low frequency results show that room modes dominate SPL distribution, and that the three curves of Wigmore Hall have no negative impact on sound distribution within the audience space.

7.0 Conclusions

Many modern acousticians have been wary of introducing curved surfaces into their design due to hypotheses in regard to their negative acoustical impact. But, for hundreds of years, churches, halls, and many other buildings have functioned very well acoustically with curved features. The lack of information concerning curved envelopes has not assisted the situation. Therefore, the current major research project analyzed how the concave elements within an enclosed room affected the audience space.

The research found that the SPL distribution in the Gallery, St. Martin's and Wigmore Hall was equal throughout the audience spaces. The tested curved surfaces did not have negative impacts on the SPL distribution as was validated by on-site measurements and computer simulations. Though the simulations produced interesting results for the Gallery, it was most interesting to validate and clarify the existing information for St. Martin's and Wigmore Hall which proved their good acoustics. The simulations showed that curved envelopes can diffuse SPL equally throughout an enclosed space, beyond the focal plane, producing good acoustic performance. It should be noted that at certain frequencies the SPL lessens as a ratio to source-receiver distance. When the ideal conditions are met, in enclosed rooms for source-receiver-medium (curve) location and distance, SPL diffuses equally beyond the focal plane, producing good acoustics. With this research, it is the hope that modern architects will be confident in utilizing more organic forms in their design, as the research proves that there were no focussing issues within the audience space with ideal source-receiver-medium locations.

Further research could study whether a concave curve surface is able to enhance the acoustic performance of an enclosed space, and if so, determine the optimal curve to room ratio, along with the ideal curve locations. If this in fact improved the acoustical performance of an enclosed room, it would be interesting to further analyze concave surfaces in the context of outdoor performance venues, to study any beneficial impacts.

Appendix A – Experiment

The experiment section in the Appendix includes images of the constructed Curve as well as the instruments used for measurements.

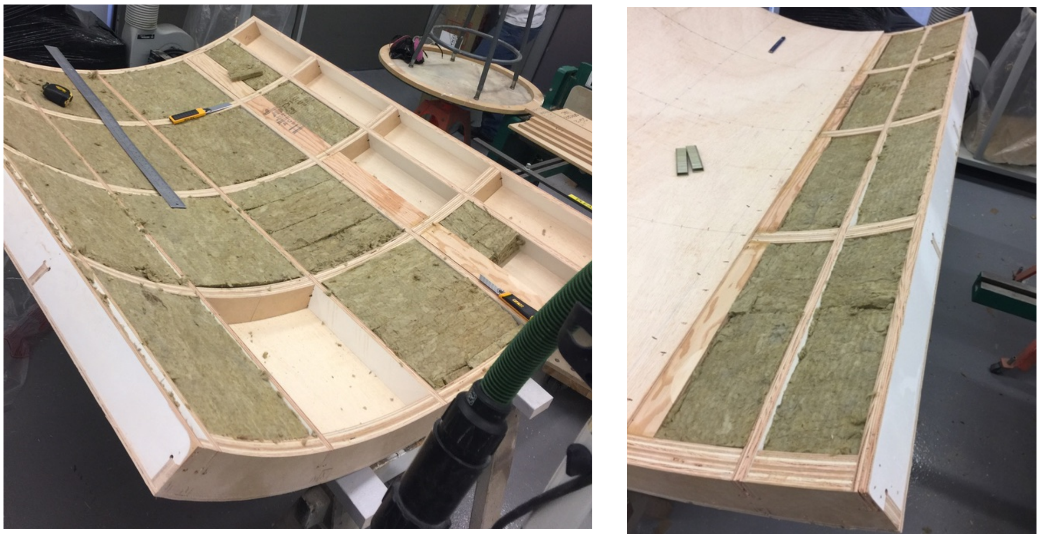


Figure 1: Curve Interior

Figure 2: Amplifier

Figure 3: Conditioning amplifier

Figure 4: HP 3569 A 2 channel real time analyzer

Appendix B – Measurement Results

The measurement results section in the appendix includes frequency analysis for the sine-sweep measurements for Bare Room and the Curve in the Gallery. It also includes Pink Noise variation analysis at receiver locations.

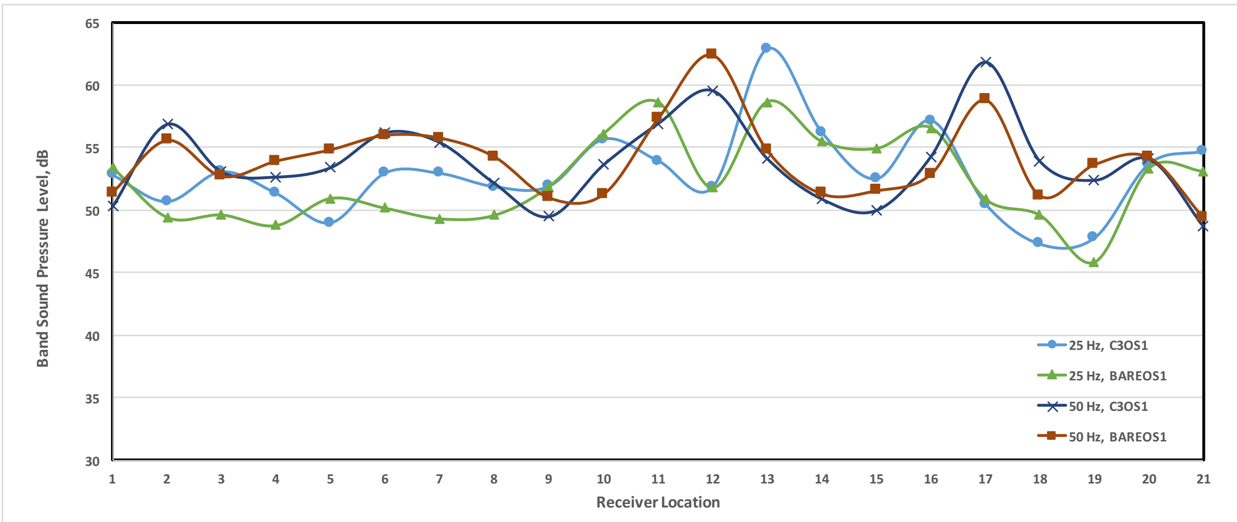


Figure 5 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 25 Hz vs. 50Hz

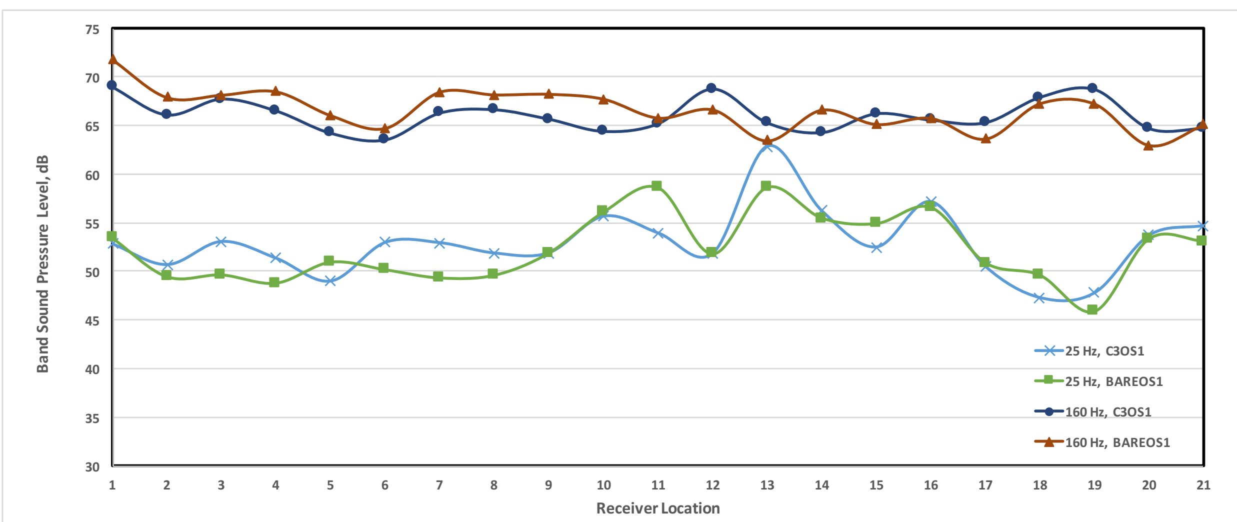


Figure 6 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 25 Hz vs. 160Hz

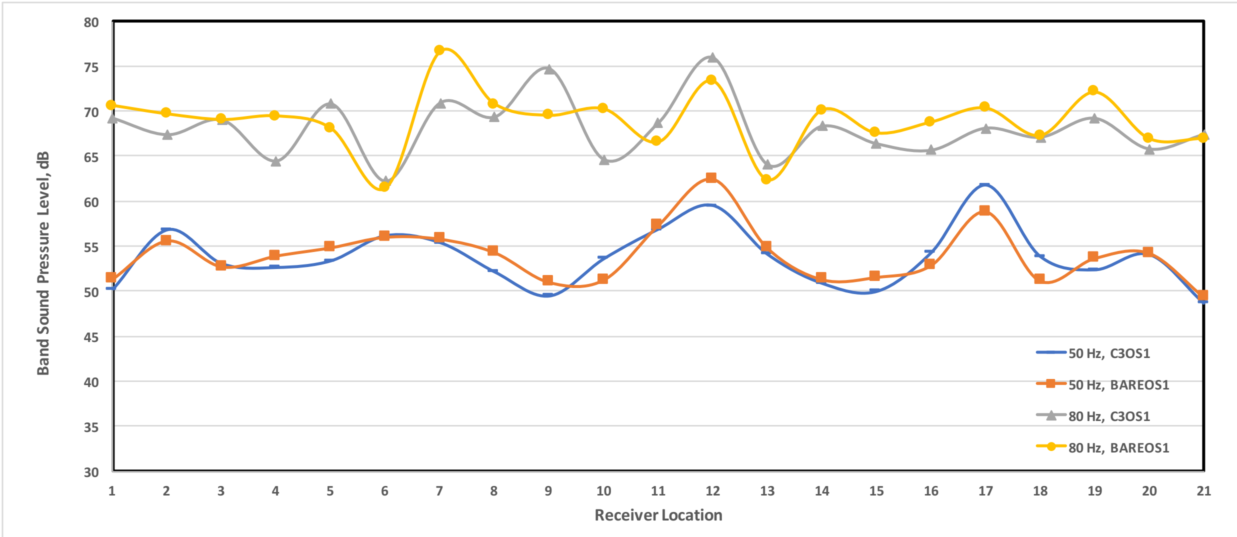


Figure 7 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 50 Hz vs. 80Hz

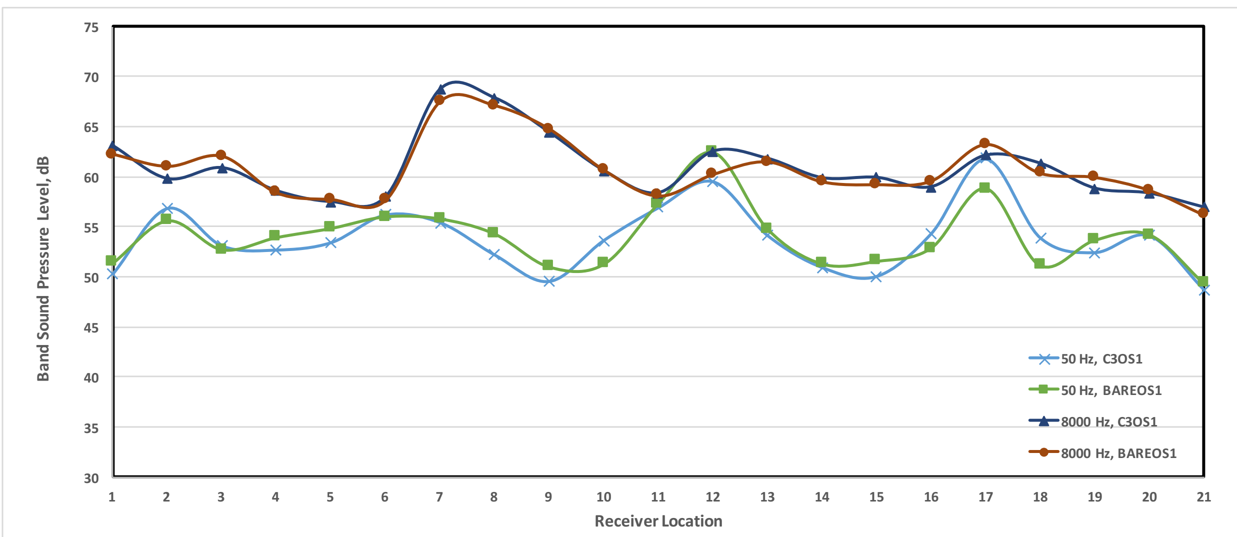


Figure 8 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 50 Hz vs.

800Hz

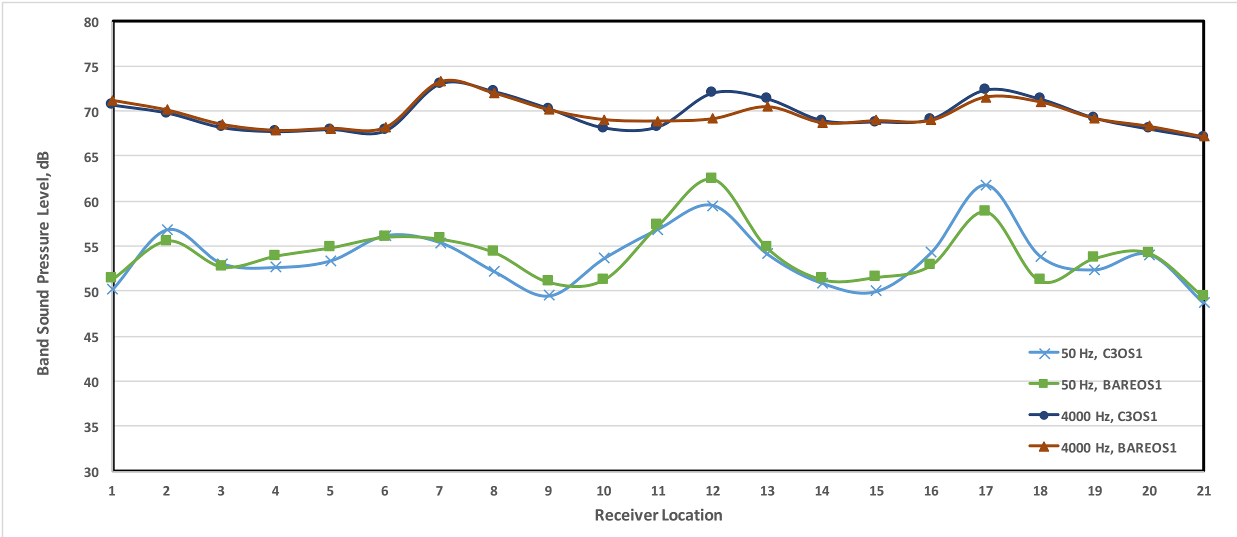


Figure 9 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 50 Hz vs. 4000Hz

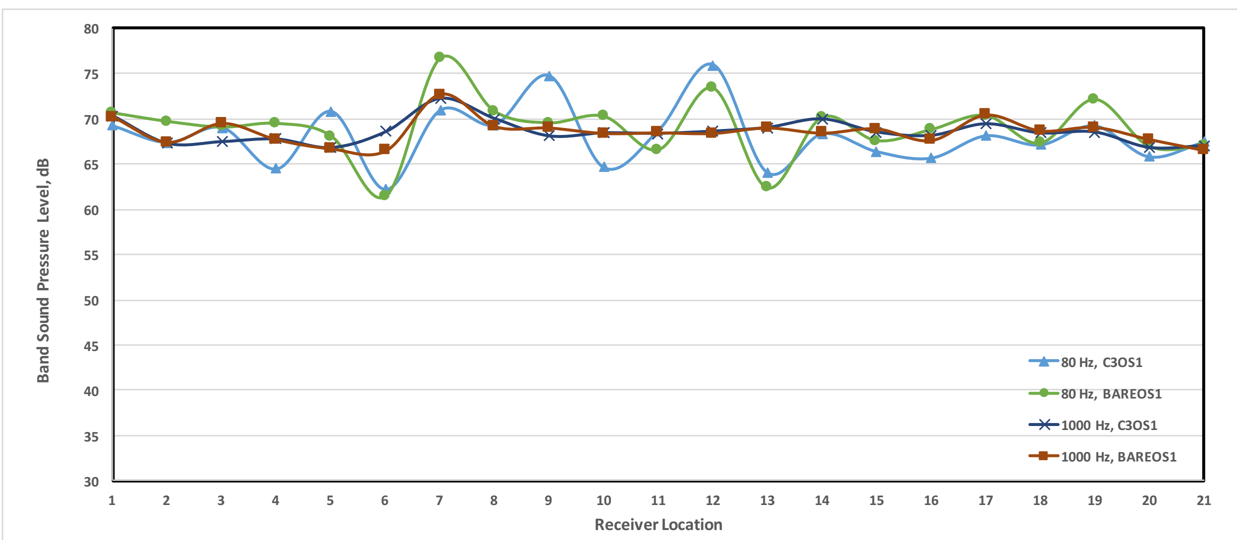


Figure 10 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 80 Hz vs. 1000Hz

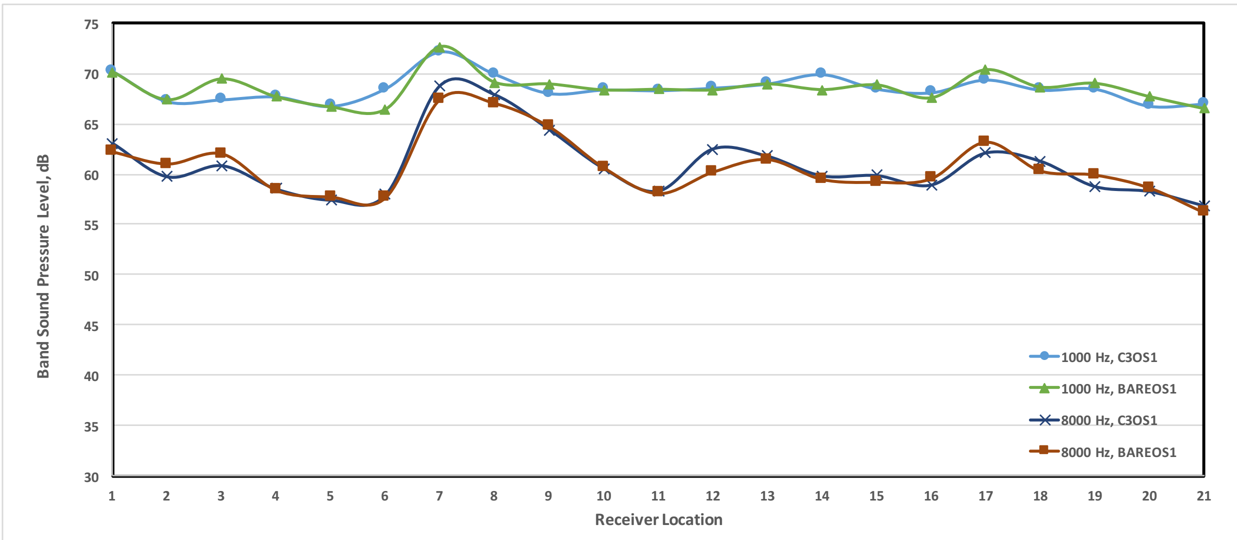


Figure 11 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 1000 Hz vs. 8000Hz

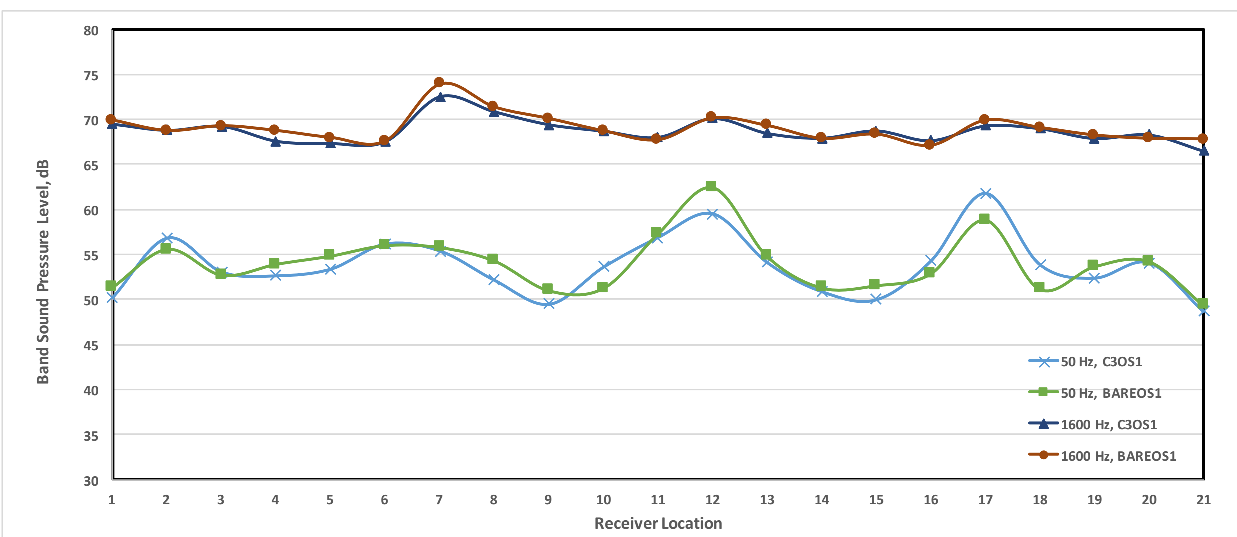


Figure 12 Gallery Measurements Frequency Analysis C-OS1 vs. BR-OS1; 50 Hz vs. 160Hz

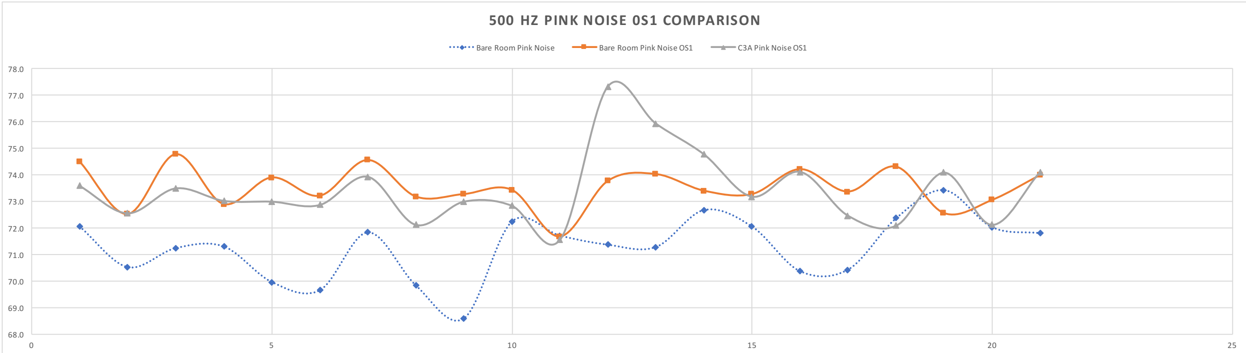


Figure 13 Gallery Measurements Pink Noise Variations - 500Hz: BR vs. BR-OS1 vs. C-OS1

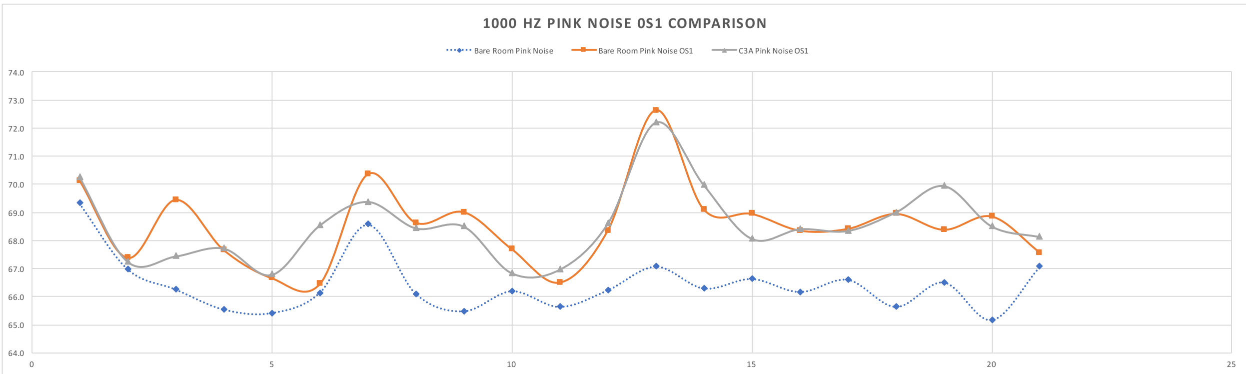


Figure 14 Gallery Measurements Pink Noise Variations - 1000Hz: BR vs. BR-OS1 vs. C-OS1

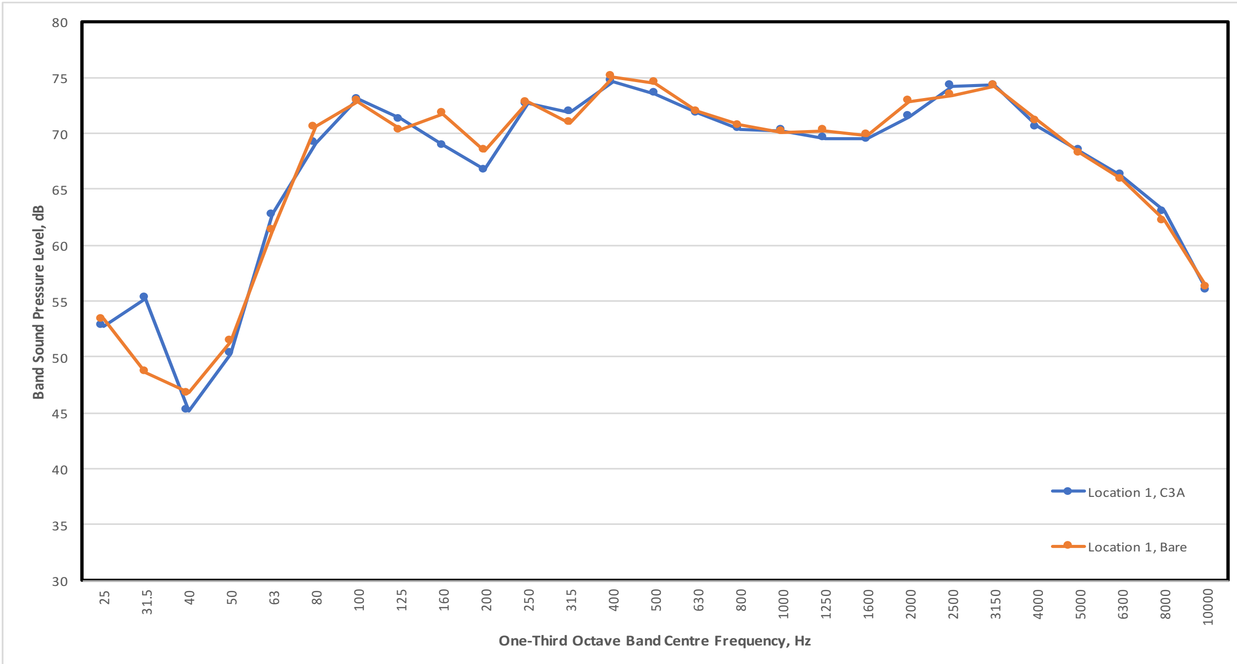


Figure 15 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 1

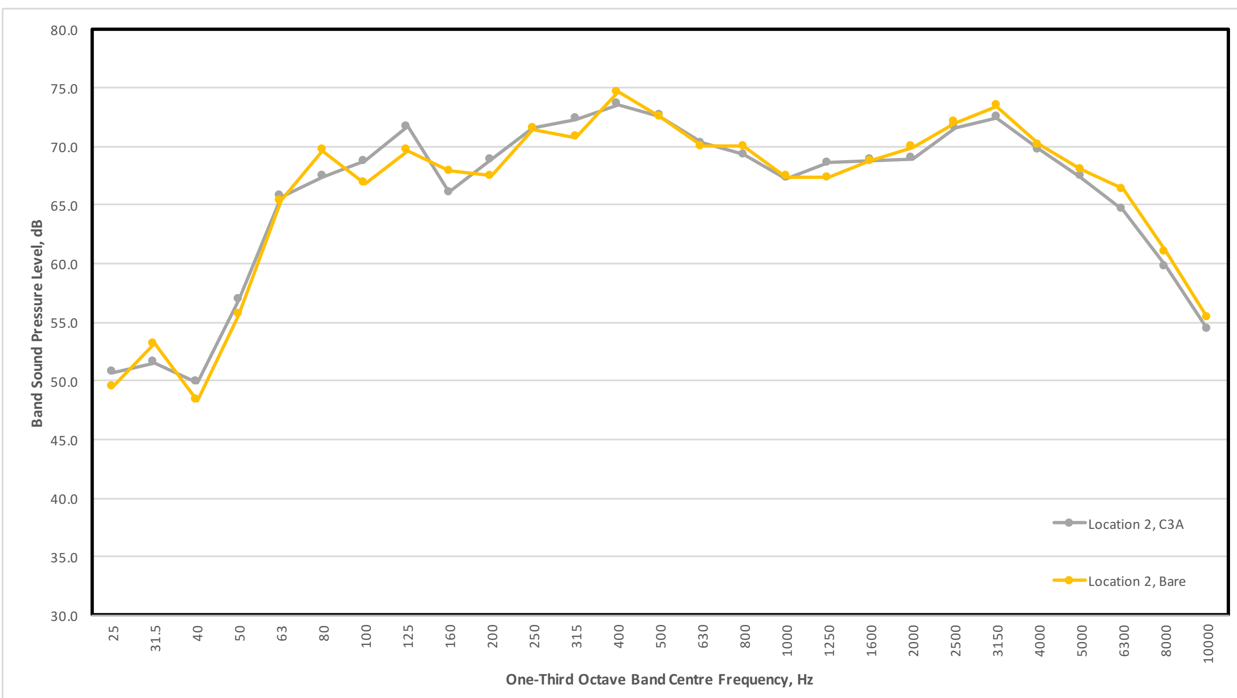


Figure 16 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 2

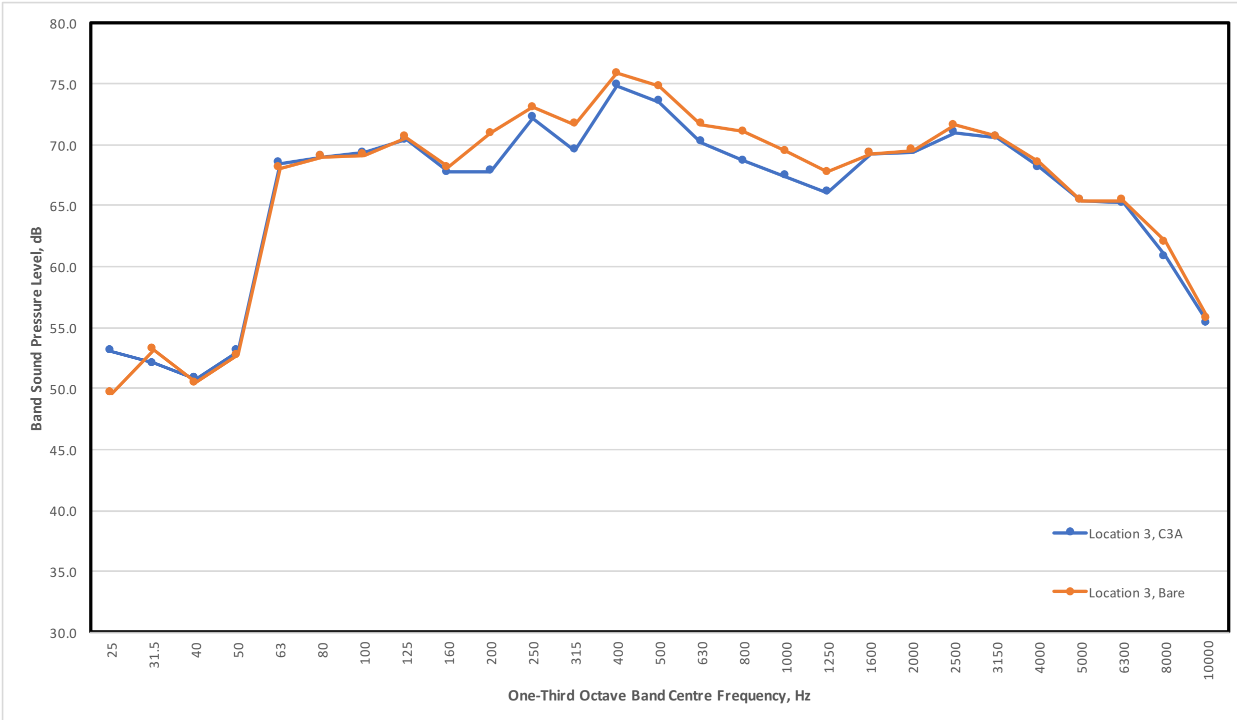


Figure 17 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 3

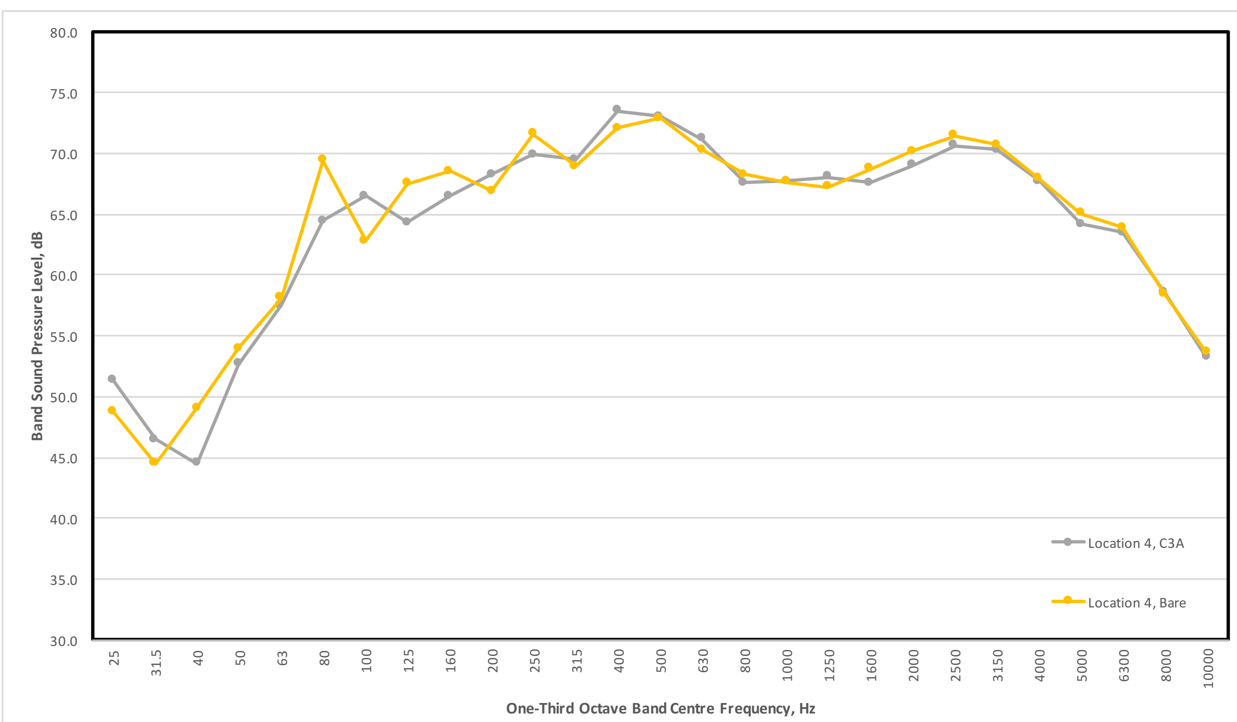


Figure 18 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 4

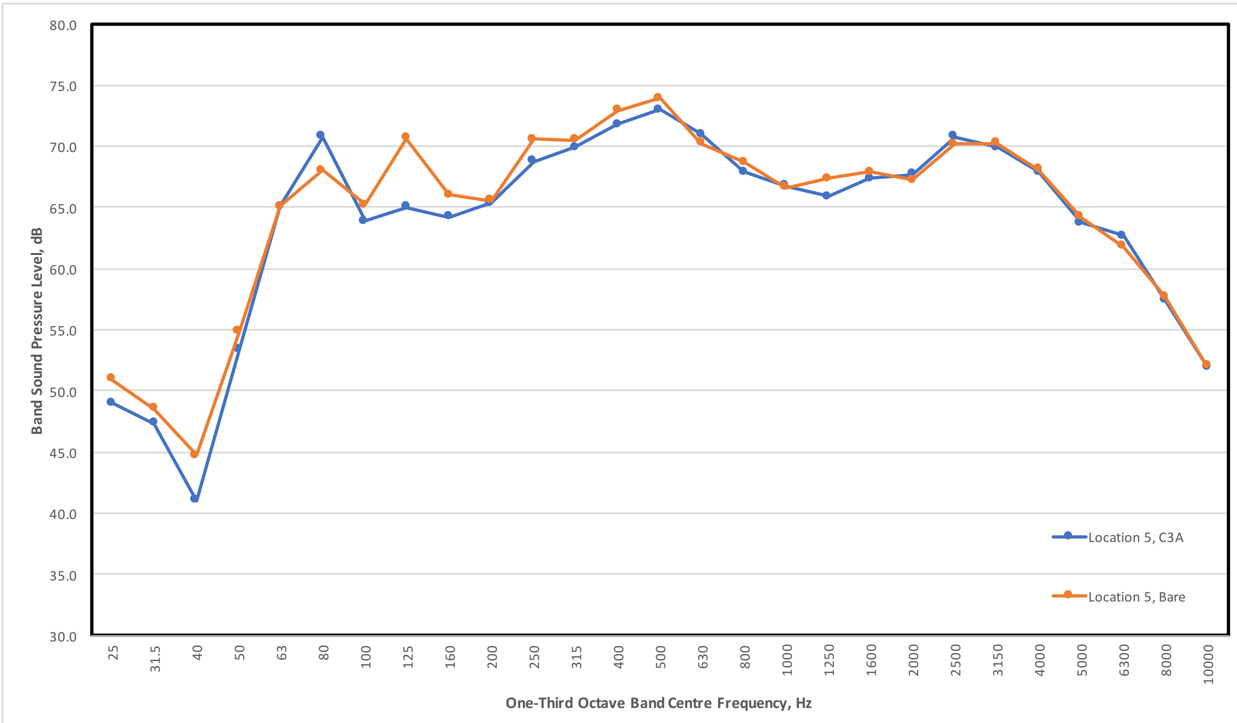


Figure 19 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 5

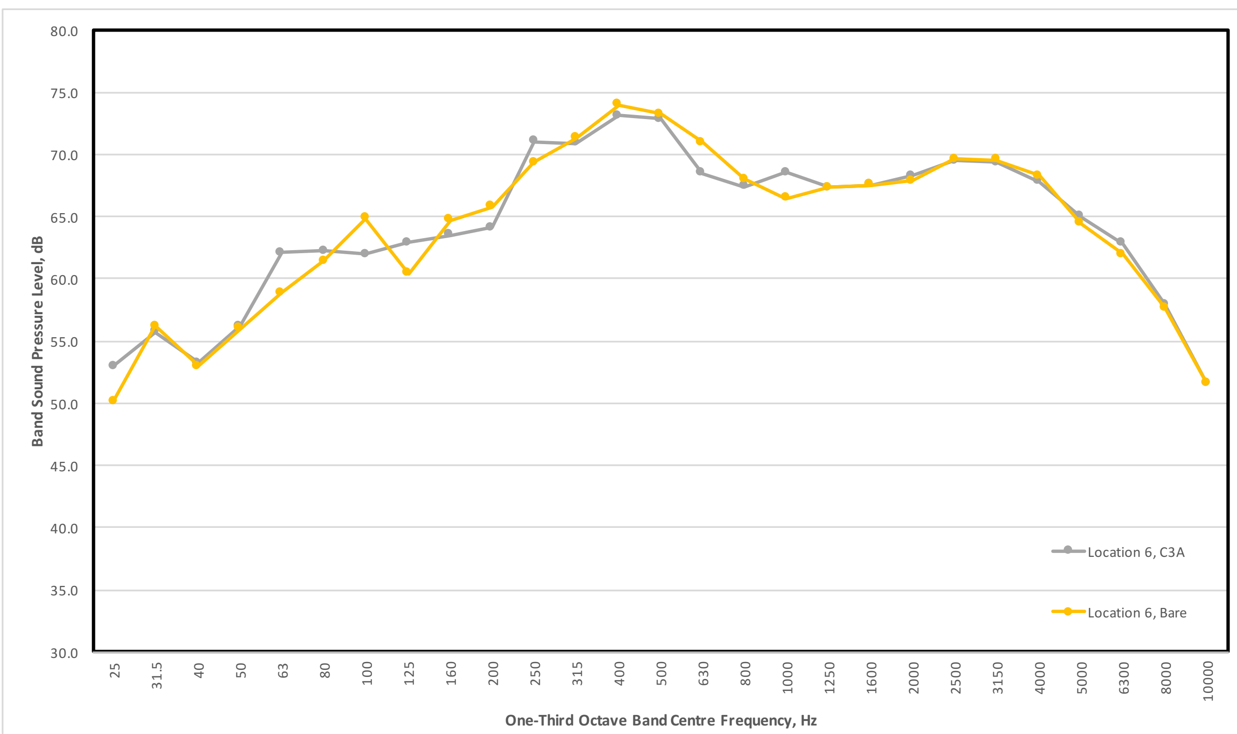


Figure 20 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 6

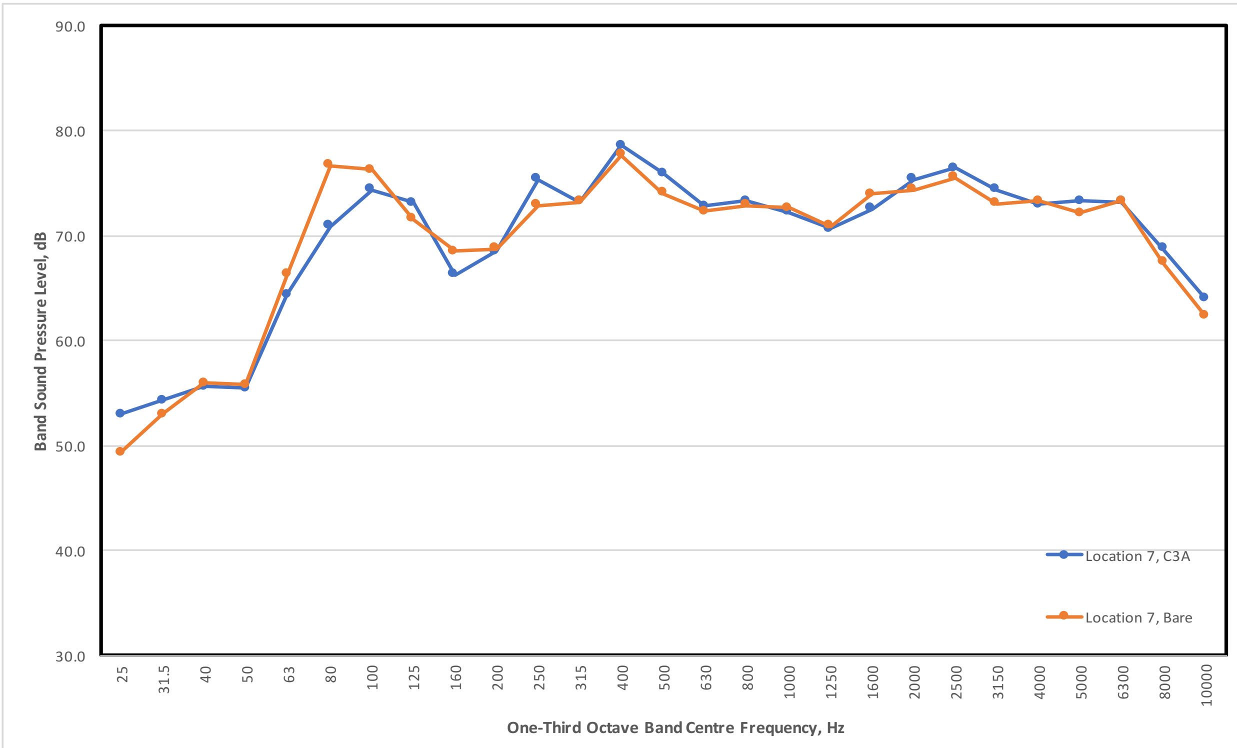


Figure 21 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 7

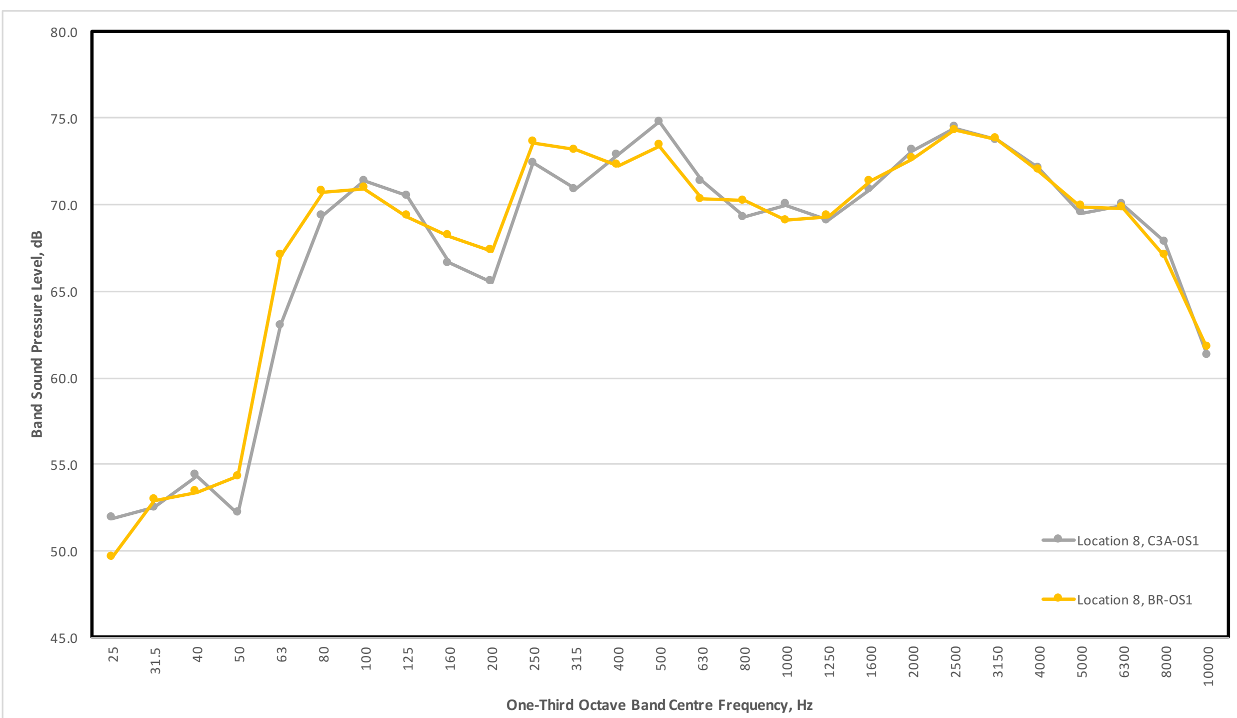


Figure 22 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 8

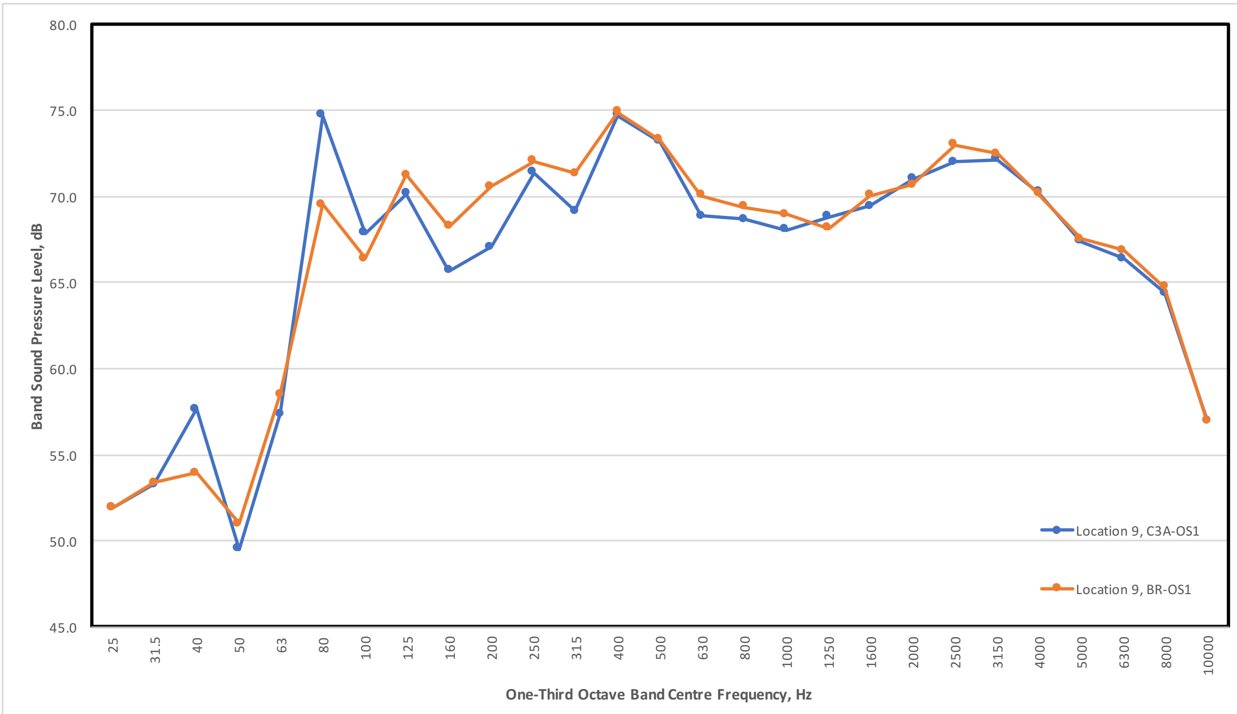


Figure 23 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 9

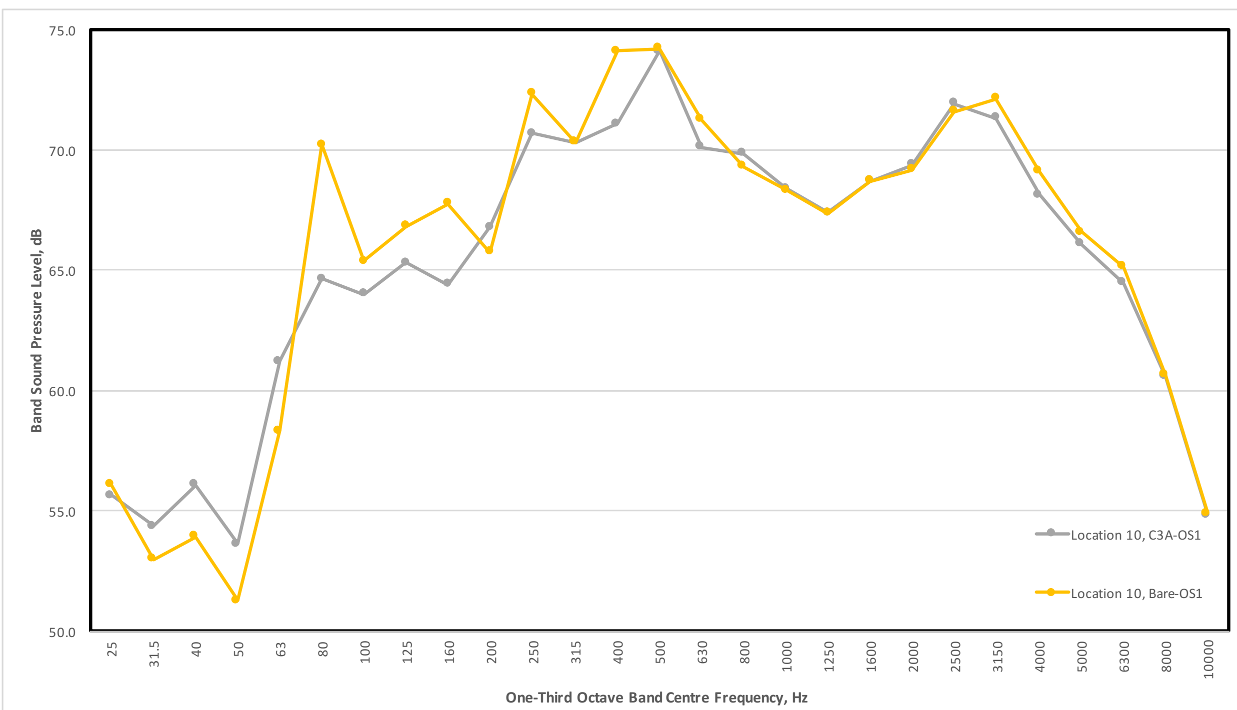


Figure 24 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 10

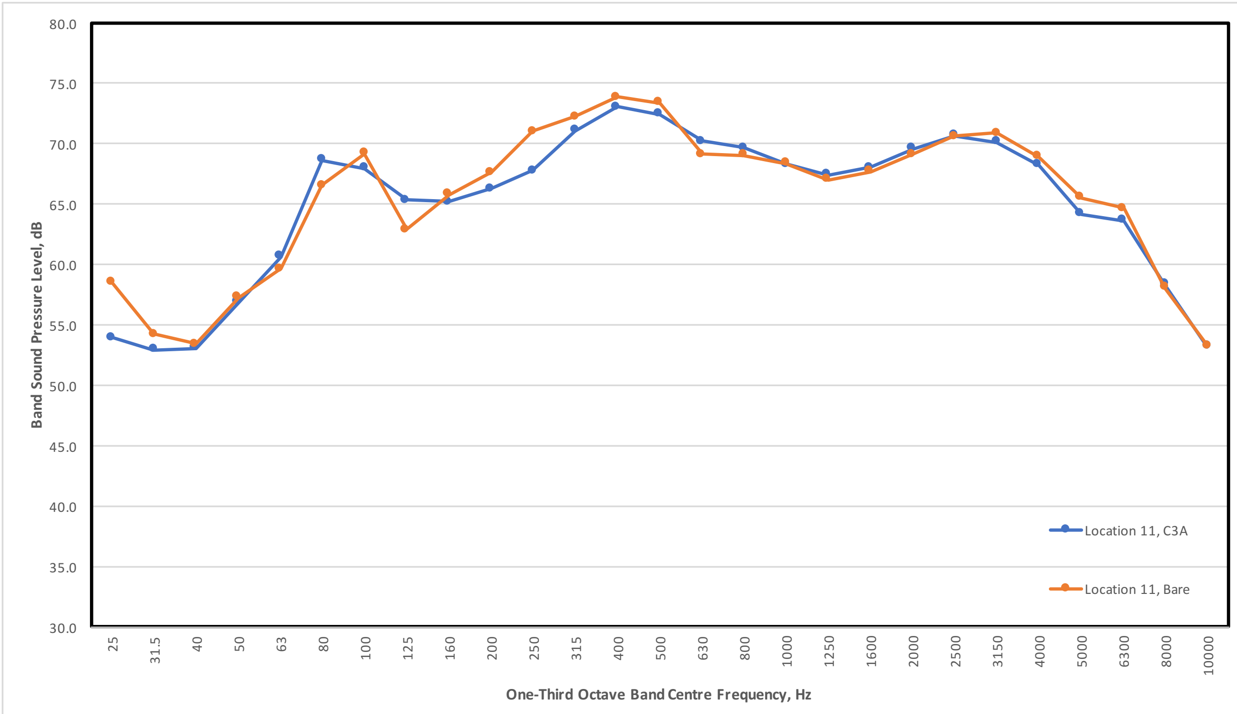


Figure 25 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 11

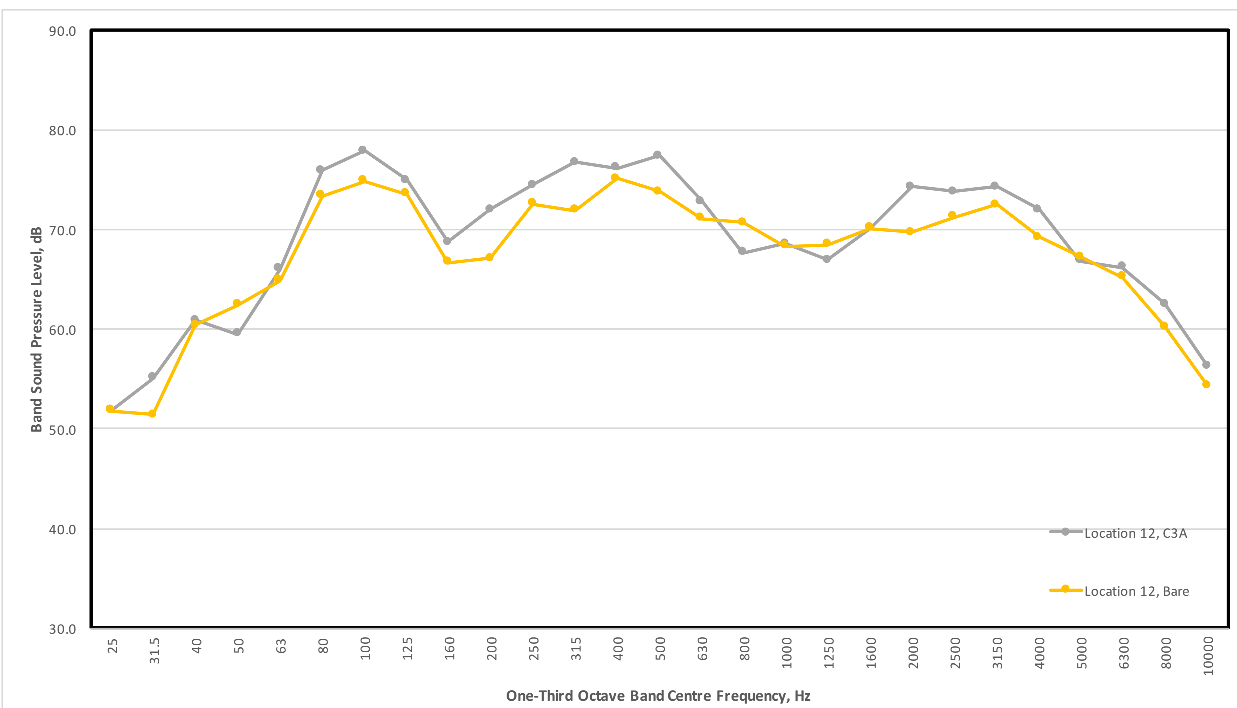


Figure 26 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 12

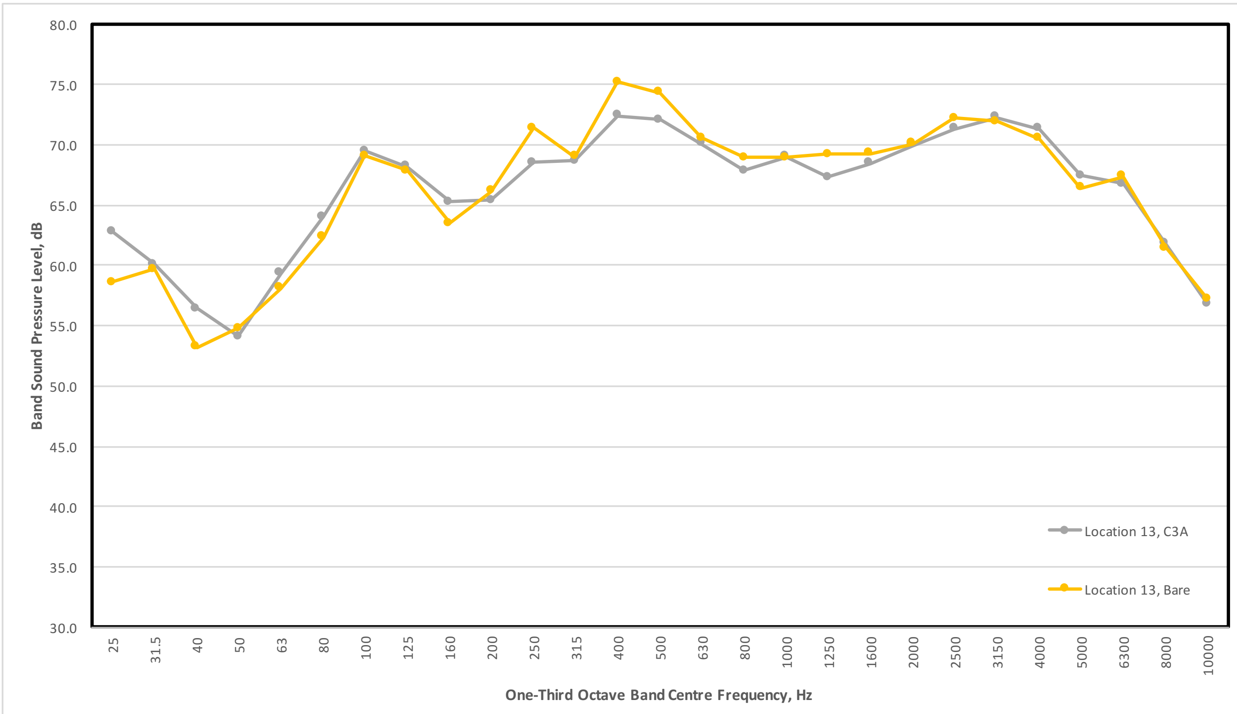


Figure 27 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 13

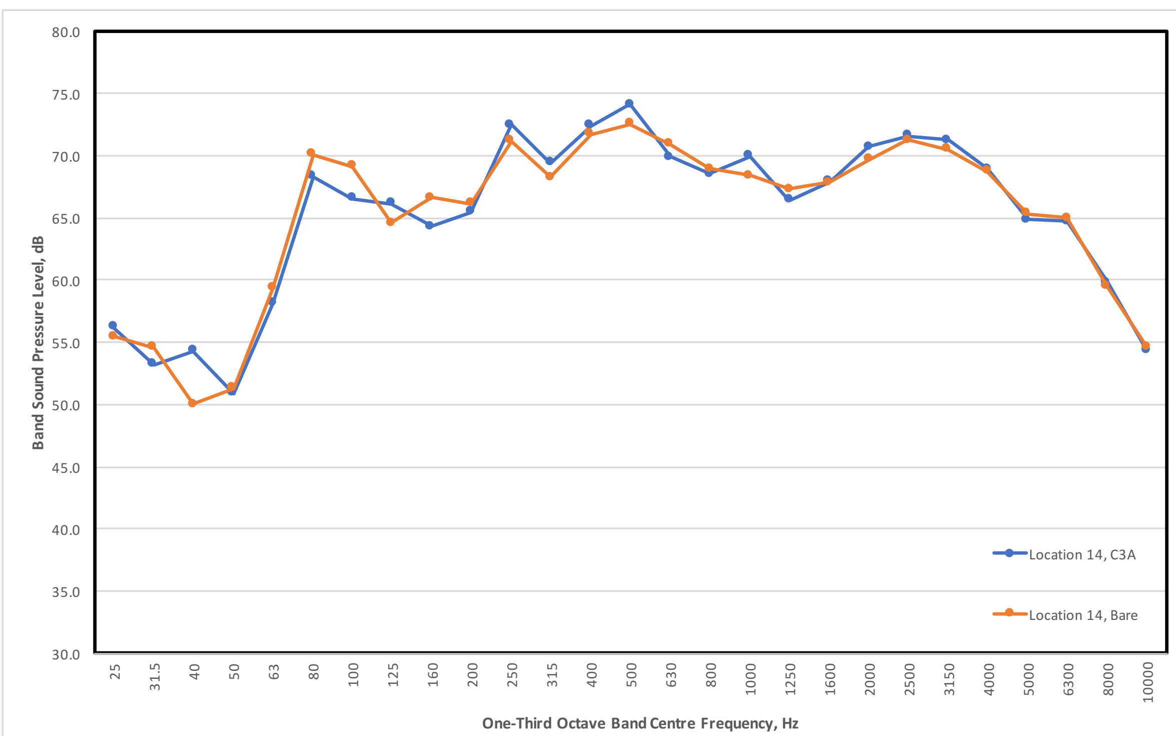


Figure 28 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 14

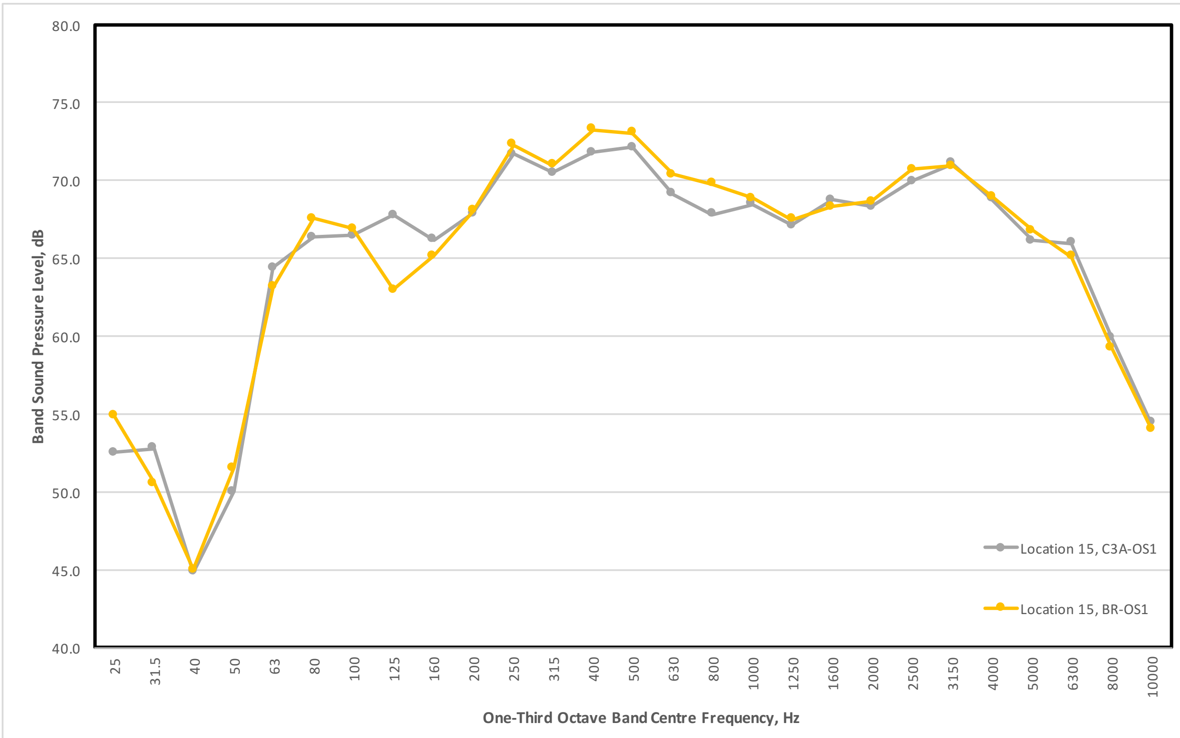


Figure 29 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 15

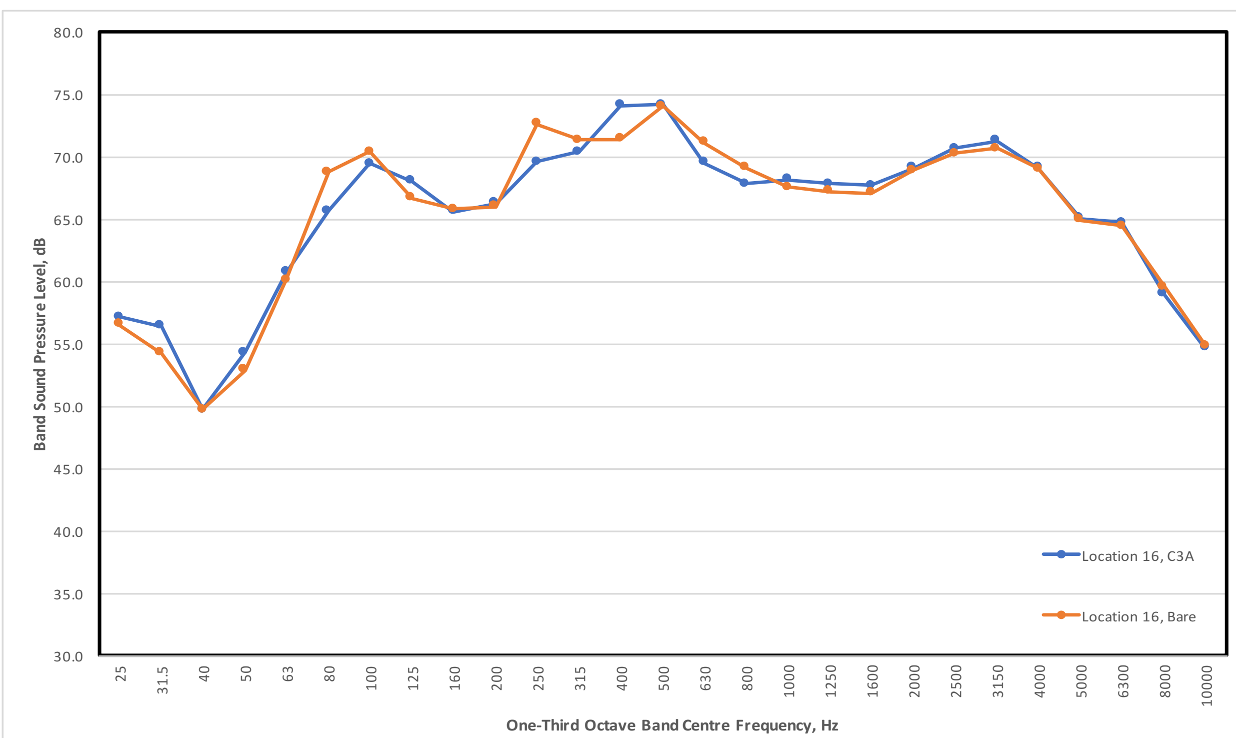


Figure 30 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 16

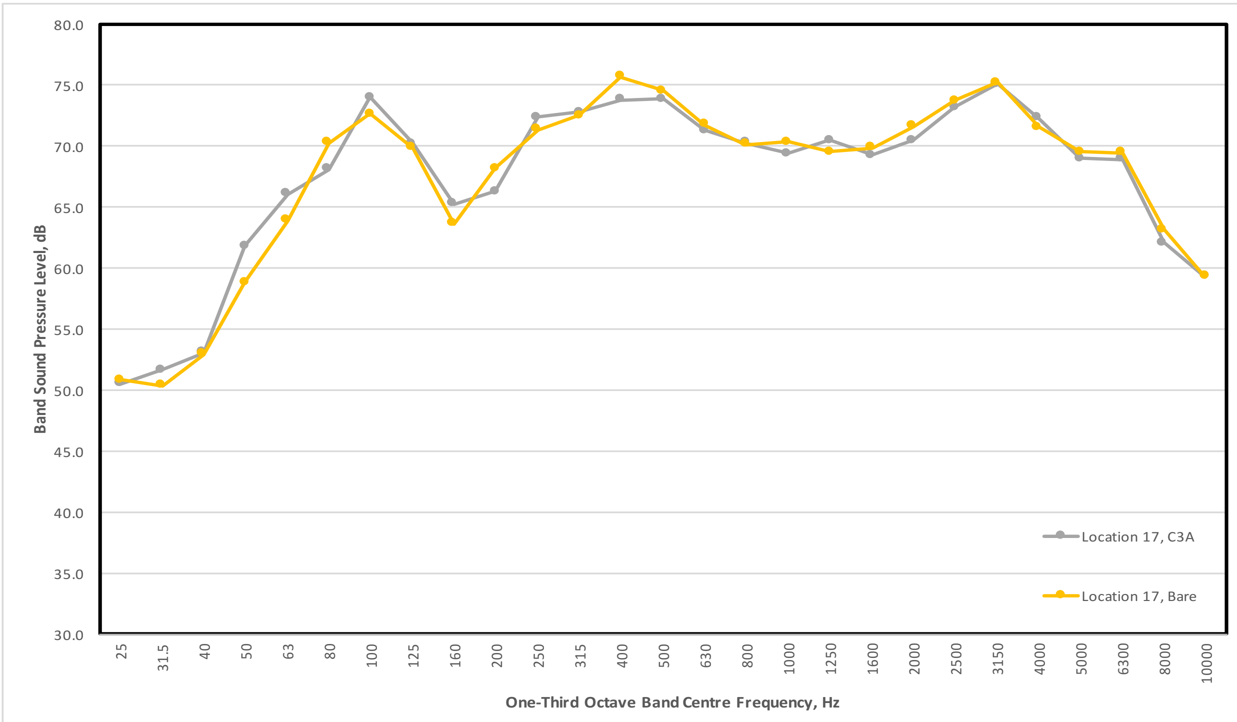


Figure 31 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 17

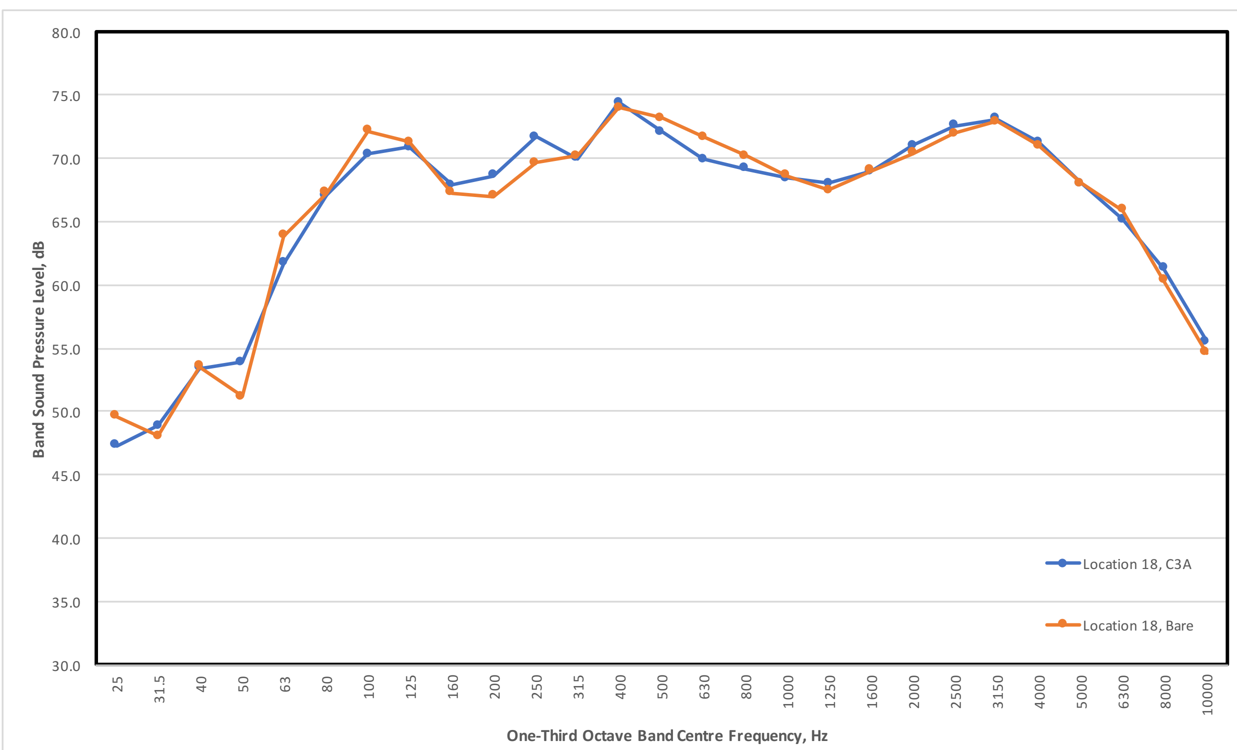


Figure 32 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 18

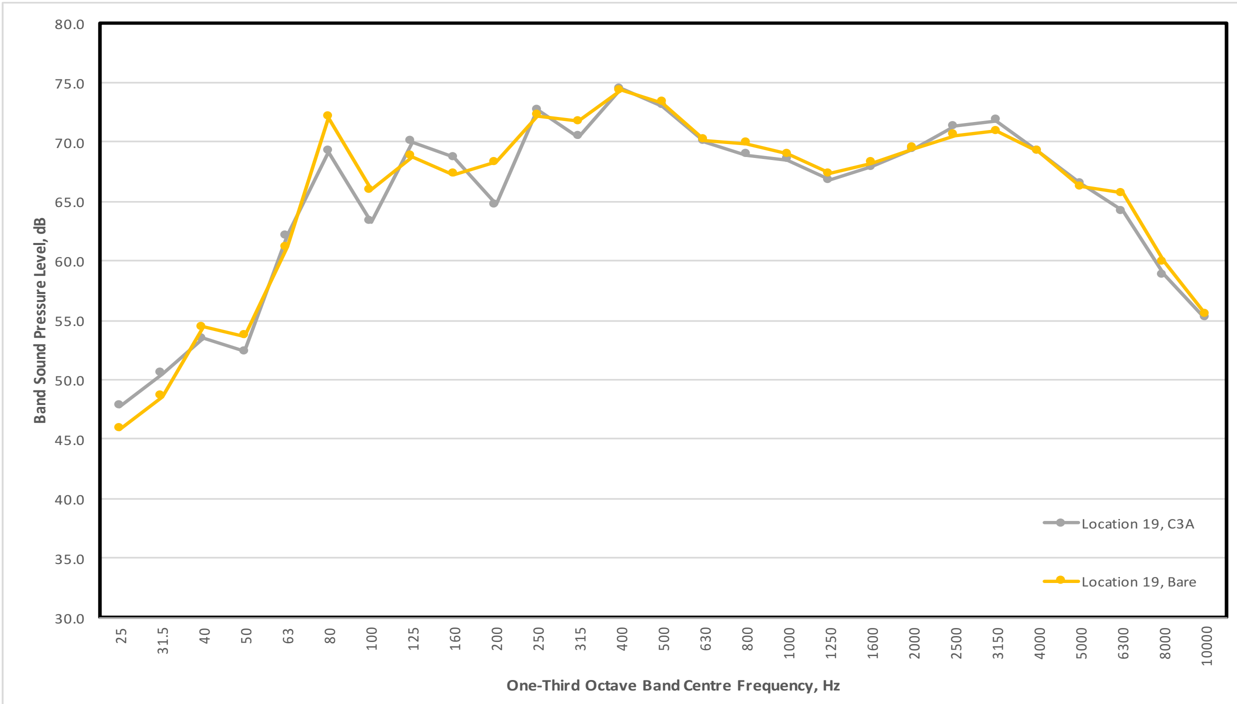


Figure 33 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 19

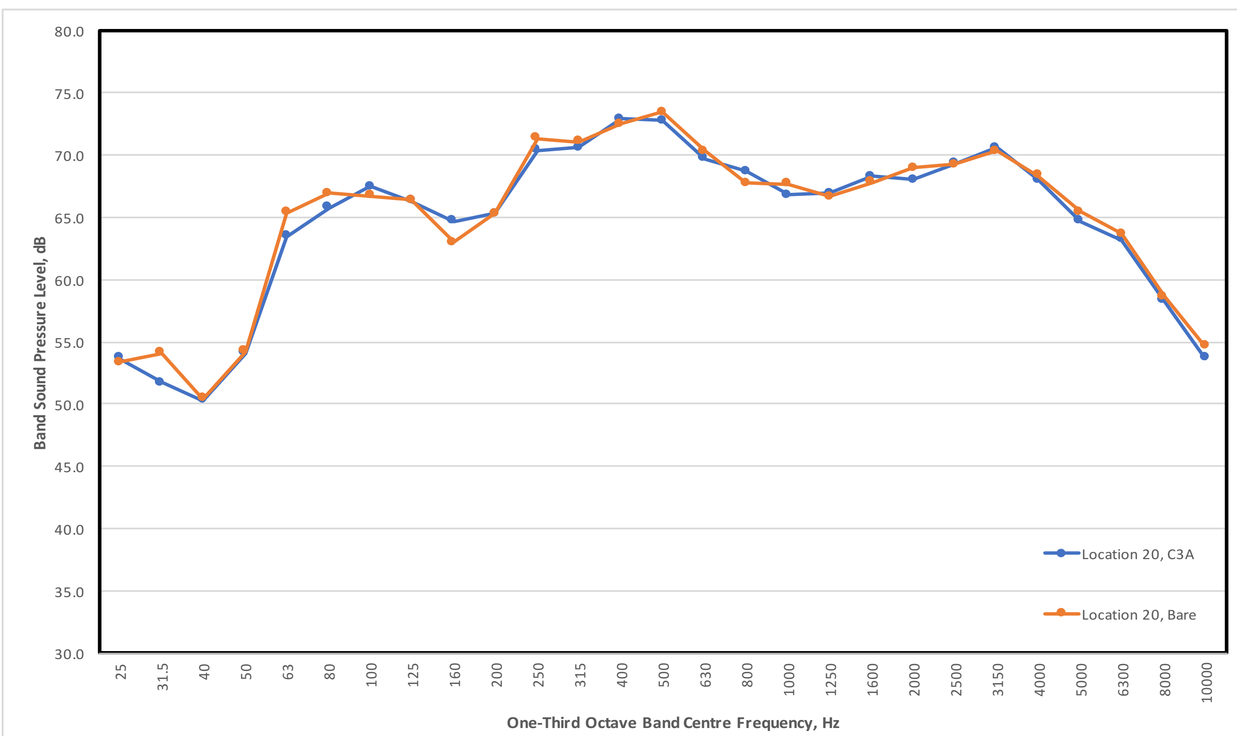


Figure 34 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 20

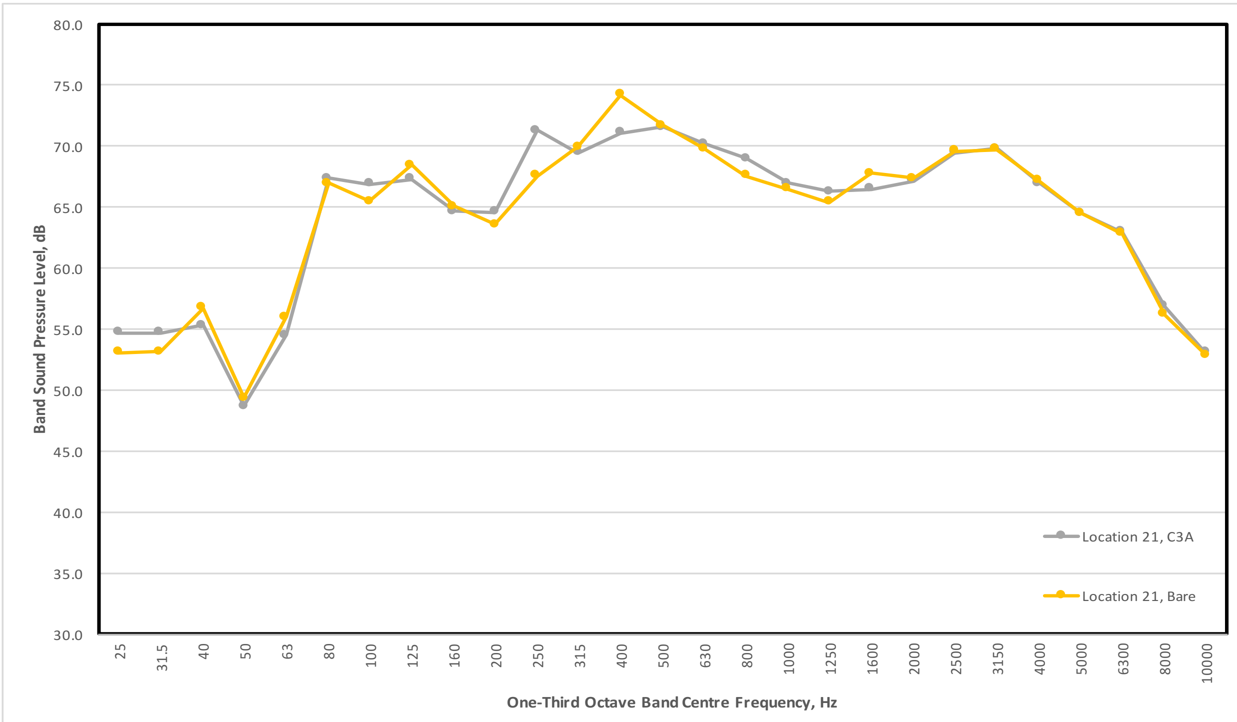


Figure 35 Gallery Measurements C-OS1 vs. BR-OS1 Receiver Response - Point 21

Appendix C: Simulation Results

The simulation results section in the appendix includes additional Ray (ODEON) and Wave (COMSOL) theory SPL distribution simulations showing the grid response and vertical room mode response.

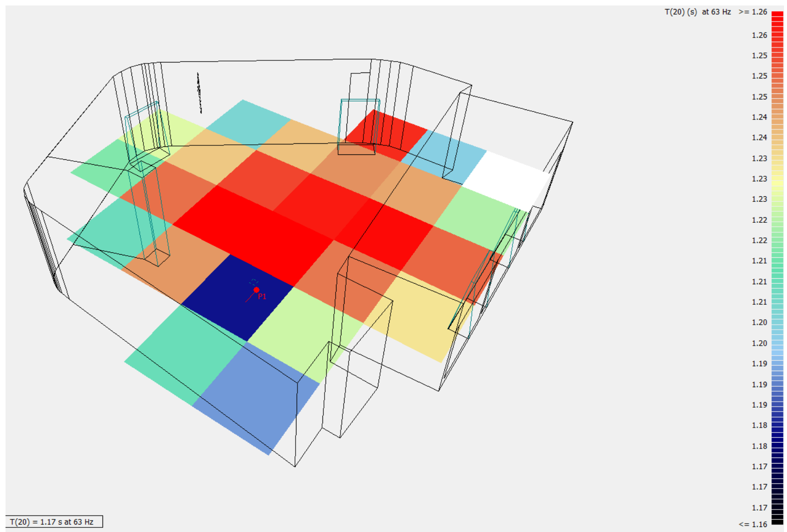


Figure 36 ODEON Validating Gallery Bare - RT – 63Hz

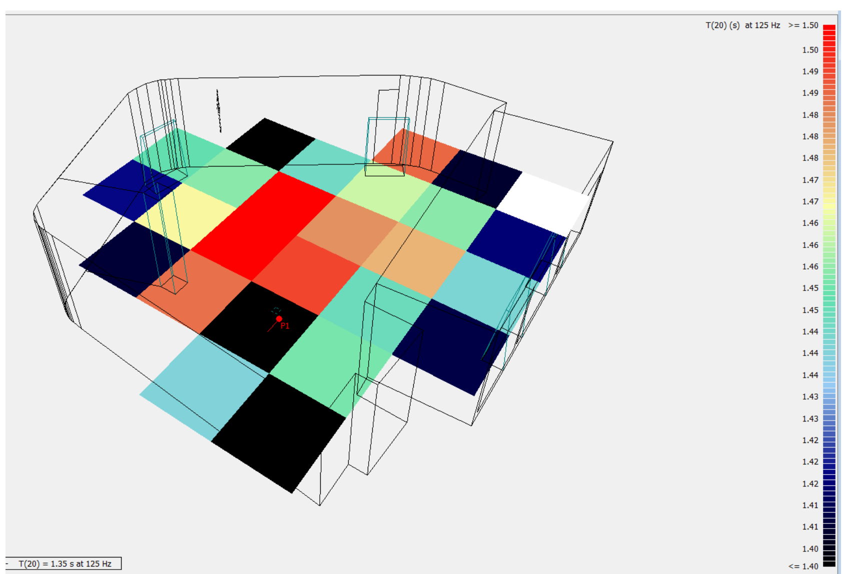


Figure 37 ODEON Validating Gallery Bare - RT – 125Hz

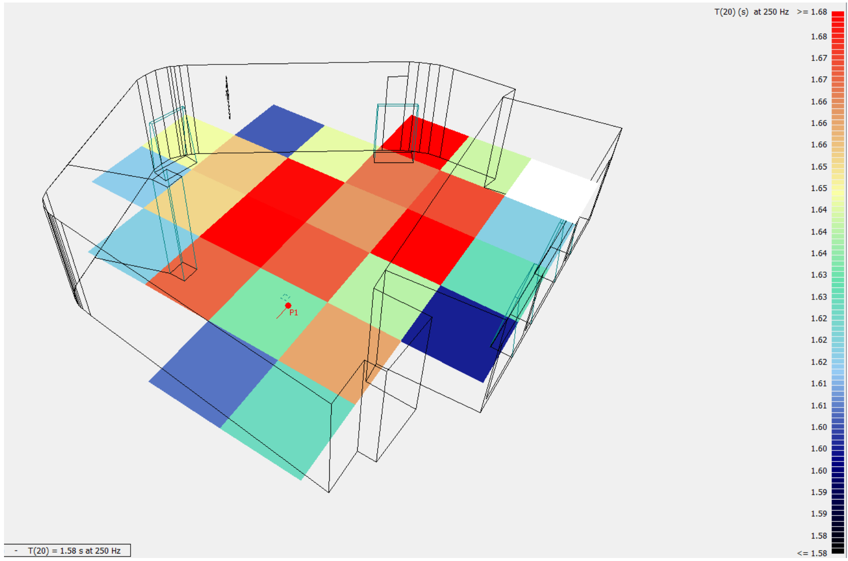


Figure 38 ODEON Validating Gallery Bare - RT – 200Hz

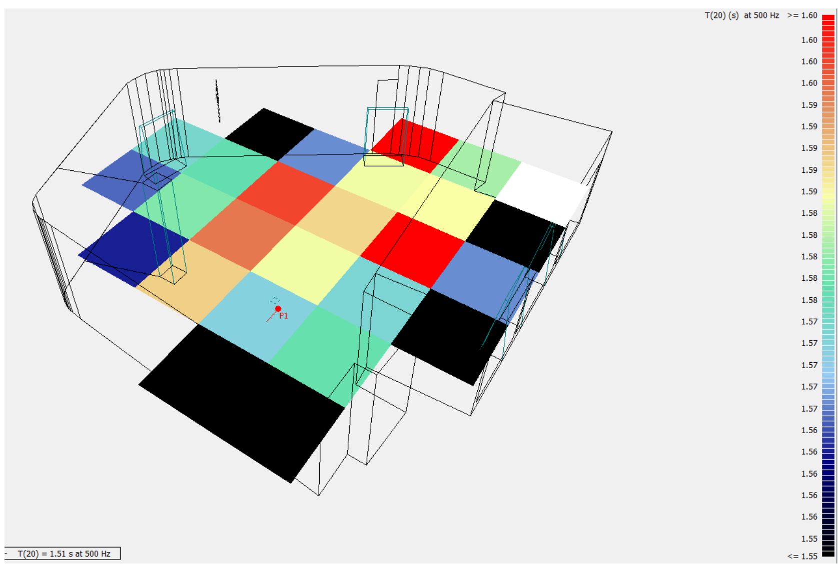


Figure 39 ODEON Validating Gallery Bare - RT – 500Hz

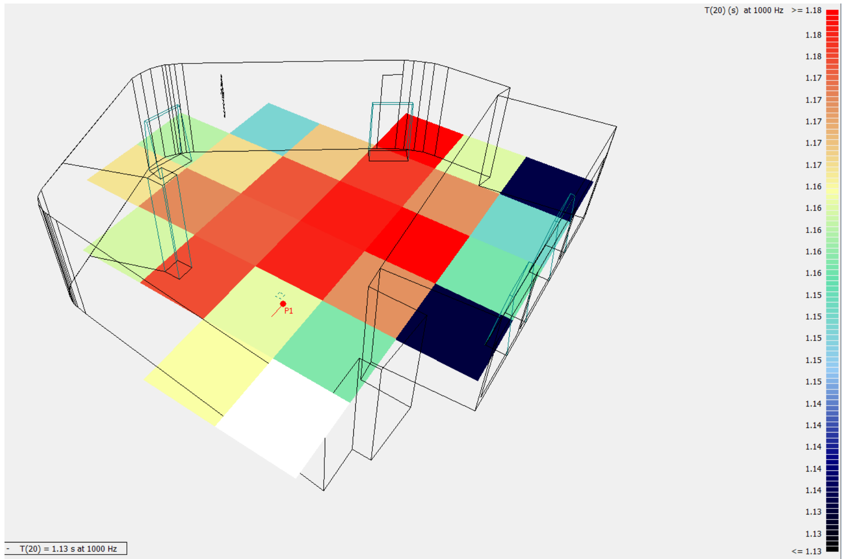


Figure 40 ODEON Validating Gallery Bare - RT – 1000Hz

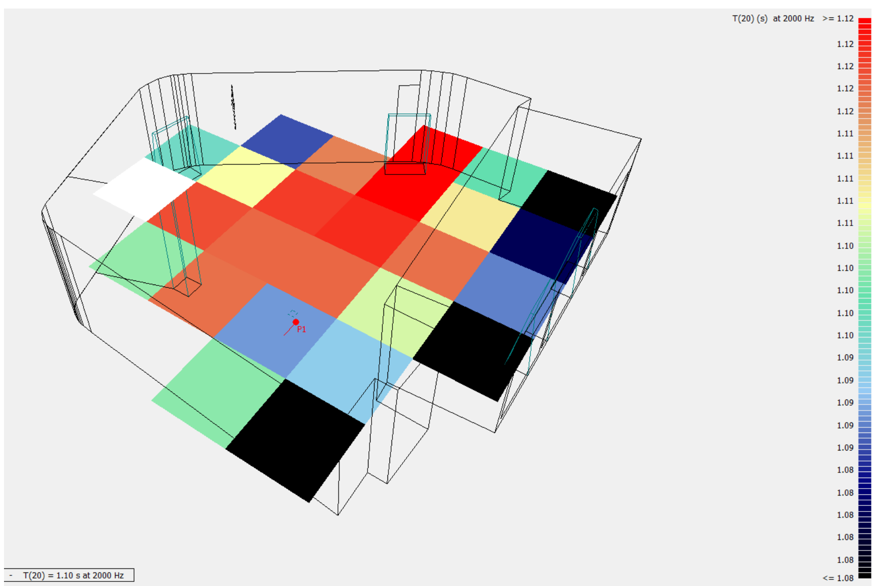


Figure 41 ODEON Validating Gallery Bare - RT – 2000Hz

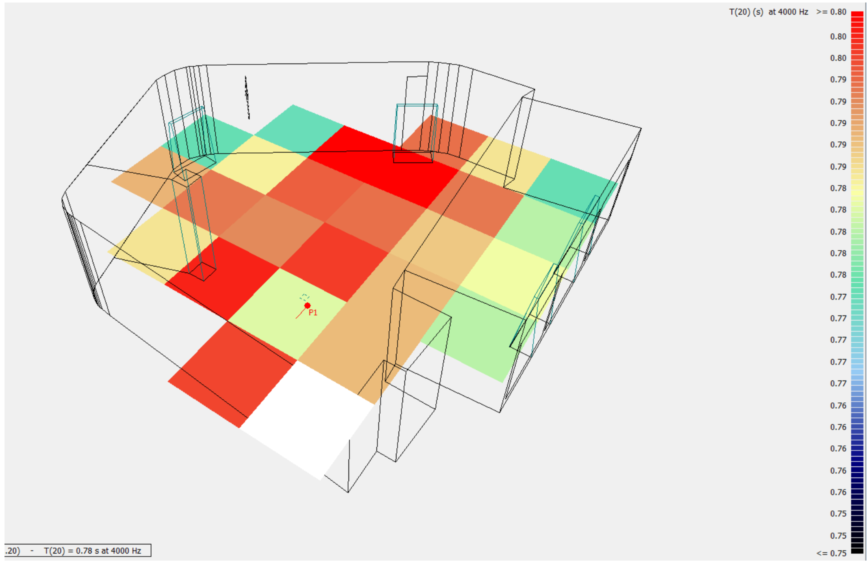


Figure 42 ODEON Validating Gallery Bare - RT – 4000Hz

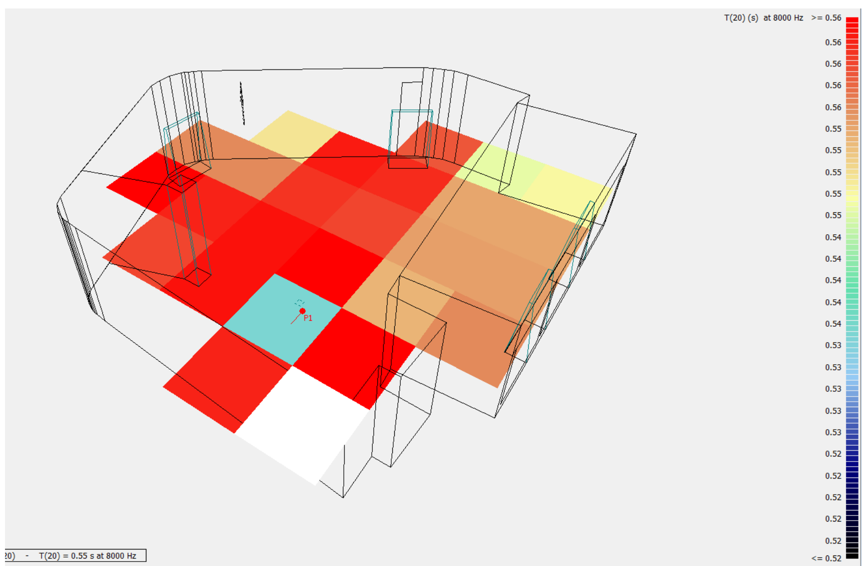


Figure 43 ODEON Validating Gallery Bare - RT – 8000Hz

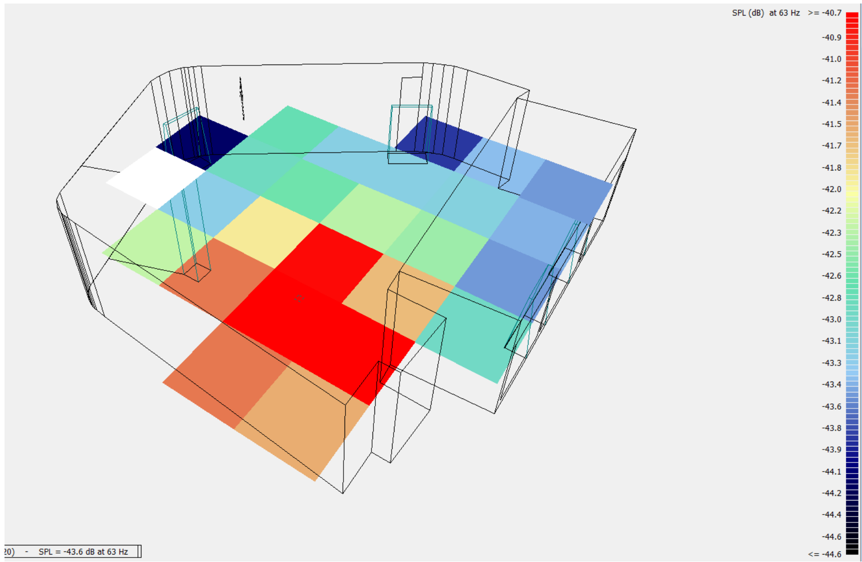


Figure 44 ODEON Validating Gallery Bare - SPL – 63Hz

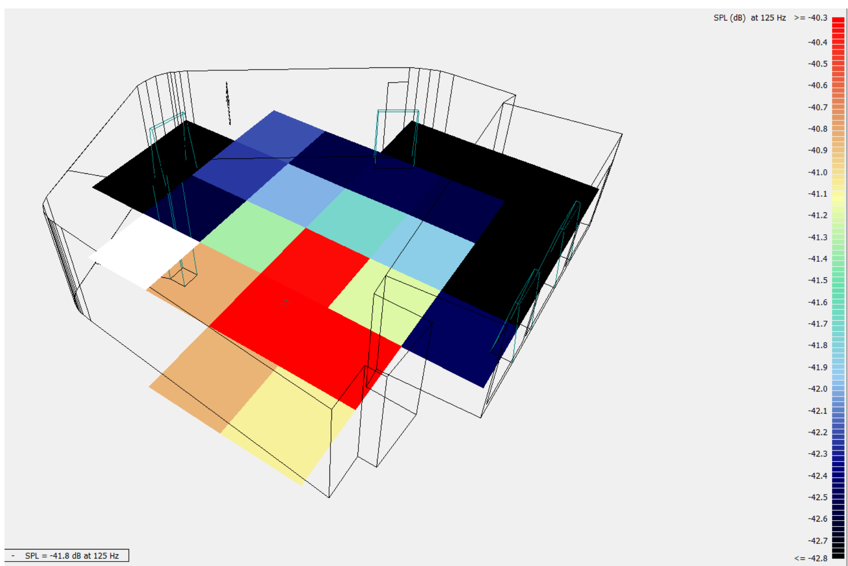


Figure 45 ODEON Validating Gallery Bare - SPL – 125Hz

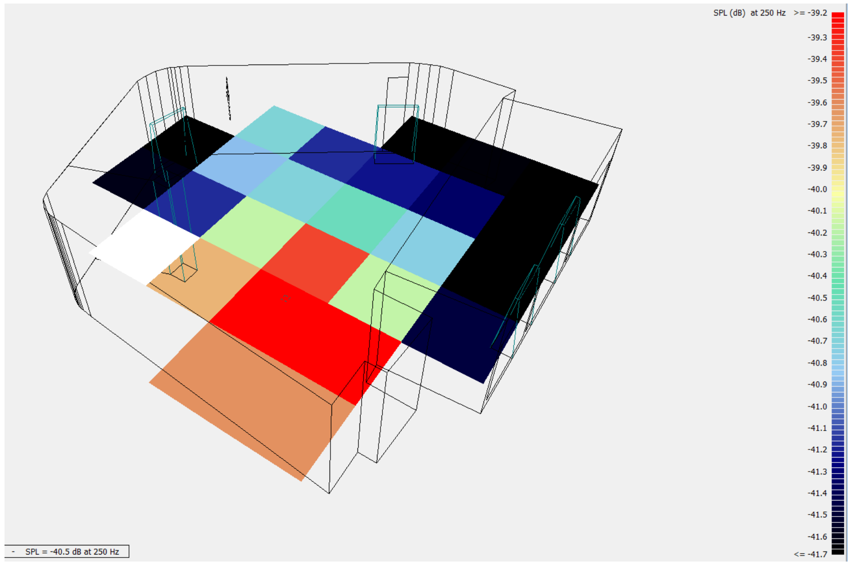


Figure 46 ODEON Validating Gallery Bare - SPL – 250Hz

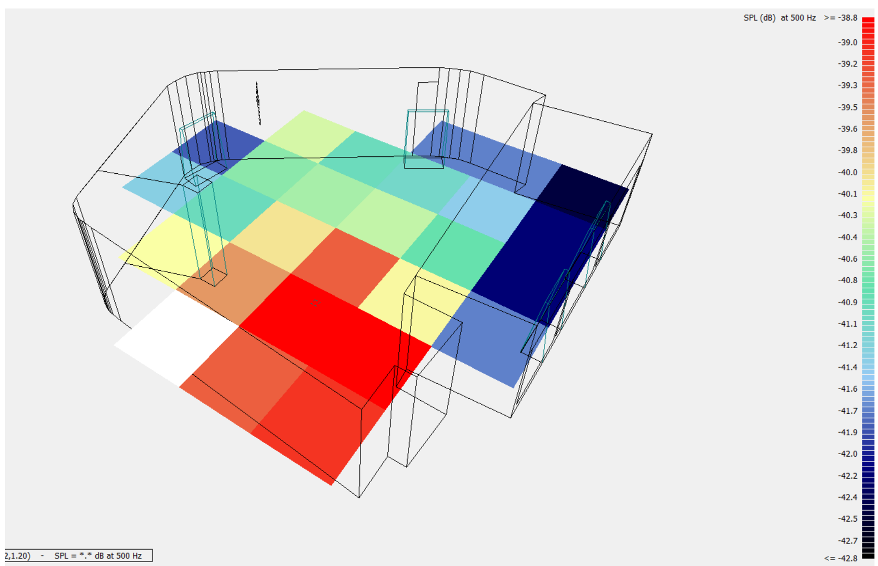


Figure 47 ODEON Validating Gallery Bare - SPL – 500Hz

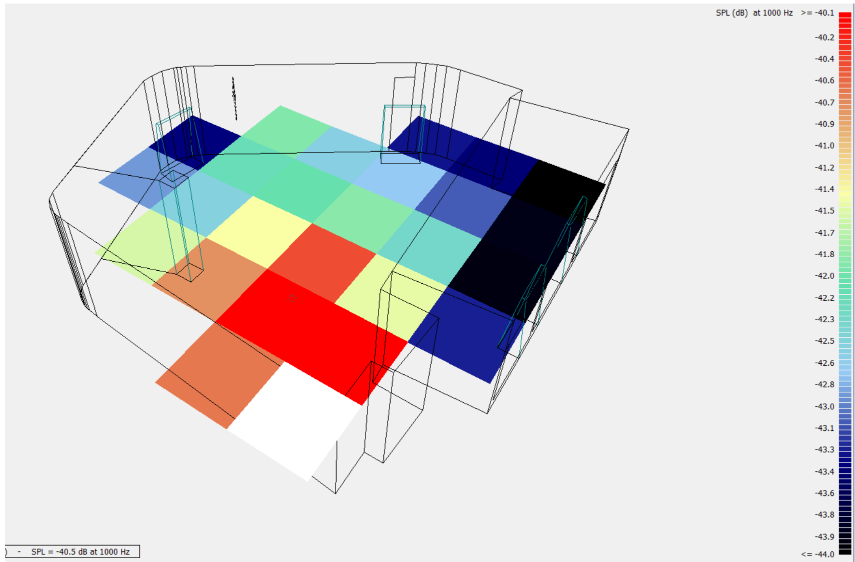


Figure 48 ODEON Validating Gallery Bare - SPL – 1000Hz

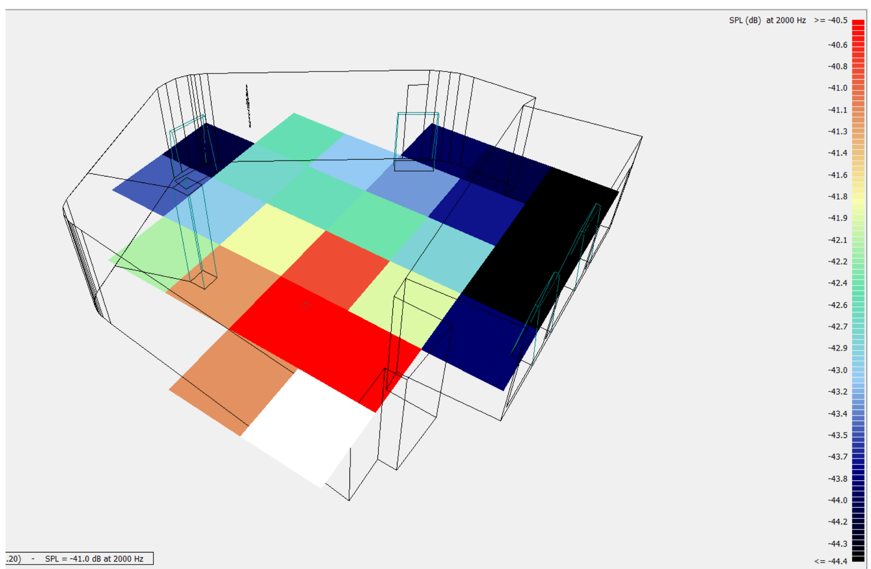


Figure 49 ODEON Validating Gallery Bare - SPL – 2000Hz

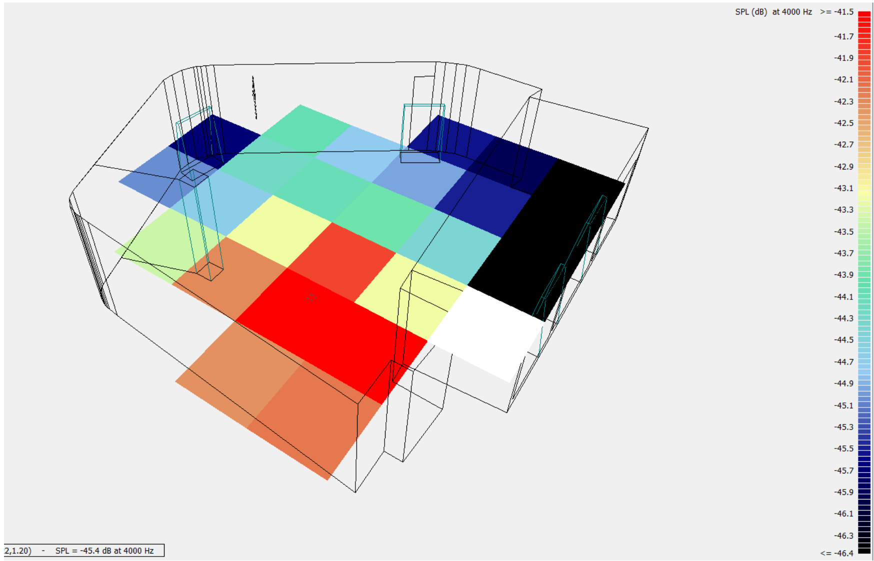


Figure 50 ODEON Validating Gallery Bare - SPL – 4000Hz

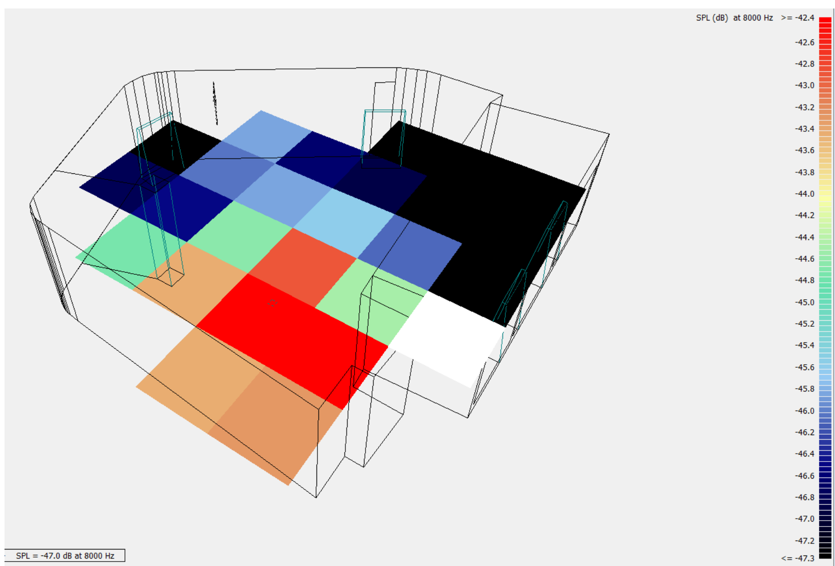


Figure 51 ODEON Validating Gallery Bare - SPL – 8000Hz

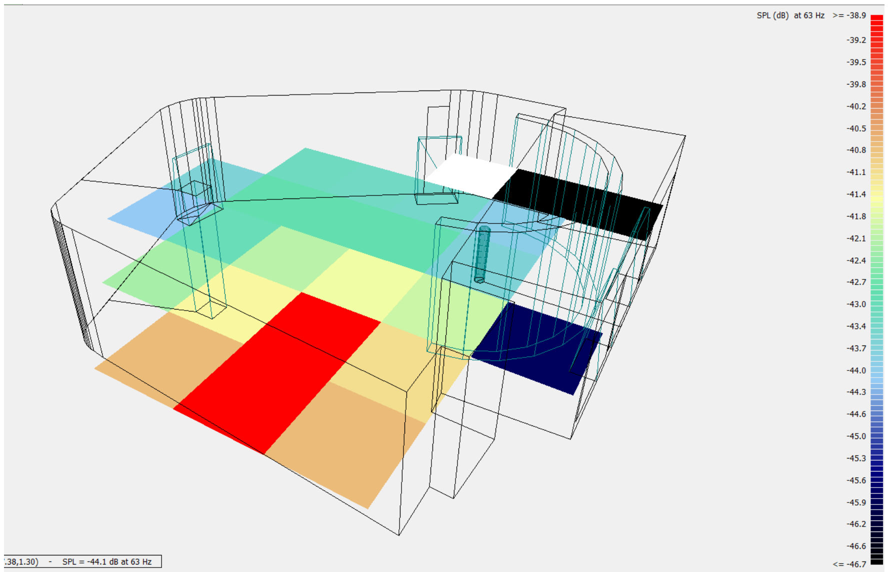


Figure 52 ODEON Gallery XL Curve – Source Location OS1 - SPL 63Hz

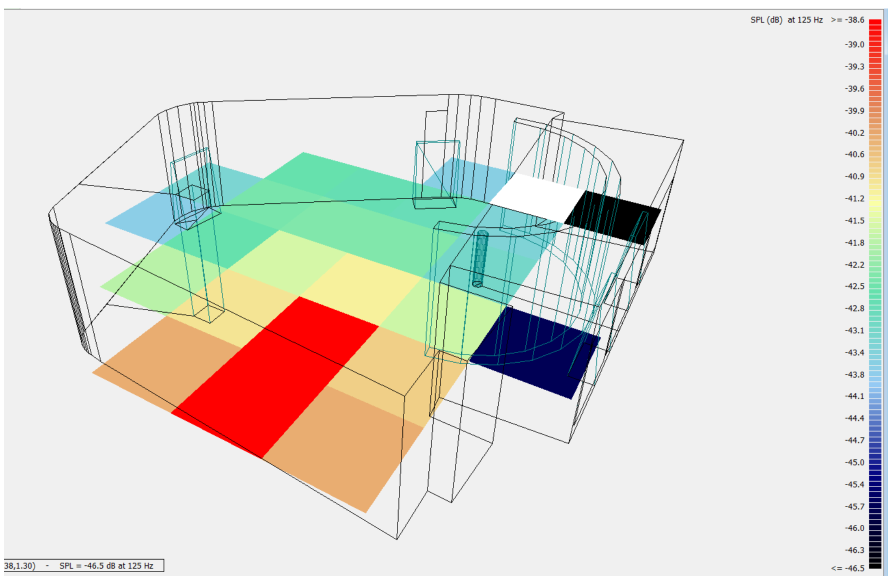


Figure 53 ODEON Gallery XL Curve – Source Location OS1 - SPL 125Hz

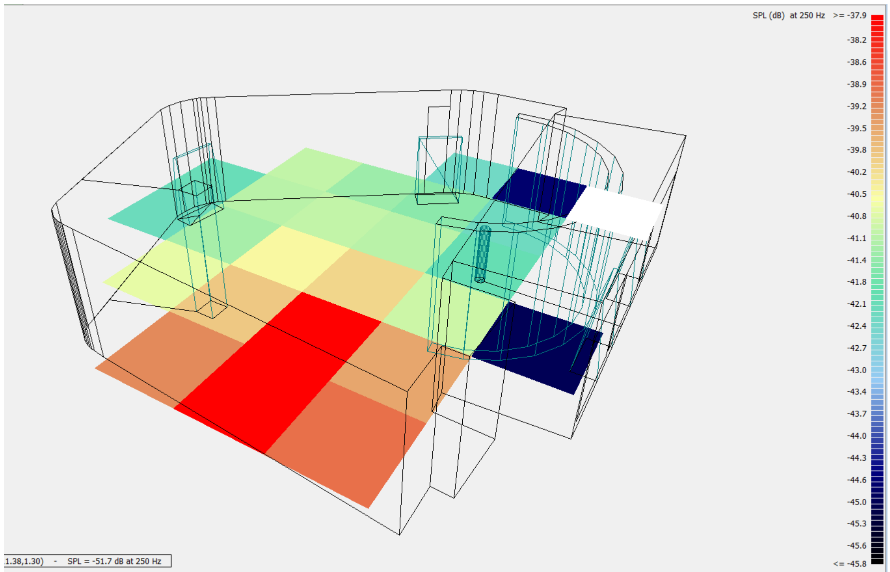


Figure 54 ODEON Gallery XL Curve – Source Location OS1 - SPL 250Hz

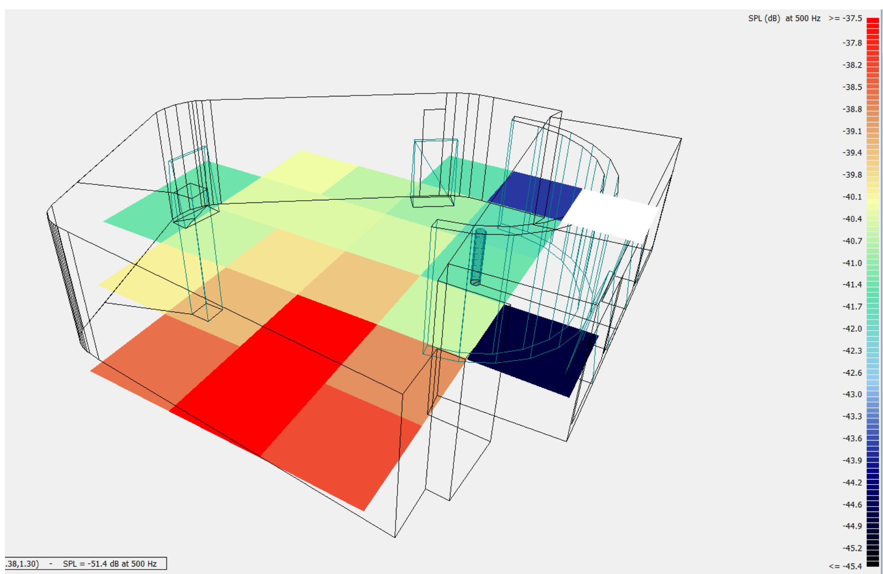


Figure 55 ODEON Gallery XL Curve – Source Location OS1 - SPL 500Hz

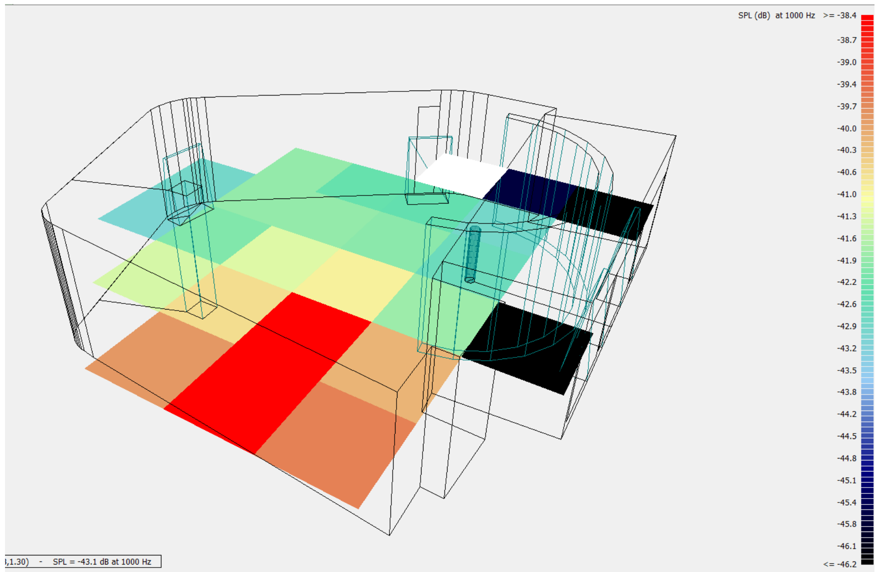


Figure 56 ODEON Gallery XL Curve – Source Location OS1 - SPL 1000Hz

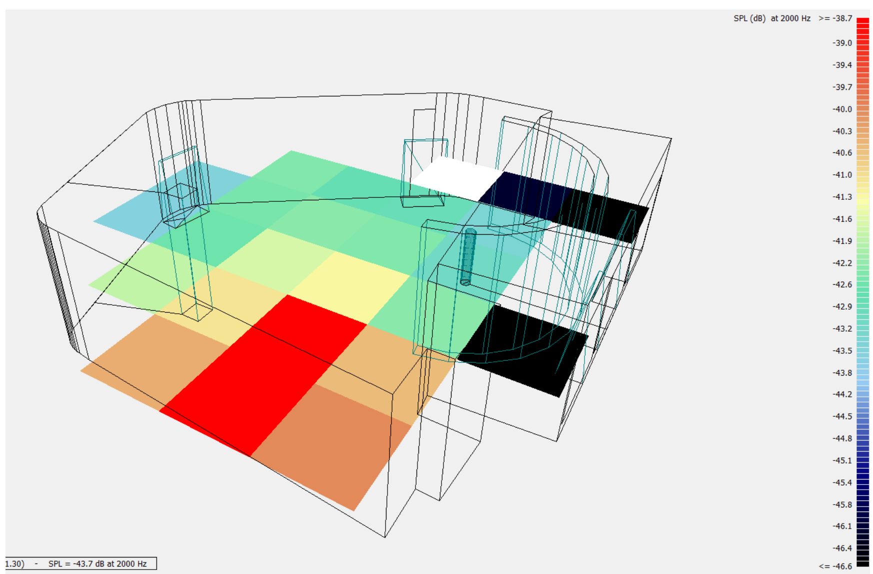


Figure 57 ODEON Gallery XL Curve – Source Location OS1 - SPL 2000Hz

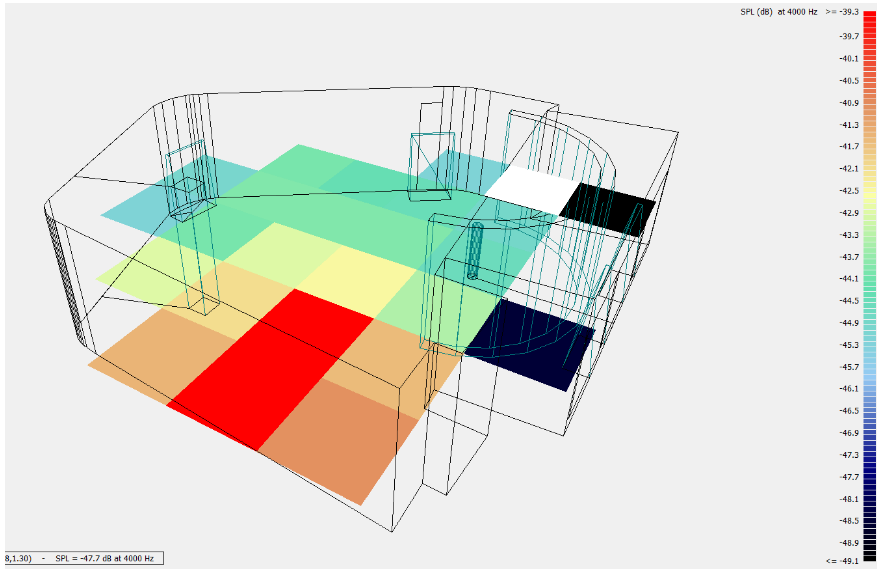


Figure 58 ODEON Gallery XL Curve – Source Location OS1 - SPL 4000Hz

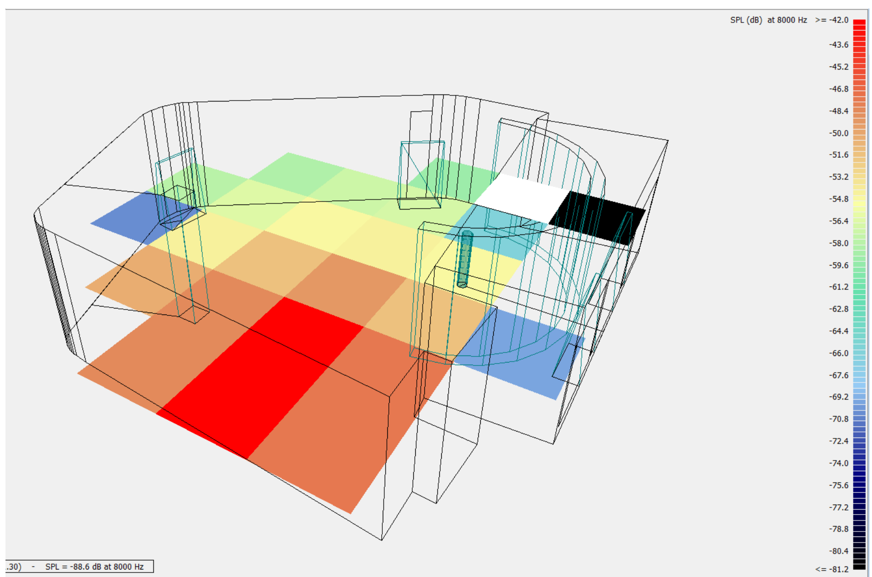


Figure 59 ODEON Gallery XL Curve – Source Location OS1 - SPL 8000Hz

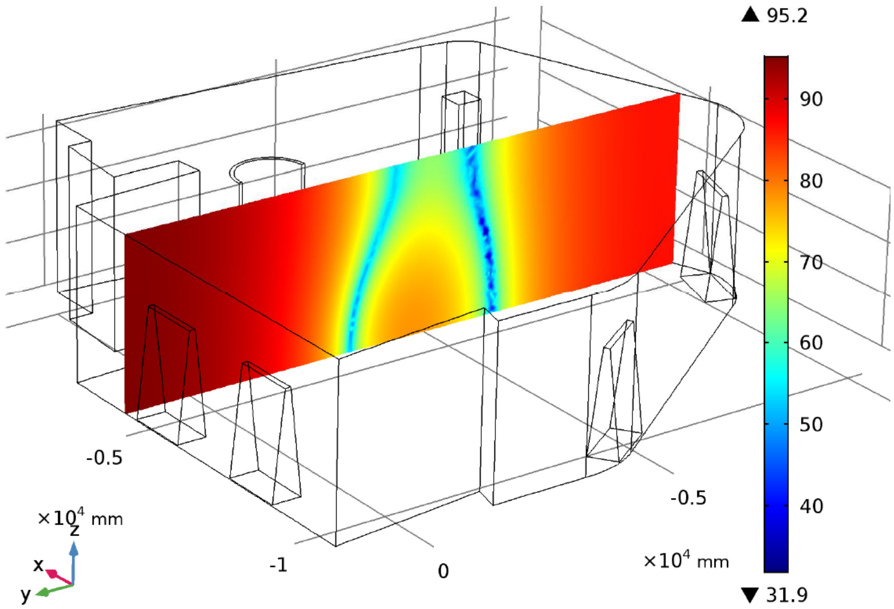


Figure 60: Gallery with Curve - Source outside curve 25Hz

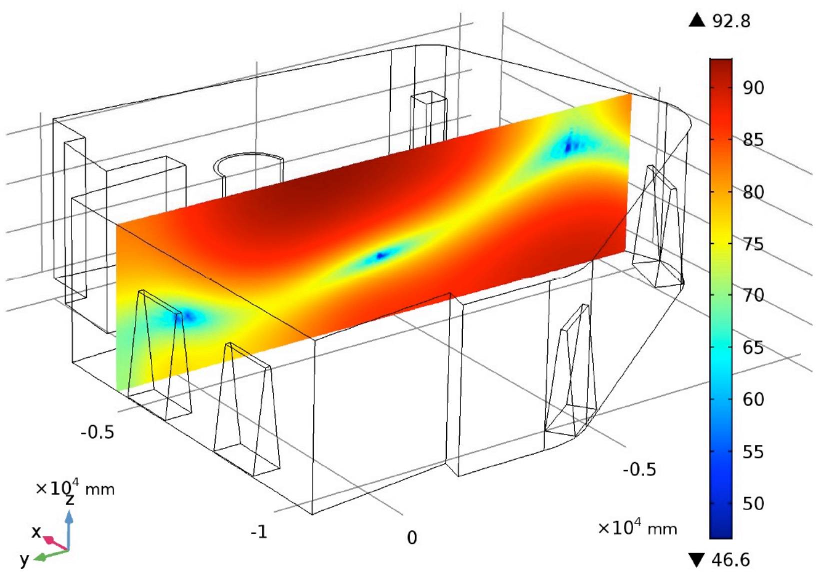


Figure 61: Gallery with Curve - Source outside curve 50Hz

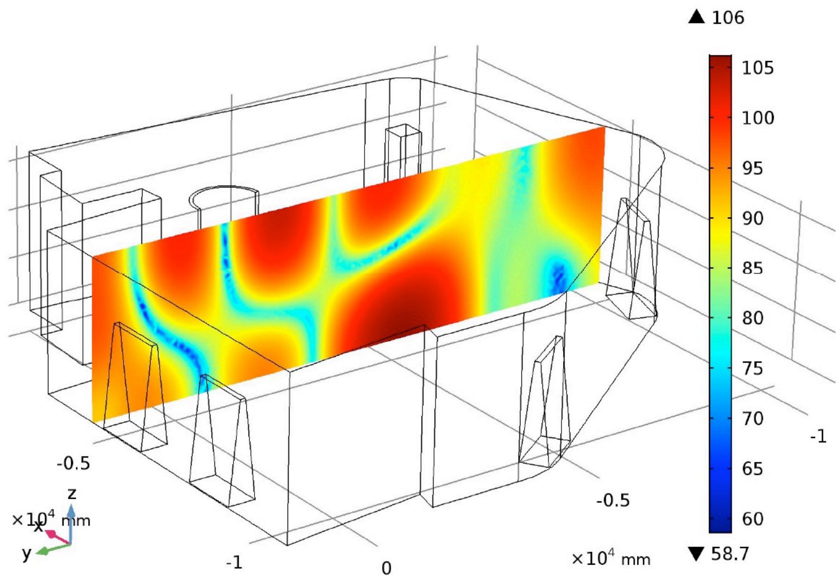


Figure 62: Gallery with Curve - Source outside curve 100Hz

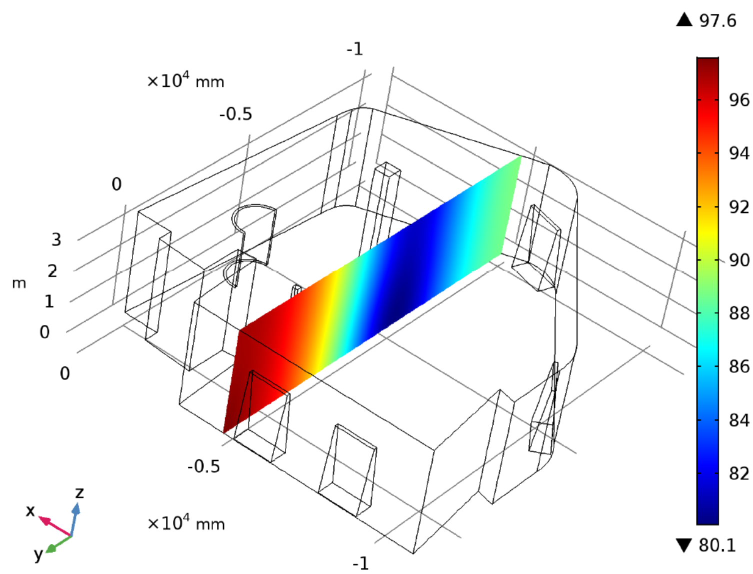


Figure 63: Gallery with Curve - Source inside curve 25Hz

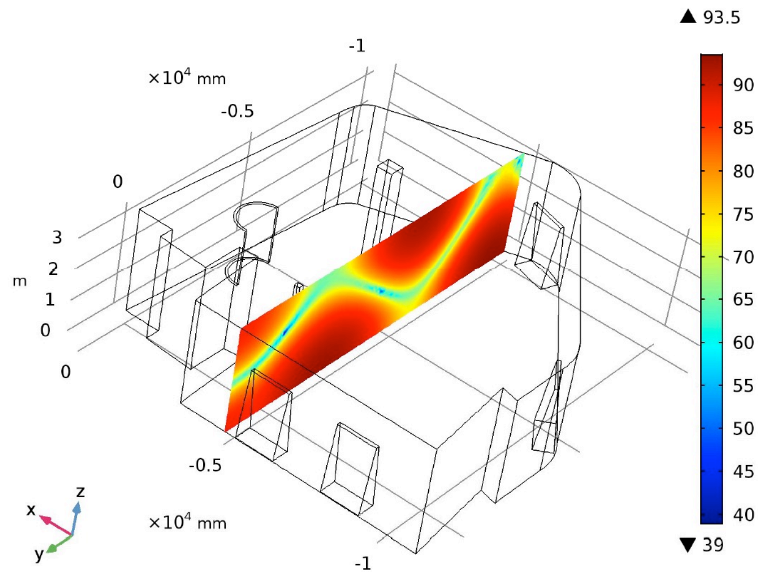


Figure 64: Gallery with Curve - Source inside curve 50Hz

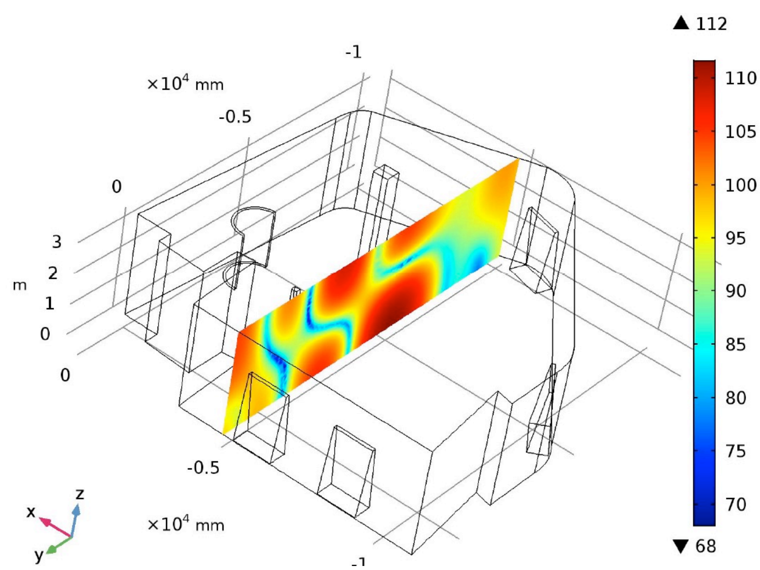


Figure 65: Gallery with Curve - Source inside curve 100Hz

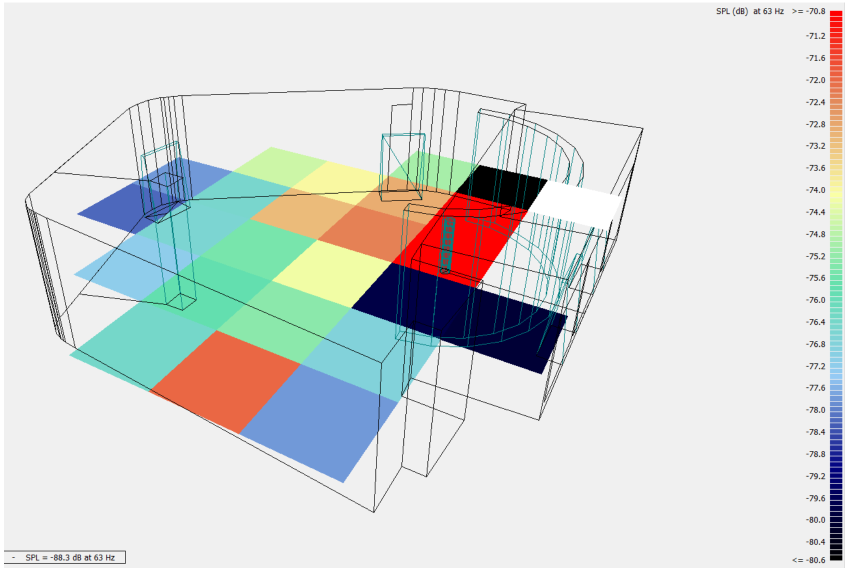


Figure 66 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 63Hz

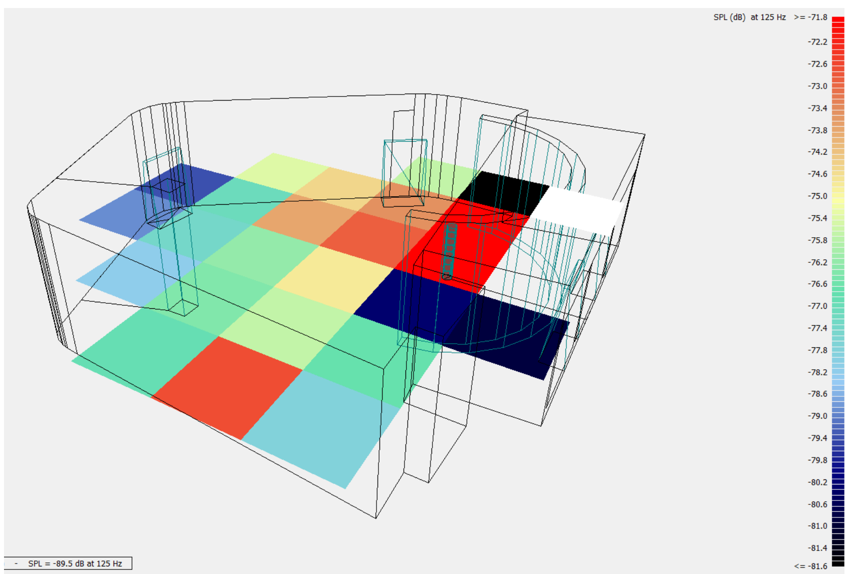


Figure 67 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 125Hz

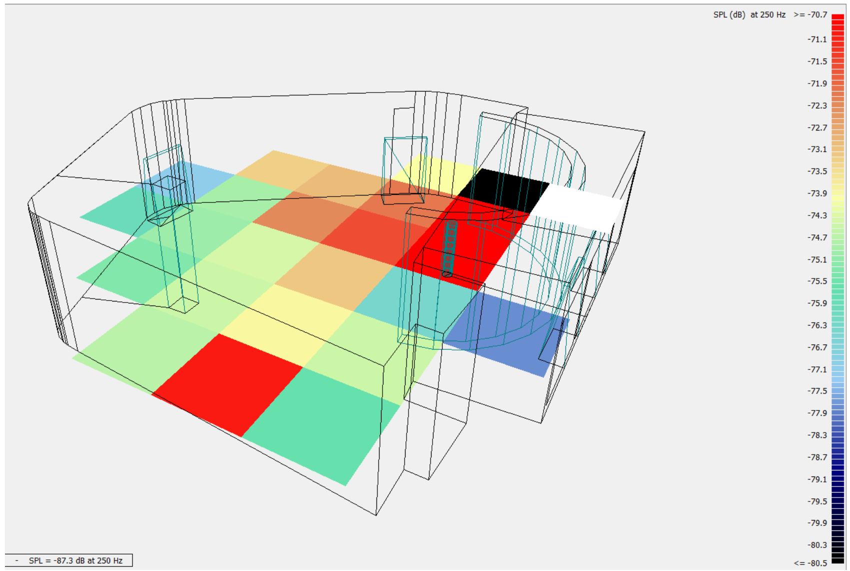


Figure 68 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 250Hz

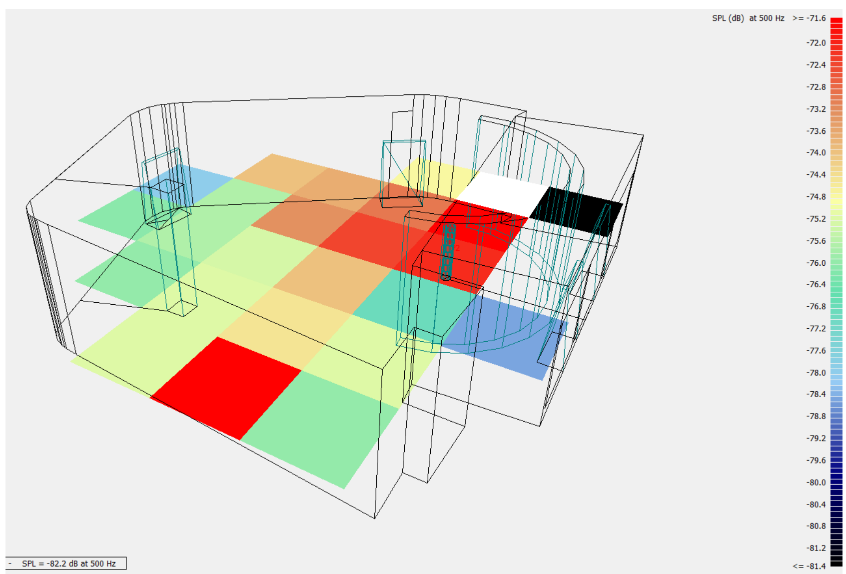


Figure 69 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 500Hz

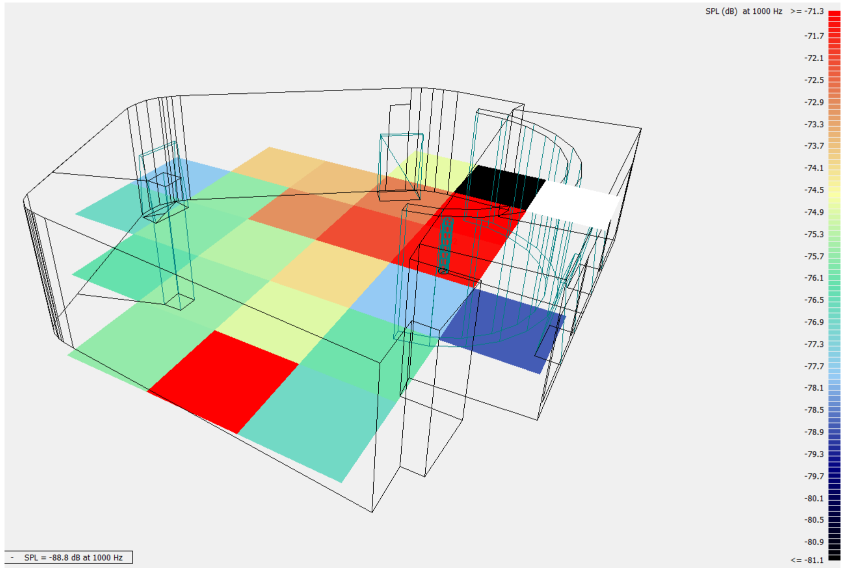


Figure 70 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 1000Hz

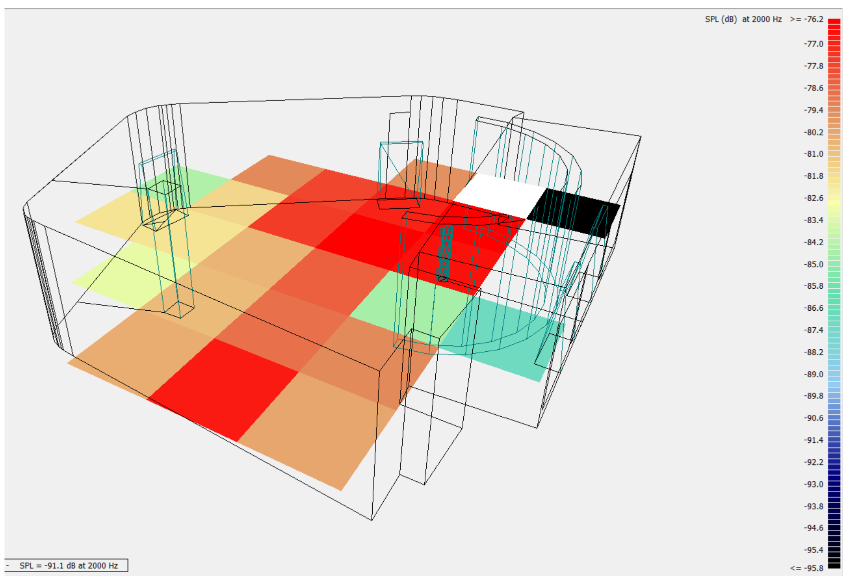


Figure 71 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 2000Hz

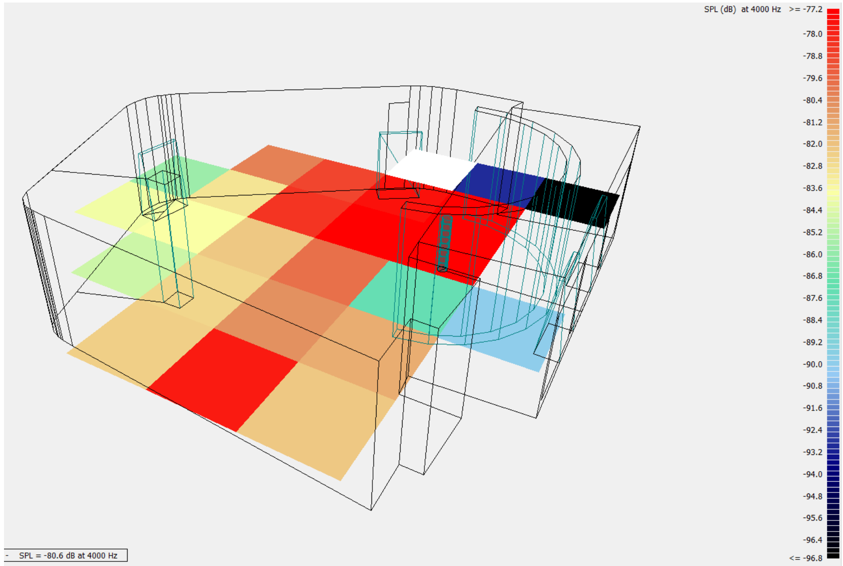


Figure 72 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 4000Hz

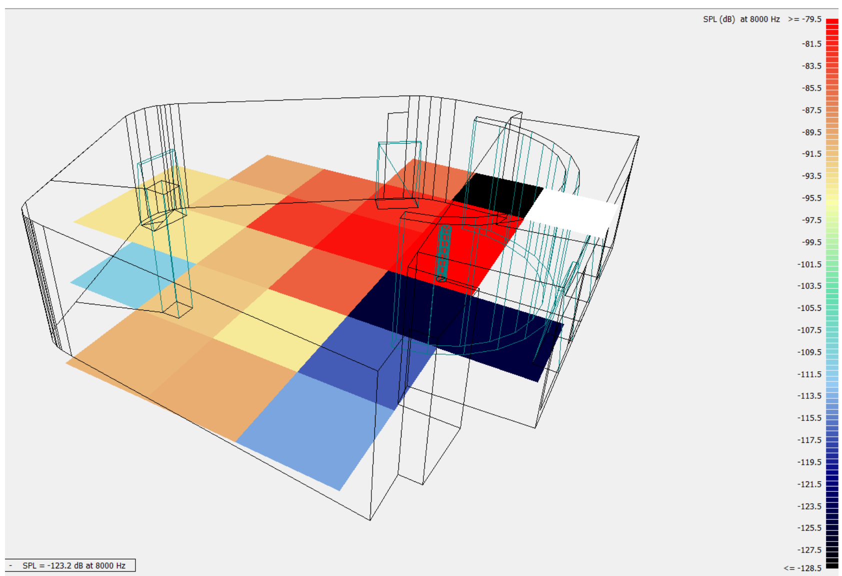


Figure 73 ODEON Gallery XL Curve – Source Location Inside Curve - SPL 8000Hz

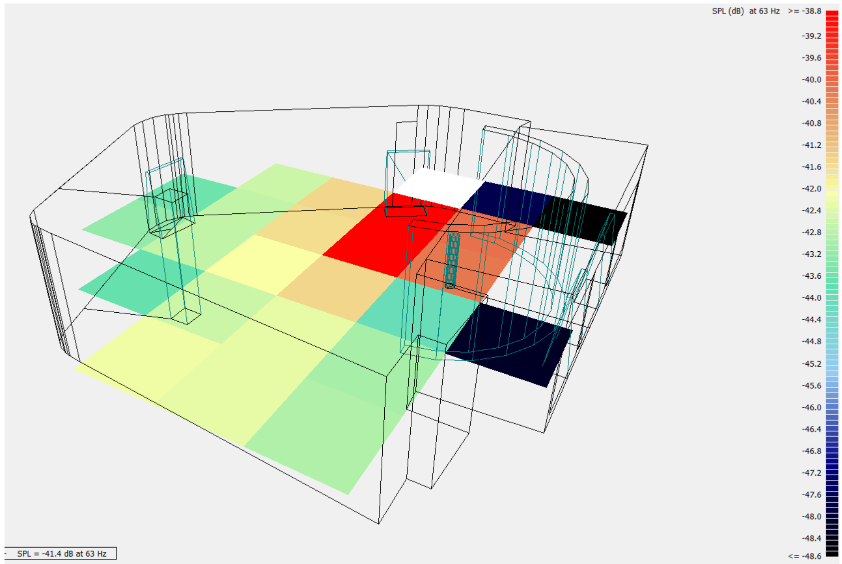


Figure 74: ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL 63Hz

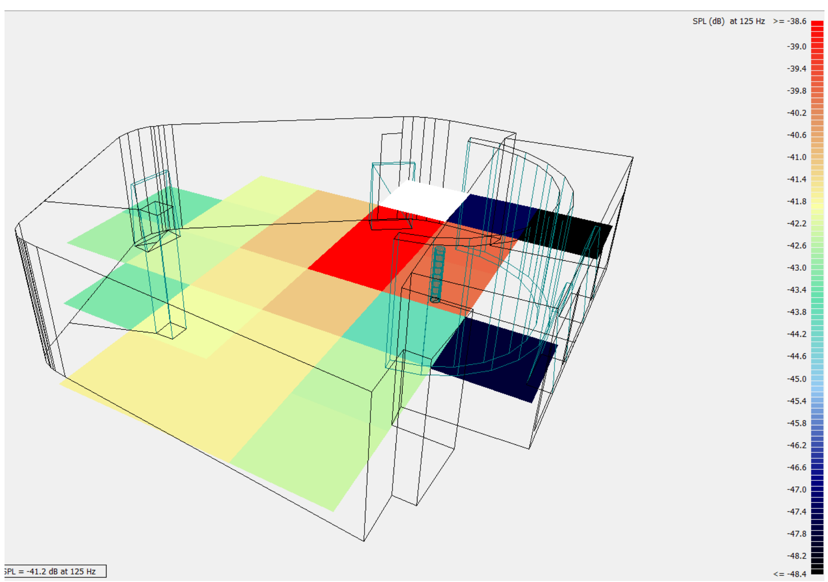


Figure 75 ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL 125Hz

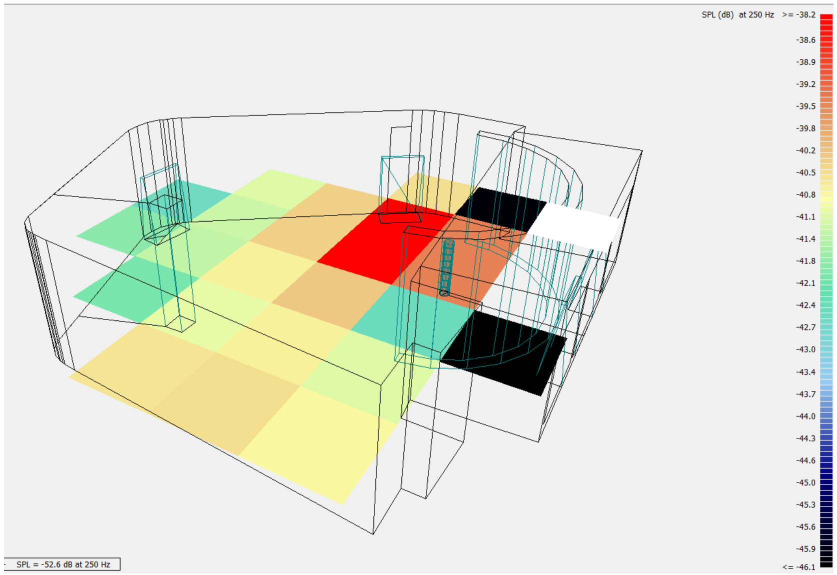


Figure 76 ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL

250Hz

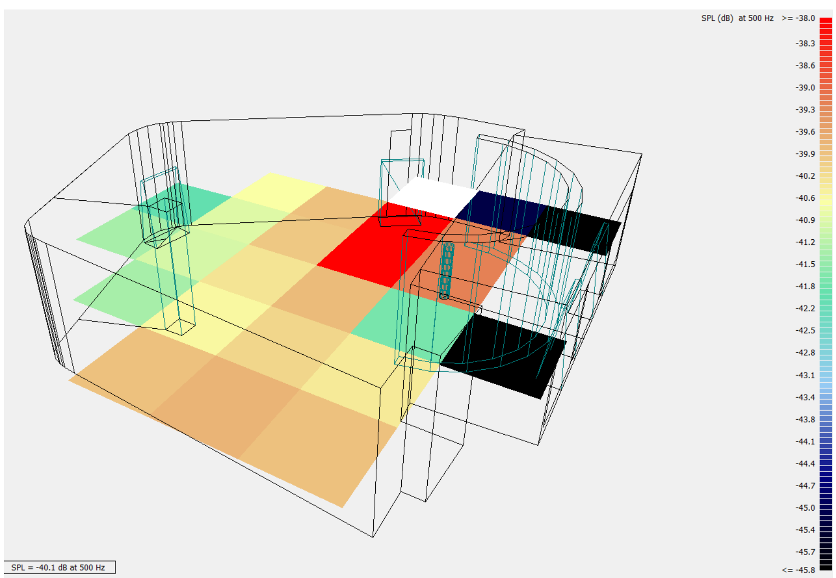


Figure 77 ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL

500Hz

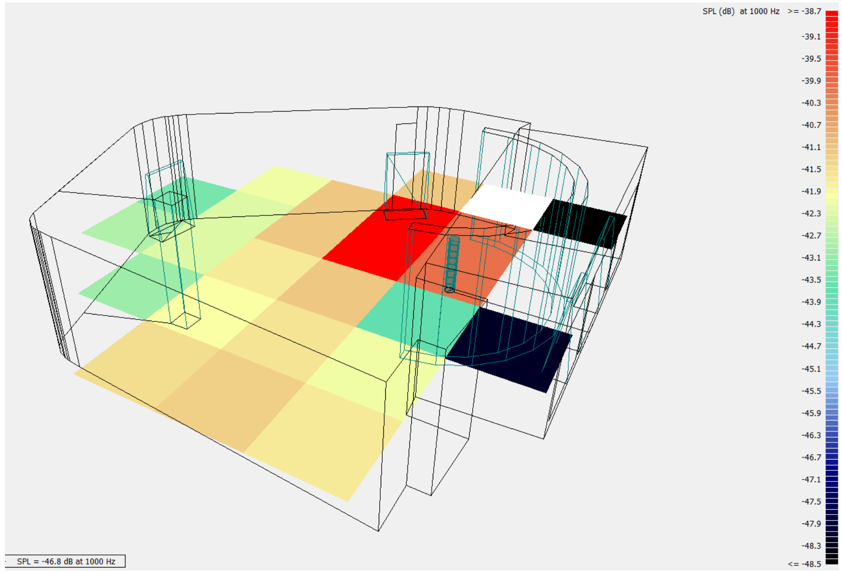


Figure 78 ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL 1000Hz

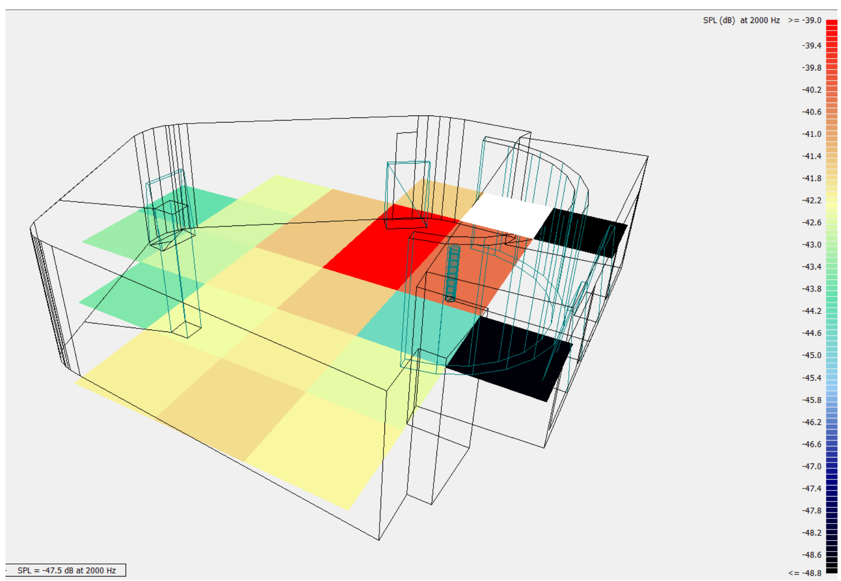


Figure 79 ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL 2000Hz

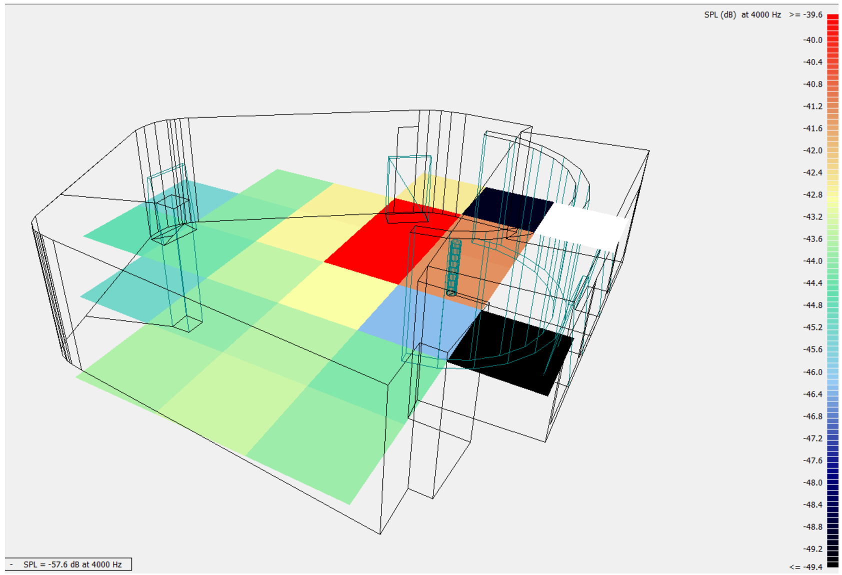


Figure 80 ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL 4000Hz

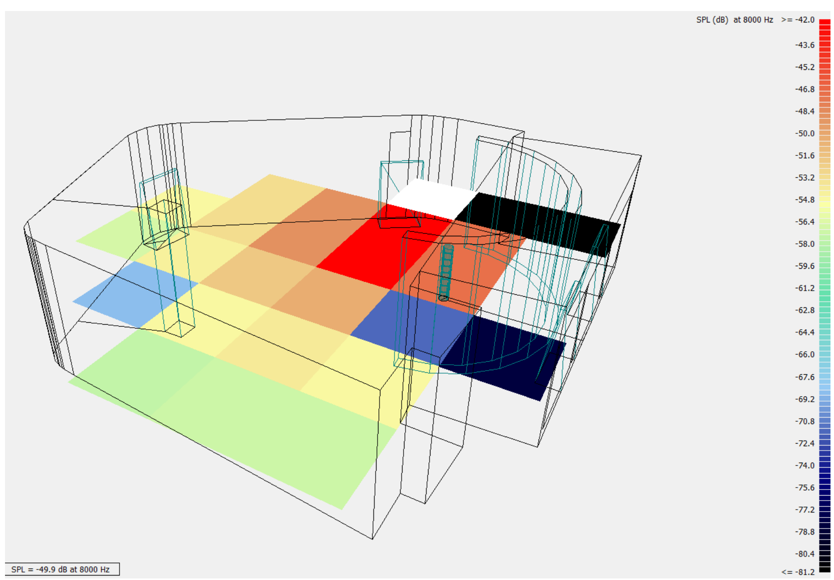


Figure 81 ODEON Gallery XL Curve – Source Location 1.3 m from centre - SPL 8000Hz

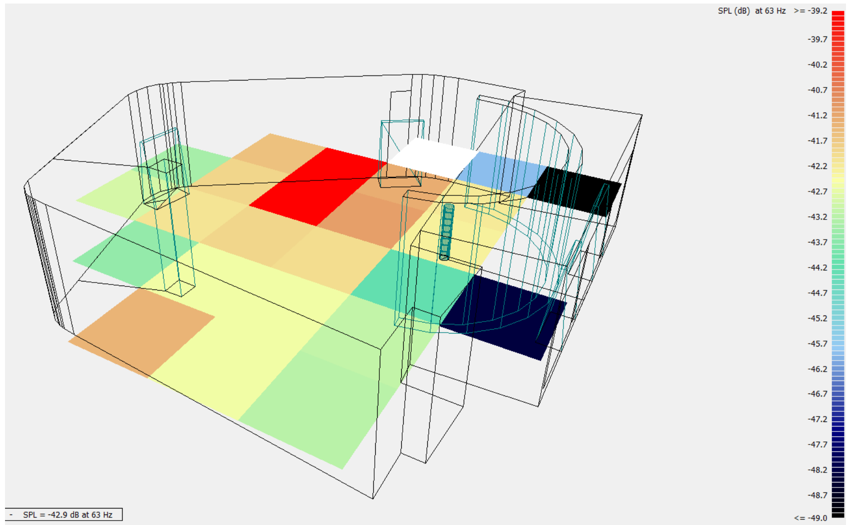


Figure 82 ODEON Gallery XL Curve – Source Location Outside Extended Circle -

SPL 63Hz

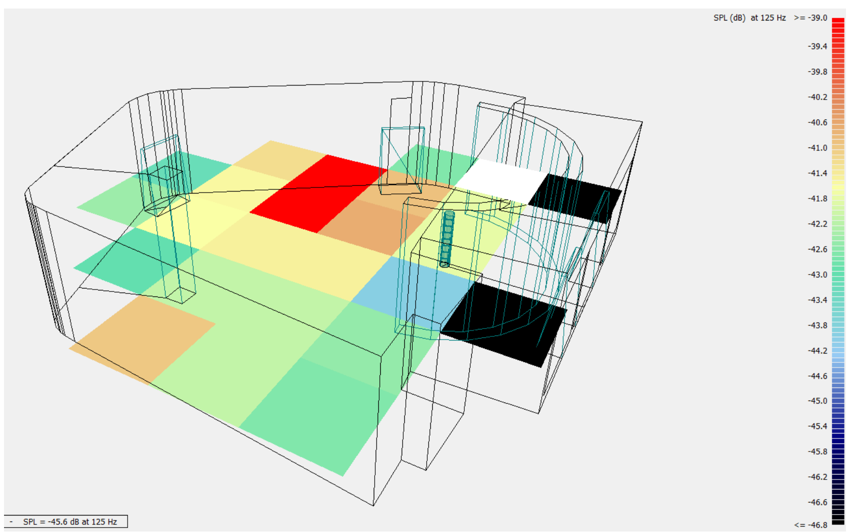


Figure 83 ODEON Gallery XL Curve – Source Location Outside Extended Circle -

SPL 125Hz

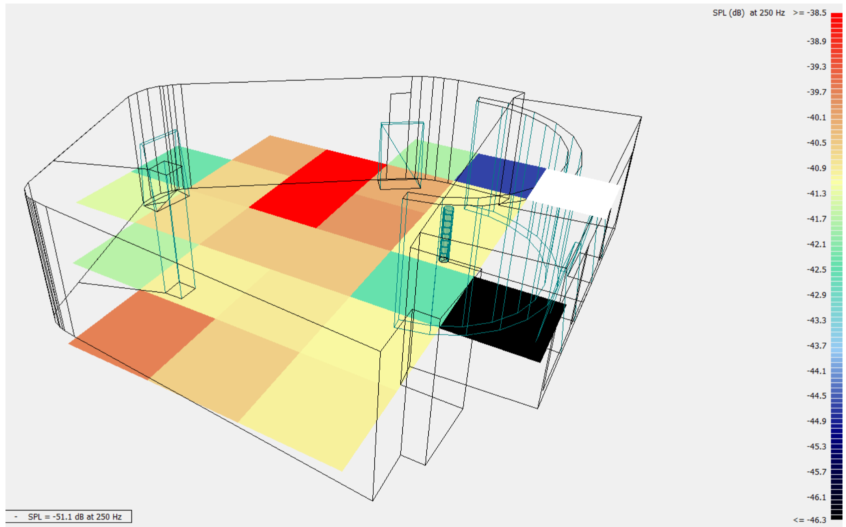


Figure 84 ODEON Gallery XL Curve – Source Location Outside Extended Circle - SPL 250Hz

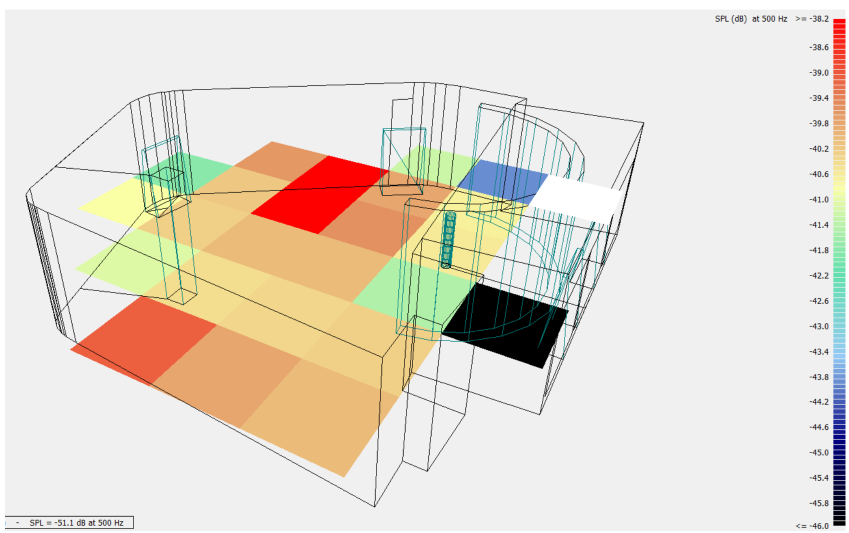


Figure 85 ODEON Gallery XL Curve – Source Location Outside Extended Circle - SPL 500Hz

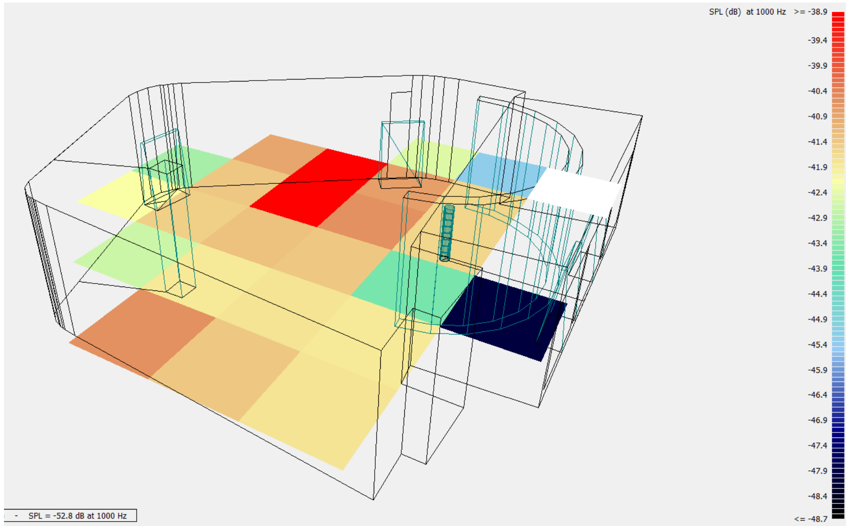


Figure 86 ODEON Gallery XL Curve – Source Location Outside Extended Circle - SPL 1000Hz

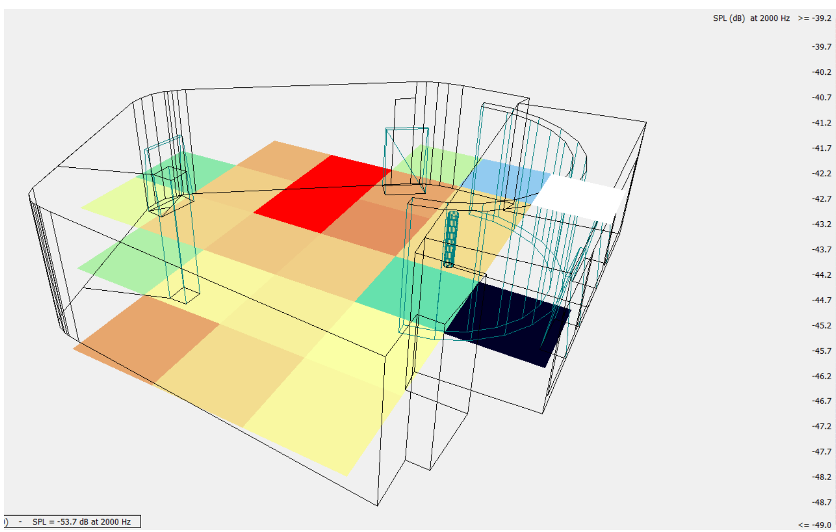


Figure 87 ODEON Gallery XL Curve – Source Location Outside Extended Circle - SPL 2000Hz

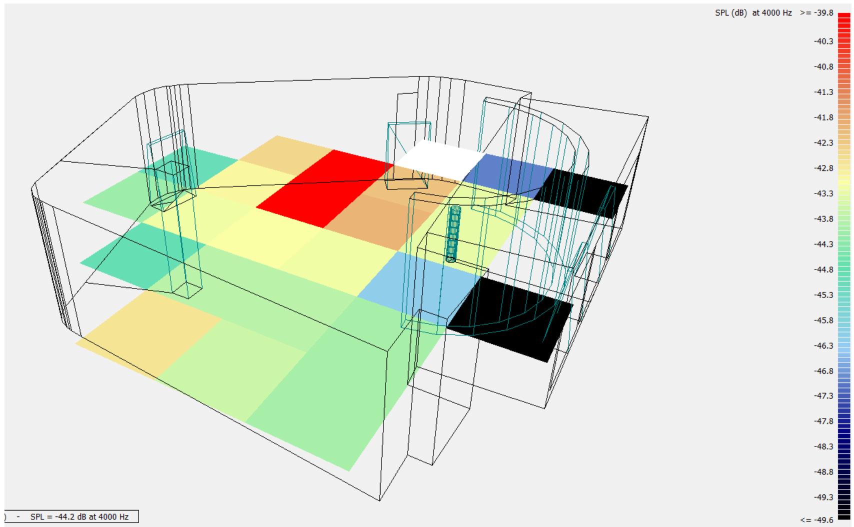


Figure 88 ODEON Gallery XL Curve – Source Location Outside Extended Circle - SPL 4000Hz

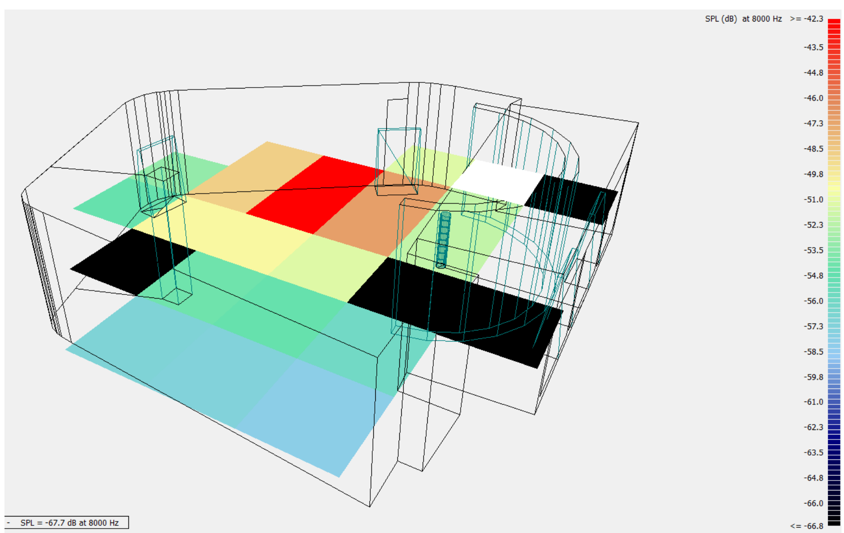


Figure 89 ODEON Gallery XL Curve – Source Location Outside Extended Circle - SPL 8000Hz

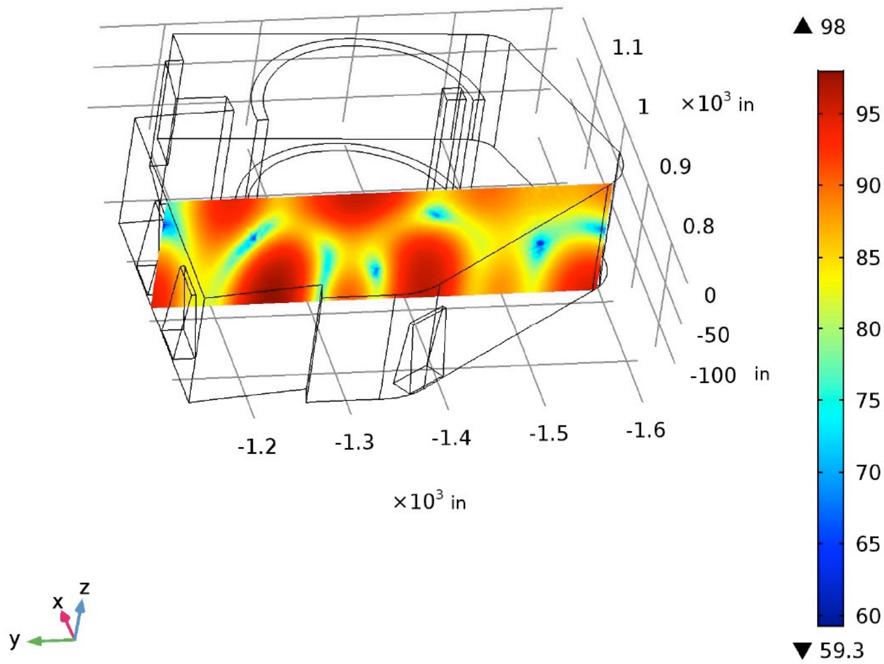


Figure 90 COMSOL Gallery XL Curve – Source Location Outside Curve – 25Hz

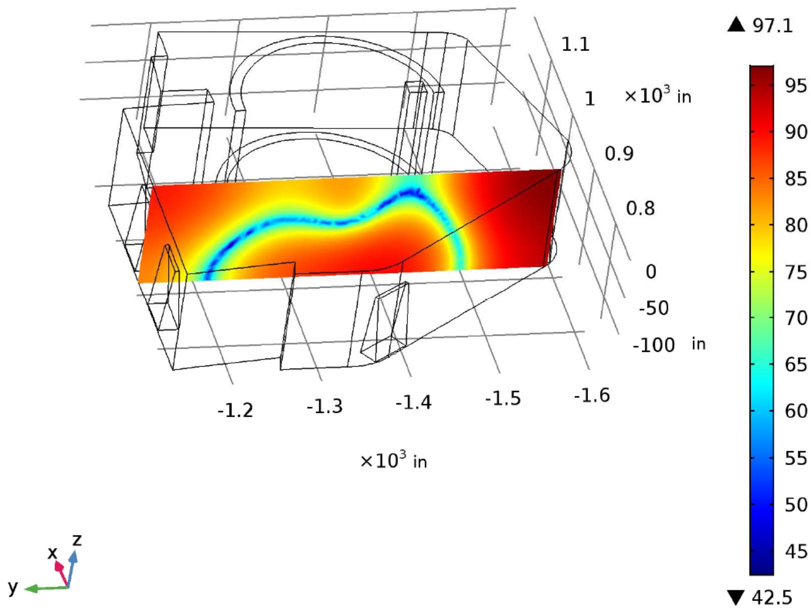


Figure 91 COMSOL Gallery XL Curve – Source Location Outside Curve – 50Hz

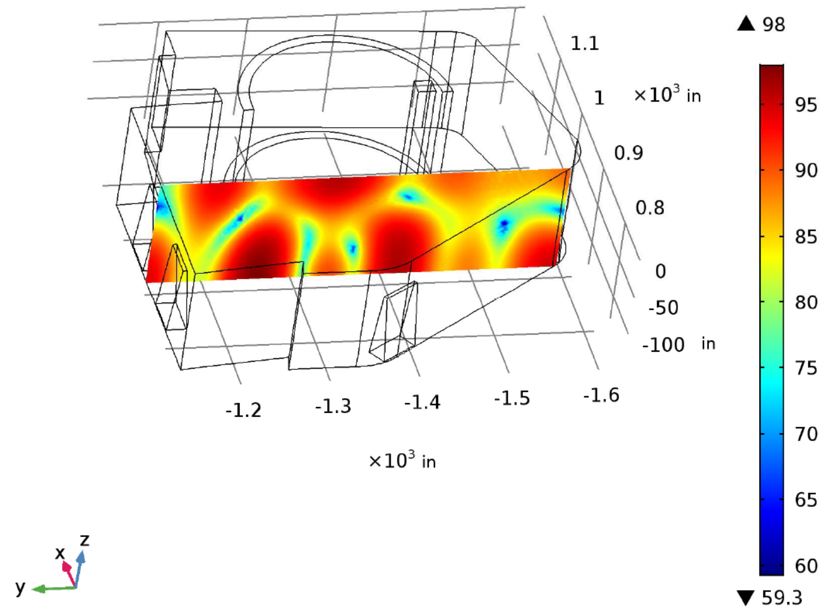


Figure 92 COMSOL Gallery XL Curve – Source Location Outside Curve – 100Hz

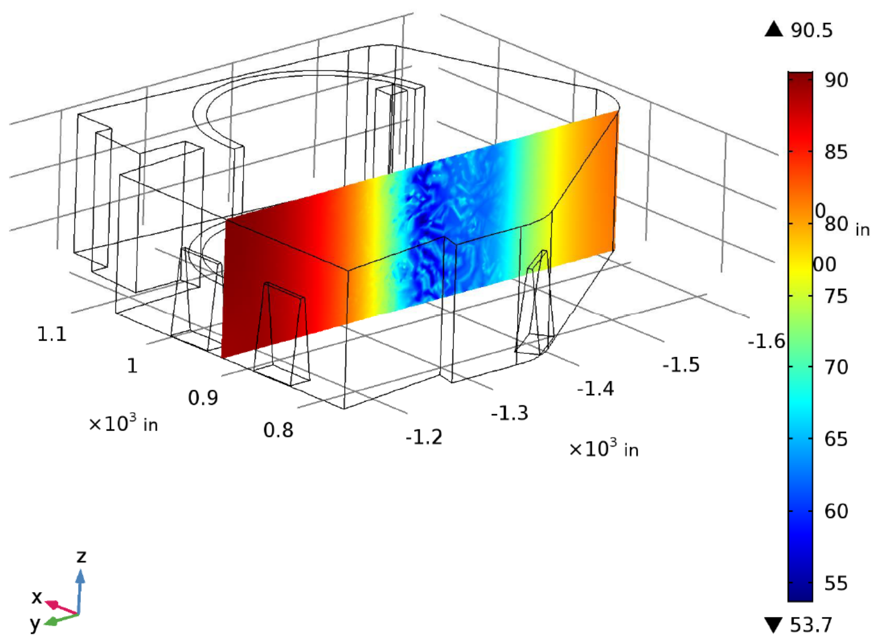


Figure 93 COMSOL Gallery XL Curve – Source Location Inside Curve – 25Hz

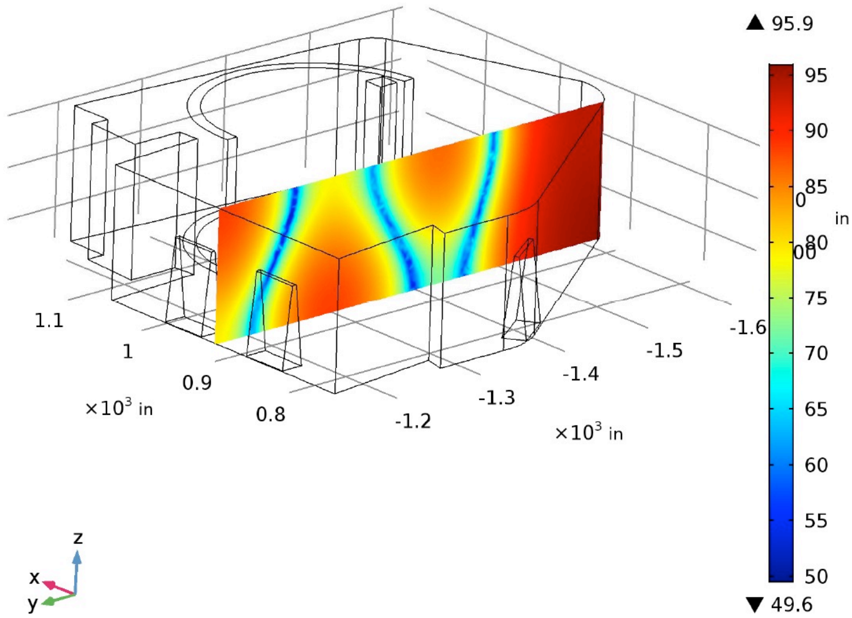


Figure 94 COMSOL Gallery XL Curve – Source Location Inside Curve – 50Hz

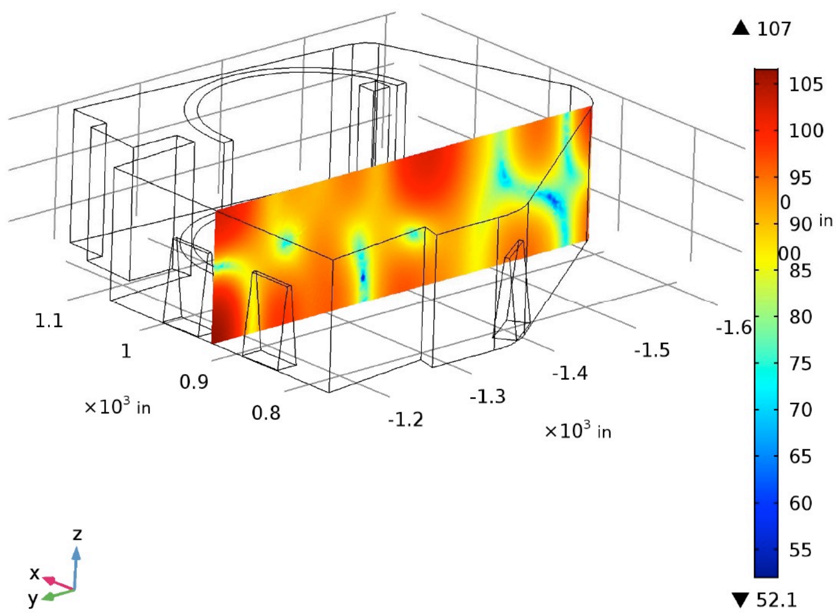


Figure 95 COMSOL Gallery XL Curve – Source Location Inside Curve – 100Hz

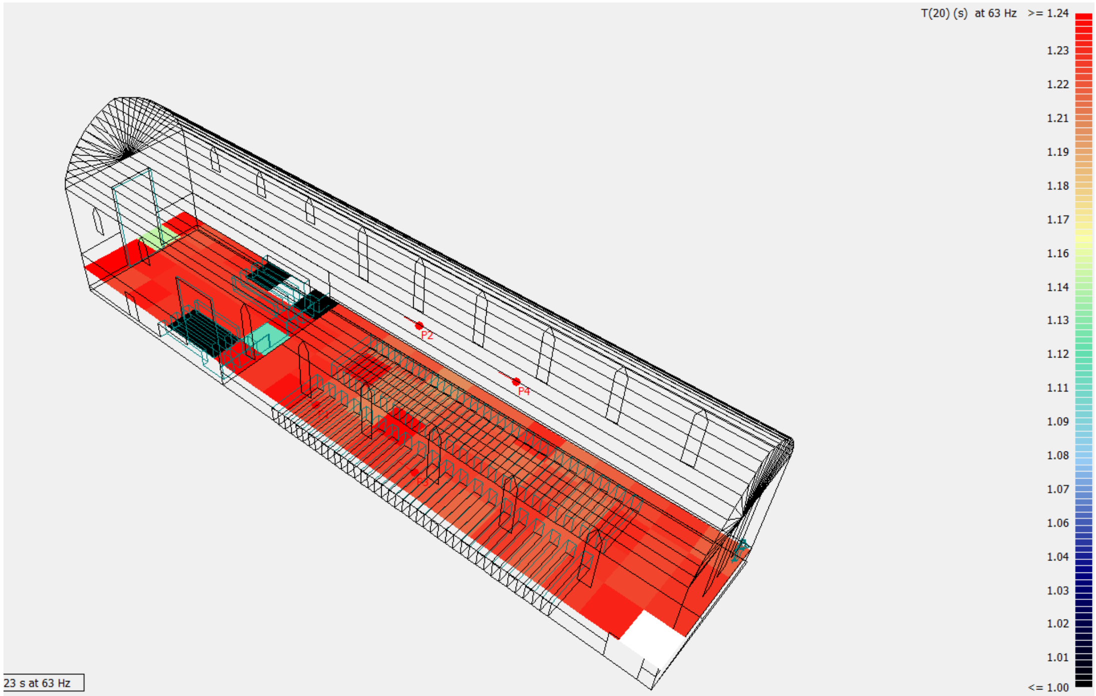


Figure 96 ODEON St. Martins - Speaker Location RT – 63Hz

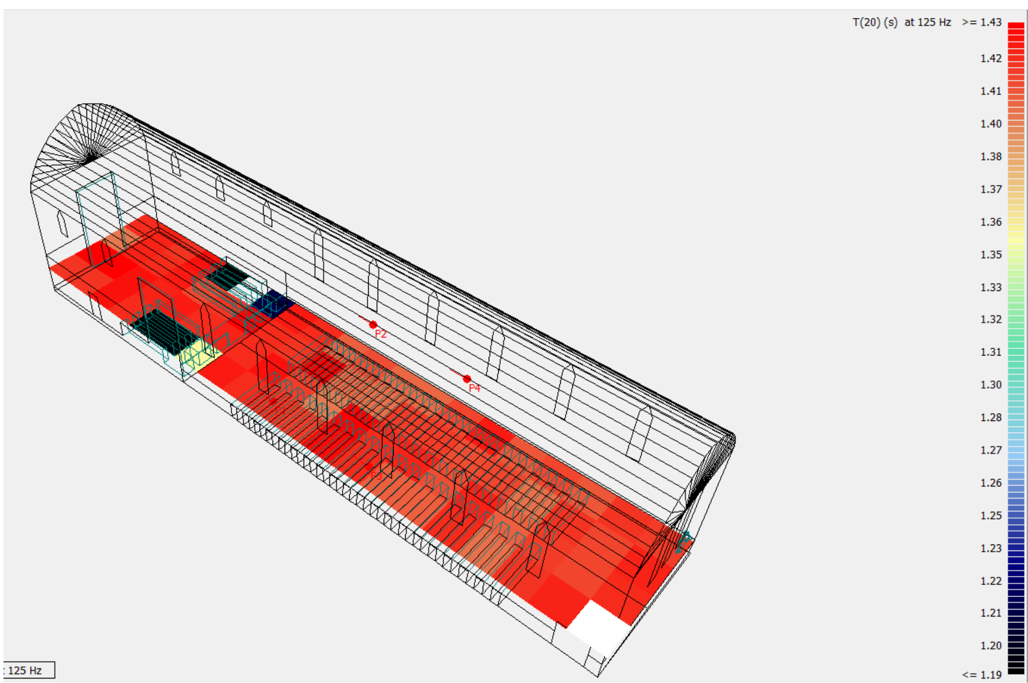


Figure 97 ODEON St. Martins - Speaker Location RT – 125Hz

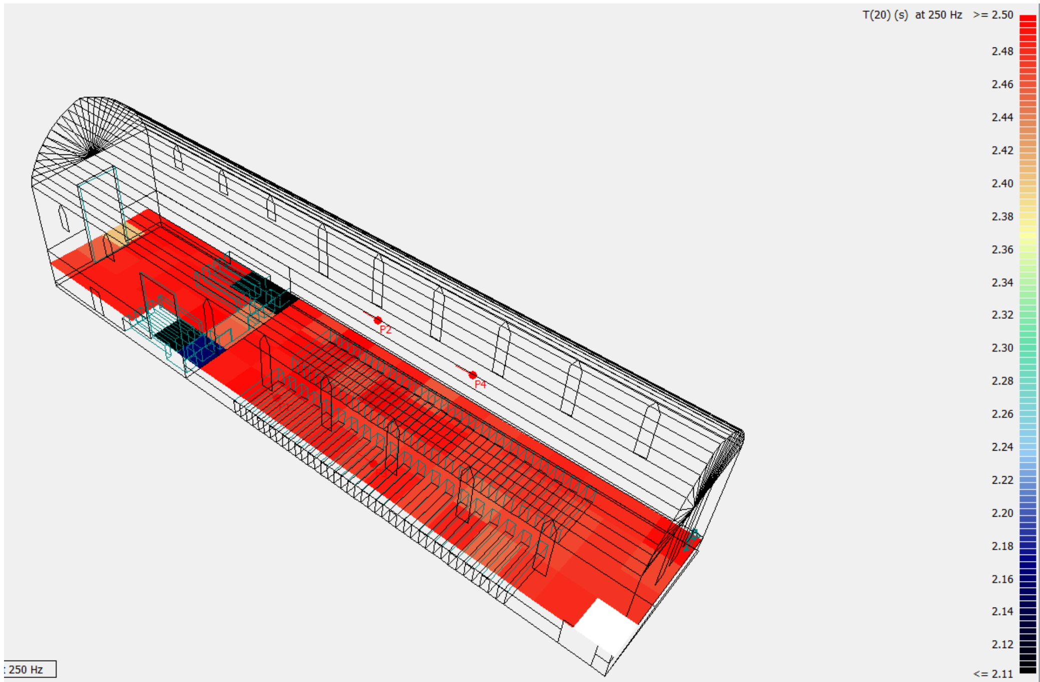


Figure 98 ODEON St. Martins - Speaker Location RT – 250Hz

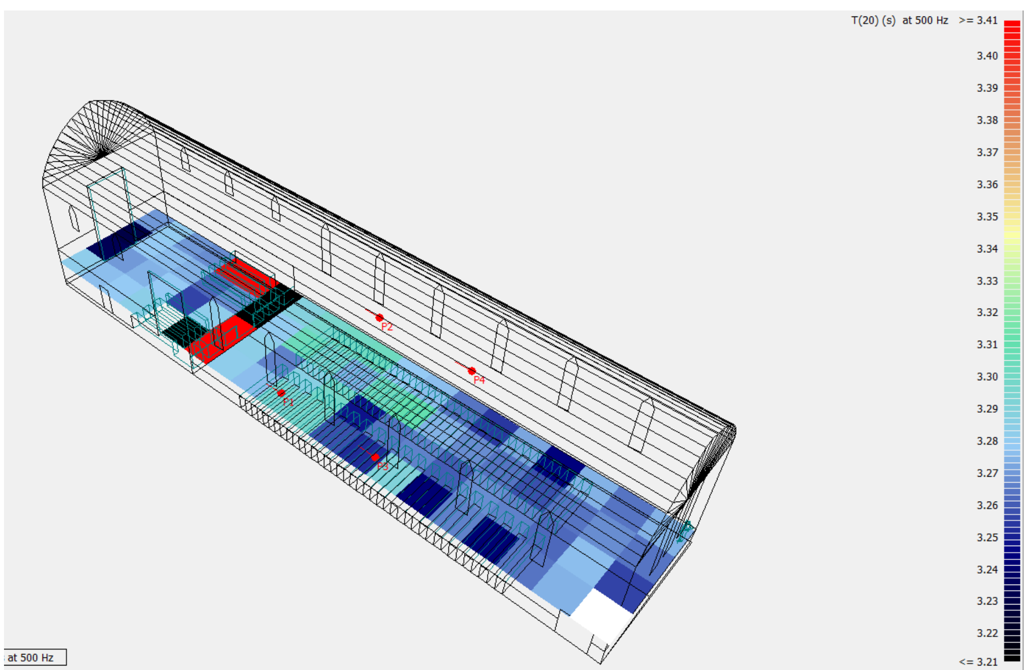


Figure 99 ODEON St. Martins - Speaker Location RT – 500Hz

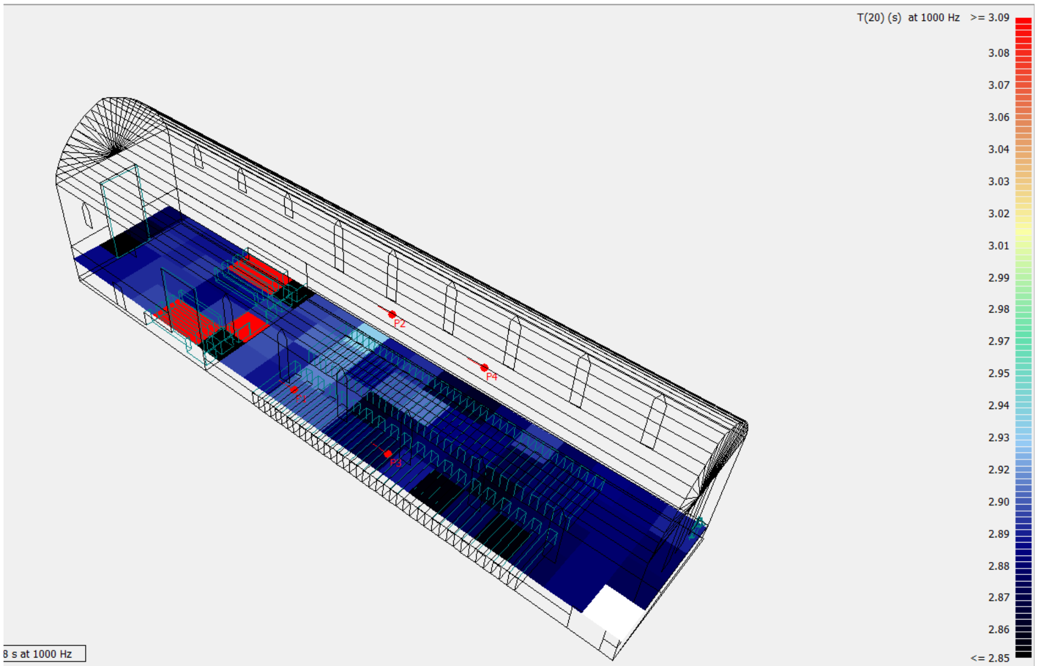


Figure 100 ODEON St. Martins - Speaker Location RT – 1000Hz

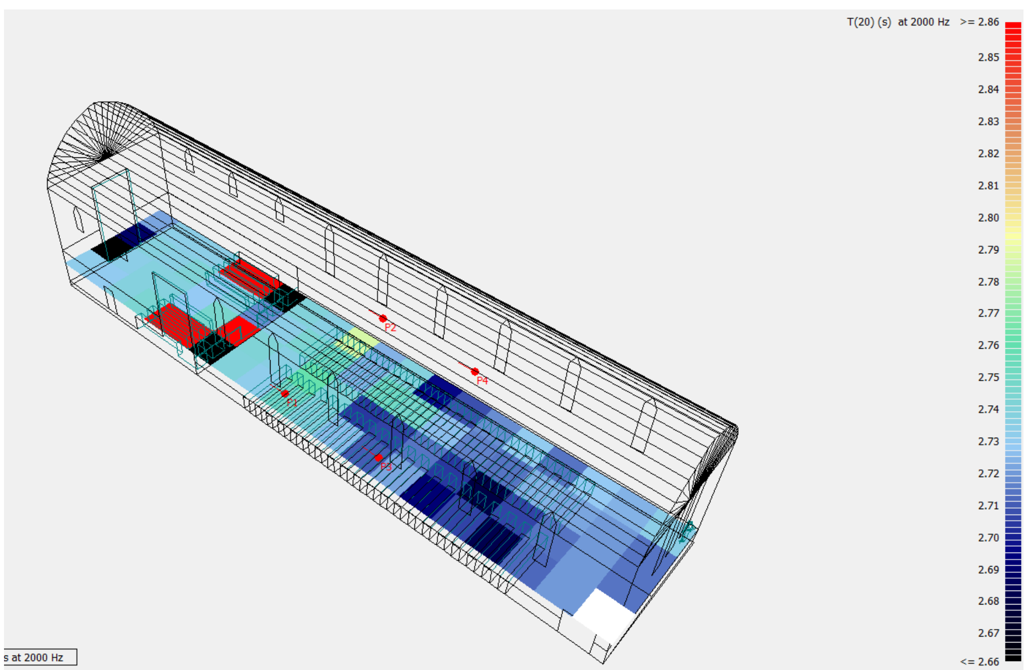


Figure 101 ODEON St. Martins - Speaker Location RT – 2000Hz

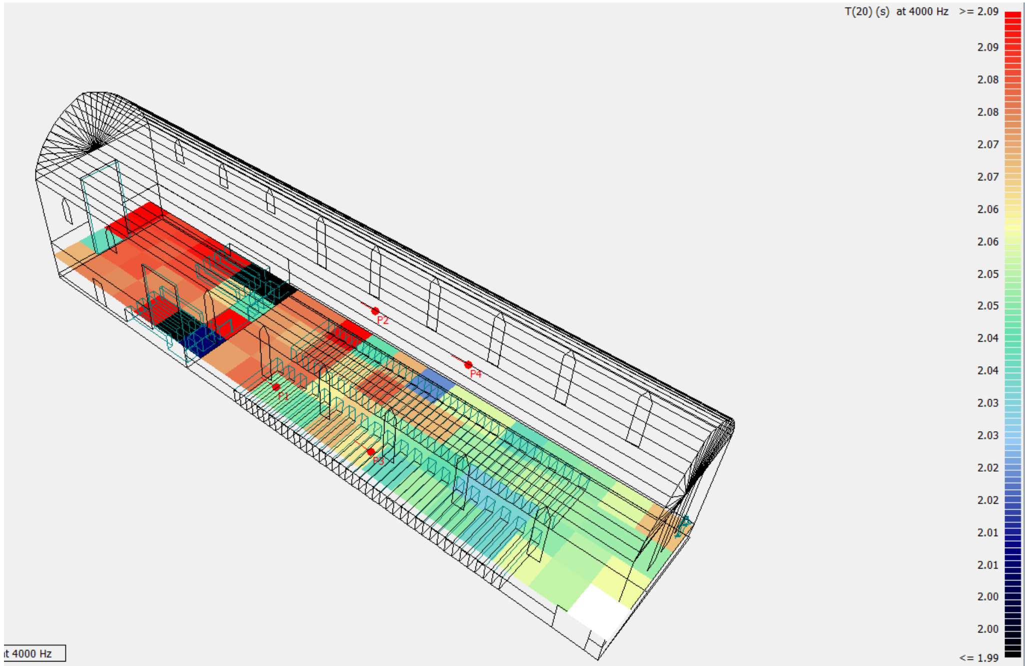


Figure 102 ODEON St. Martins - Speaker Location RT – 4000Hz

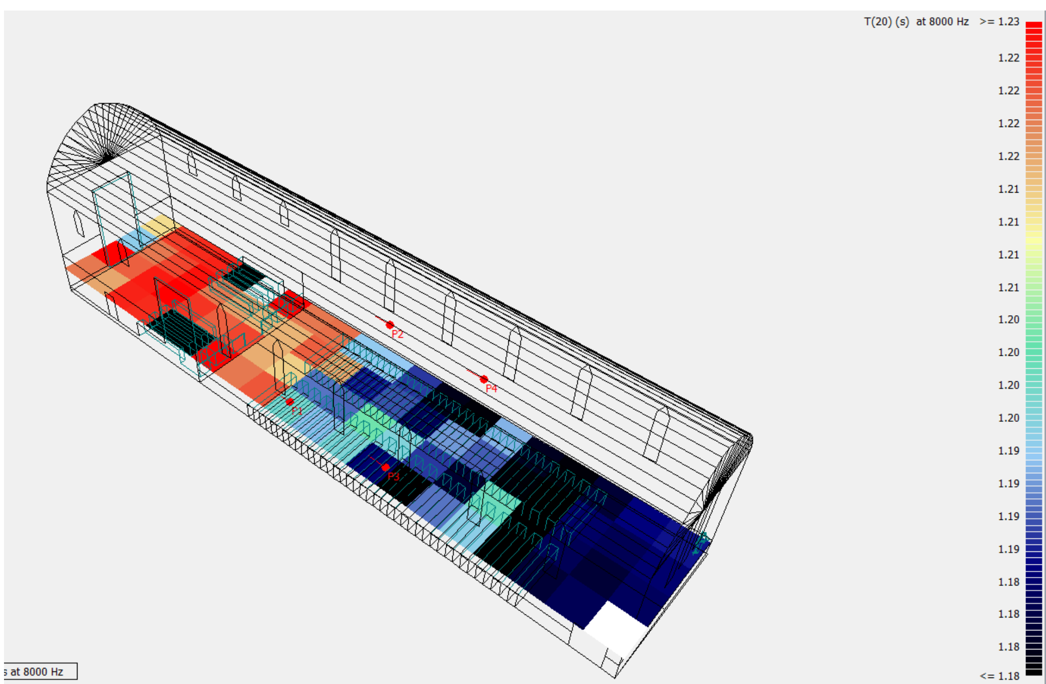


Figure 103 ODEON St. Martins - Speaker Location RT – 8000Hz

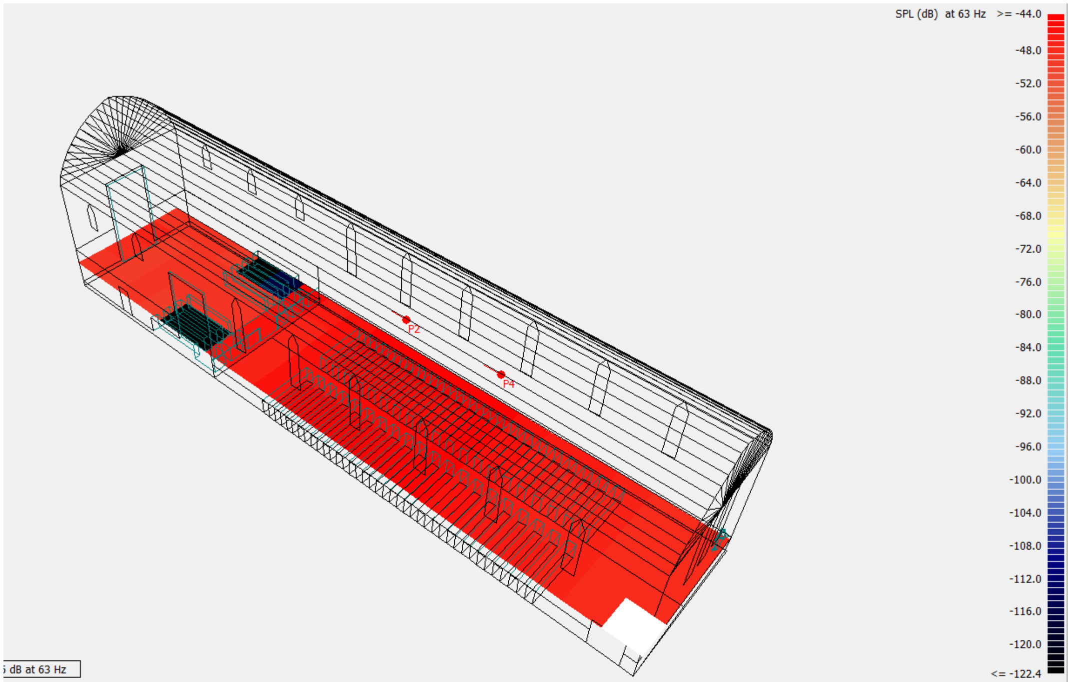


Figure 104 ODEON St. Martins - Speaker Location SPL – 63Hz

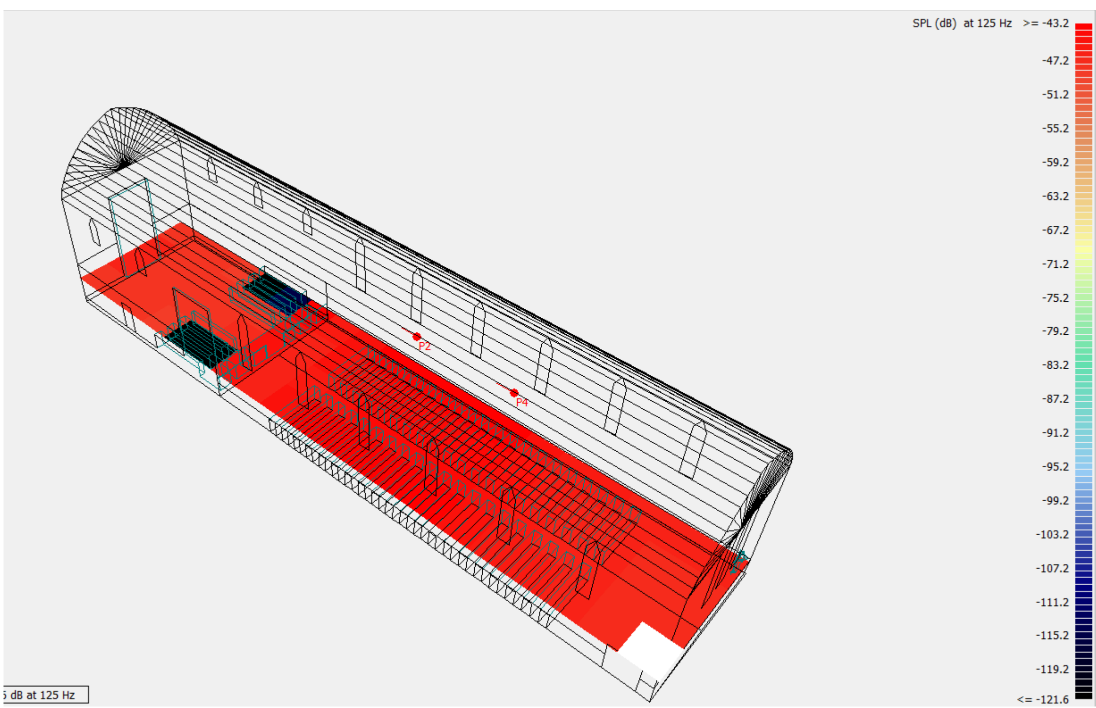


Figure 105 ODEON St. Martins - Speaker Location SPL – 125Hz

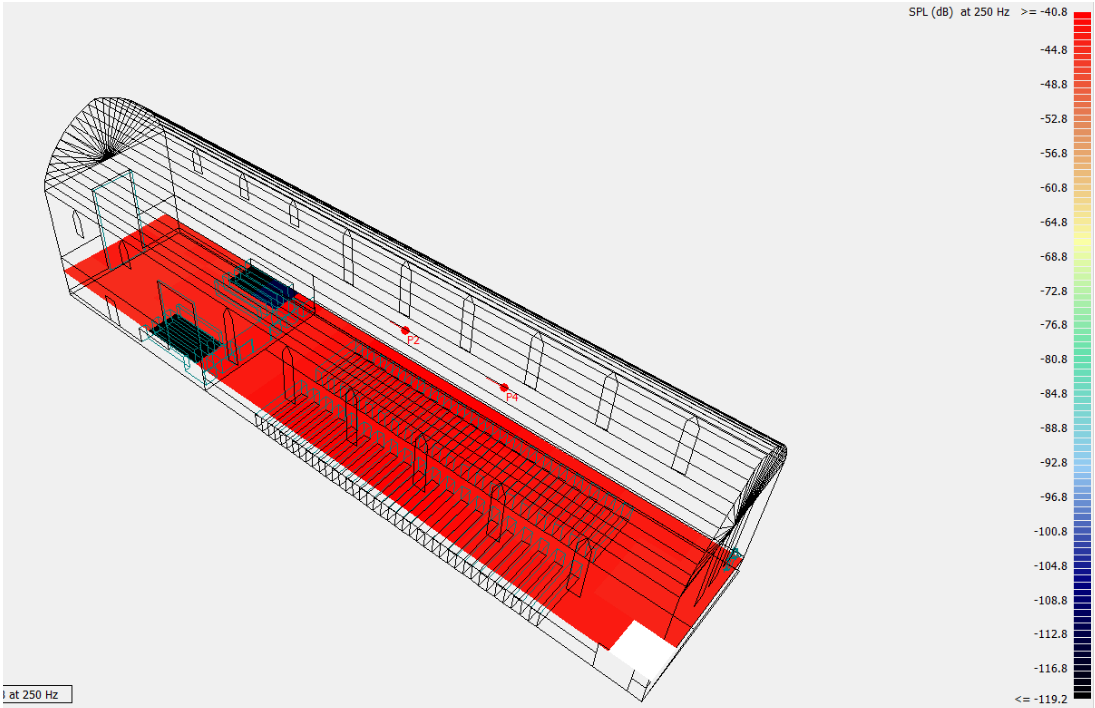


Figure 106 ODEON St. Martins - Speaker Location SPL – 250Hz

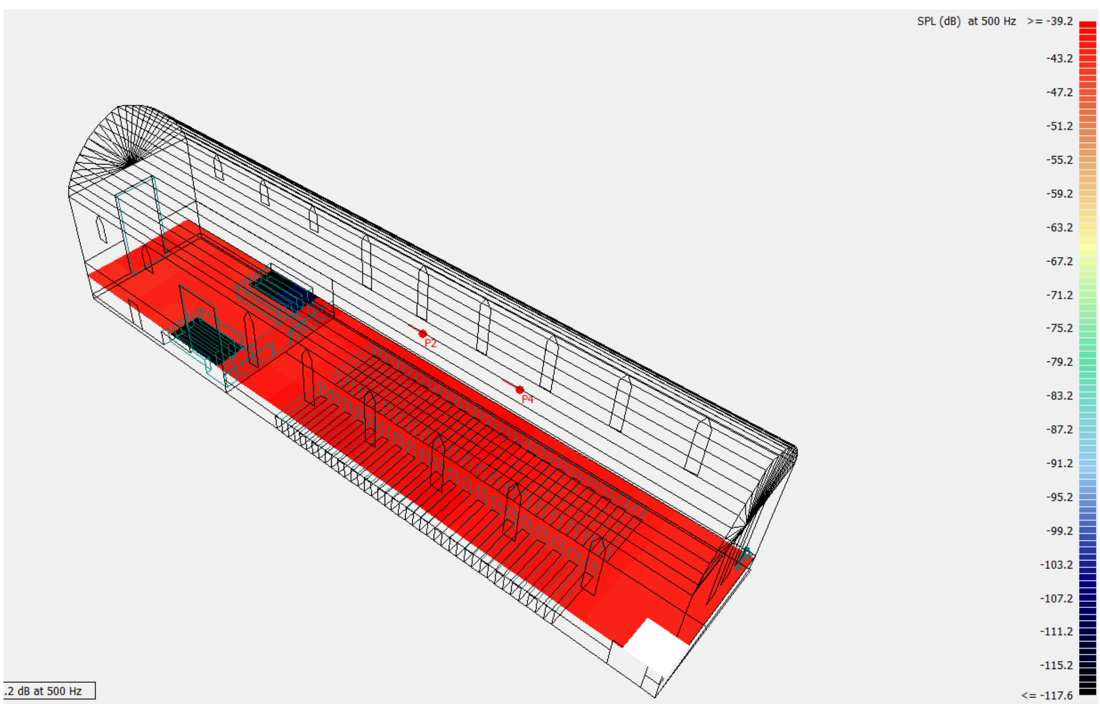


Figure 107 ODEON St. Martins - Speaker Location SPL – 500Hz

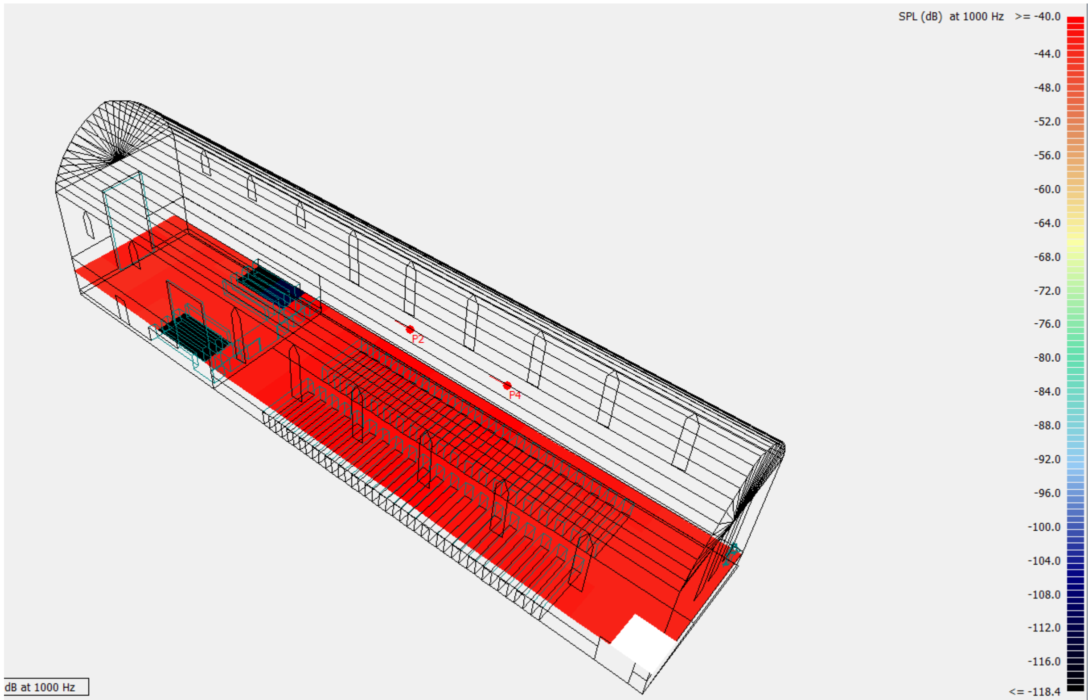


Figure 108 ODEON St. Martins - Speaker Location SPL – 1000Hz

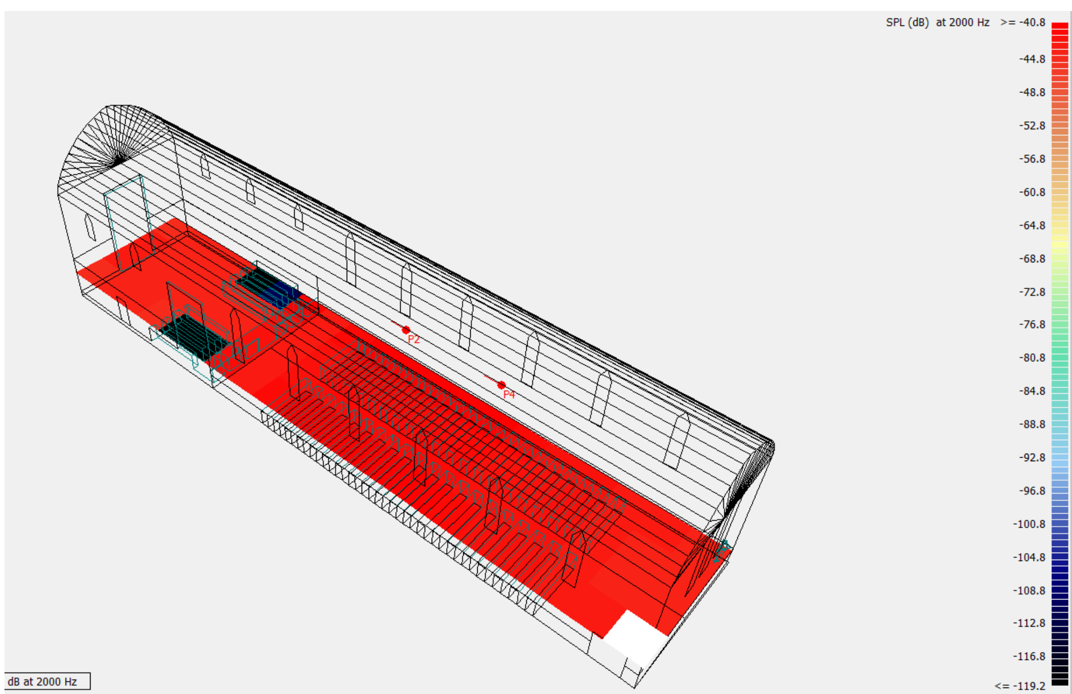


Figure 109 ODEON St. Martins - Speaker Location SPL – 2000Hz

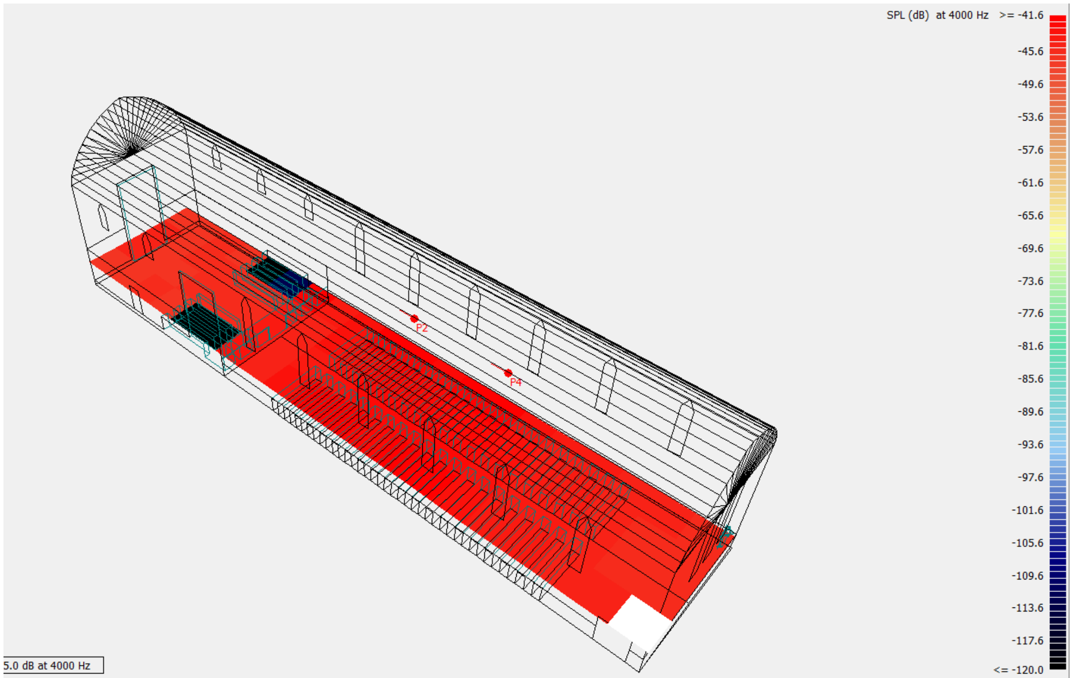


Figure 110 ODEON St. Martins - Speaker Location SPL – 4000Hz

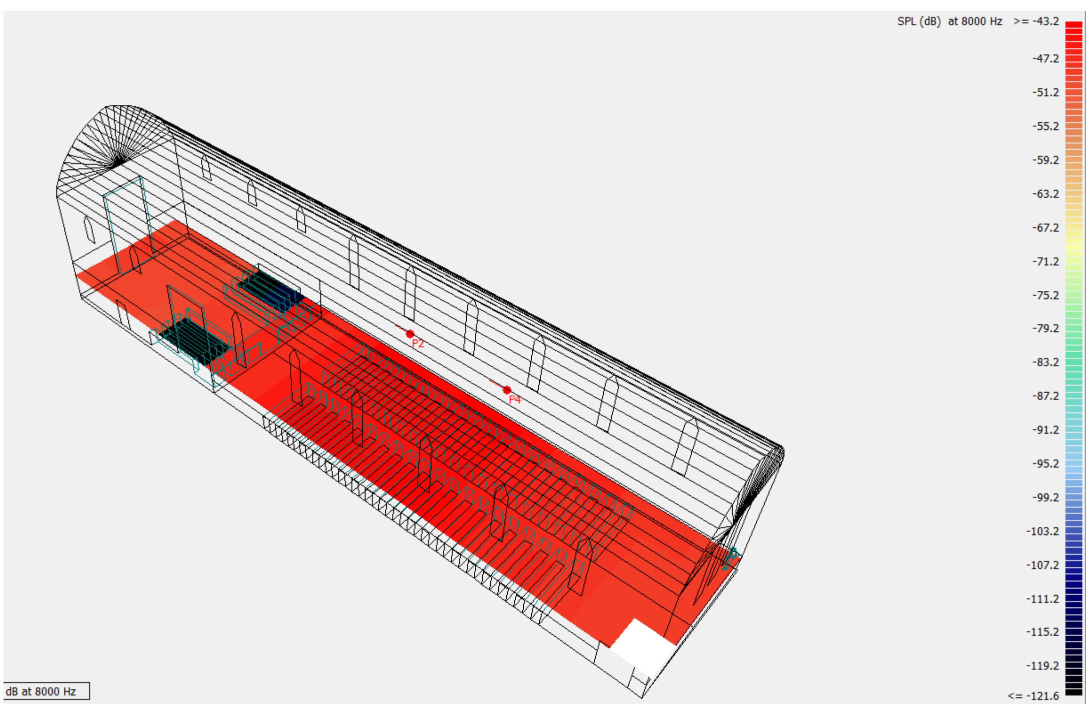


Figure 111 ODEON St. Martins - Speaker Location SPL – 8000Hz

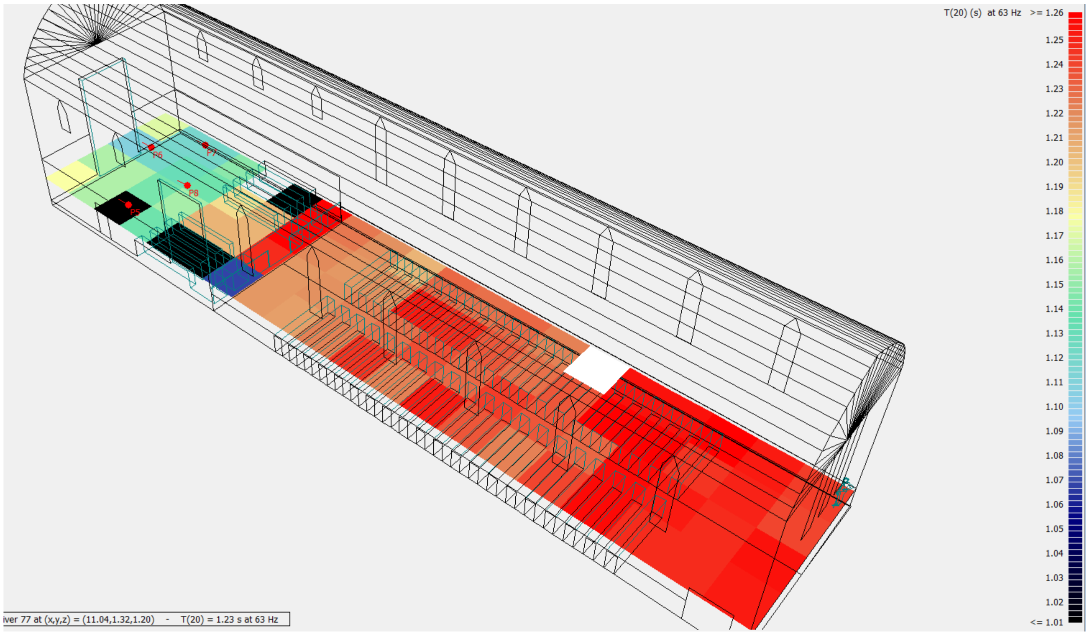


Figure 112 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 63Hz

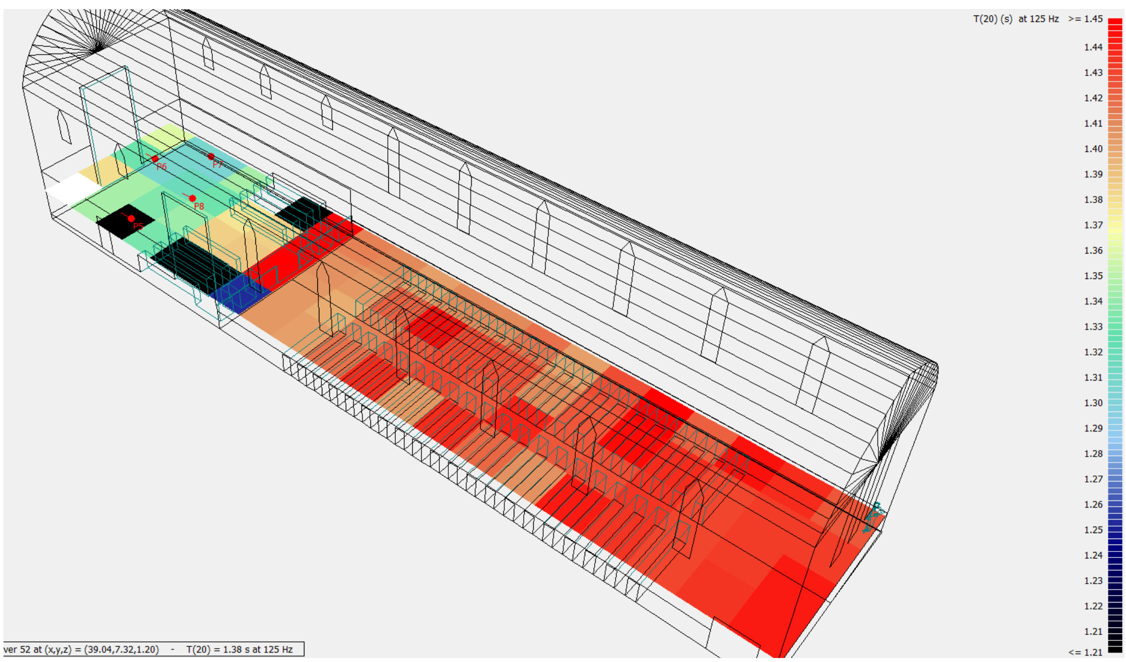


Figure 113 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 125Hz

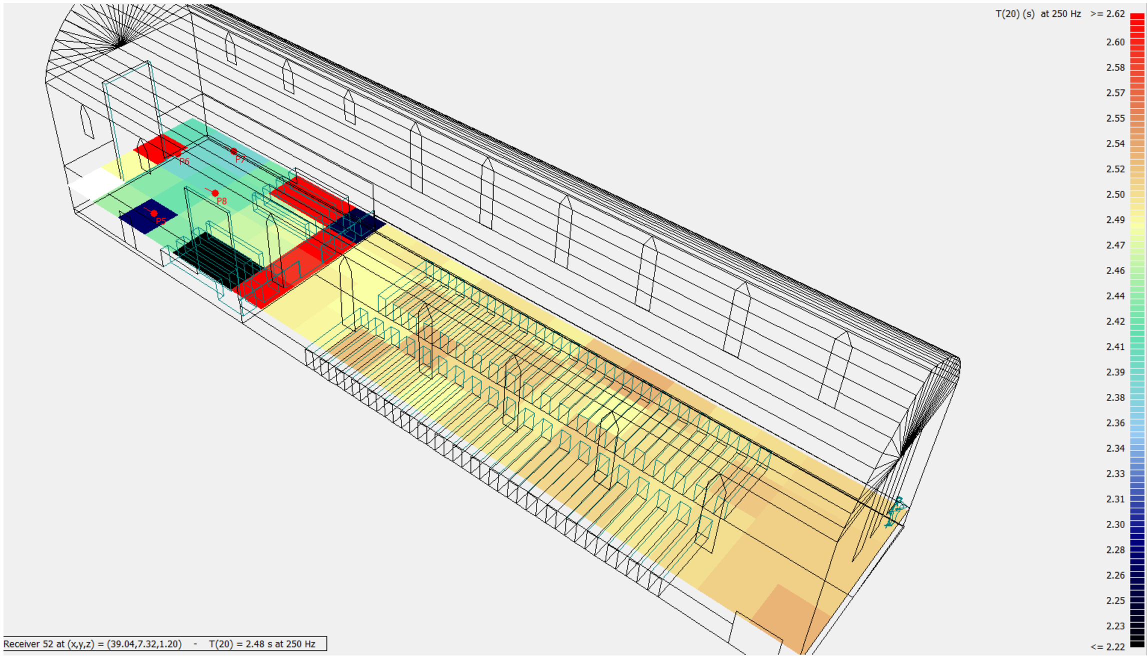


Figure 114 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 250Hz

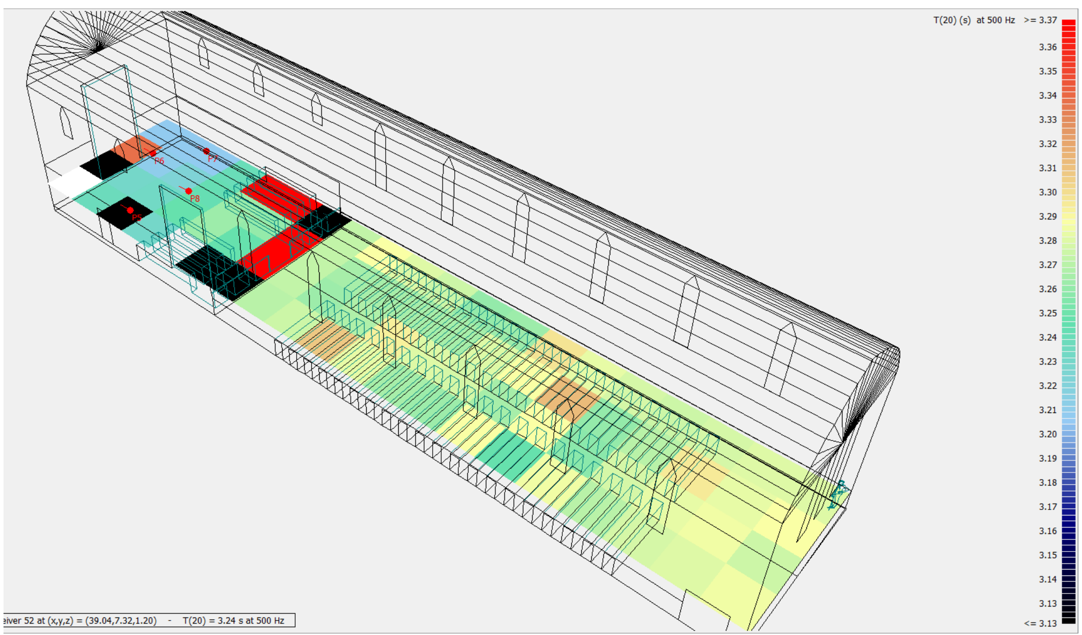


Figure 115 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 500Hz

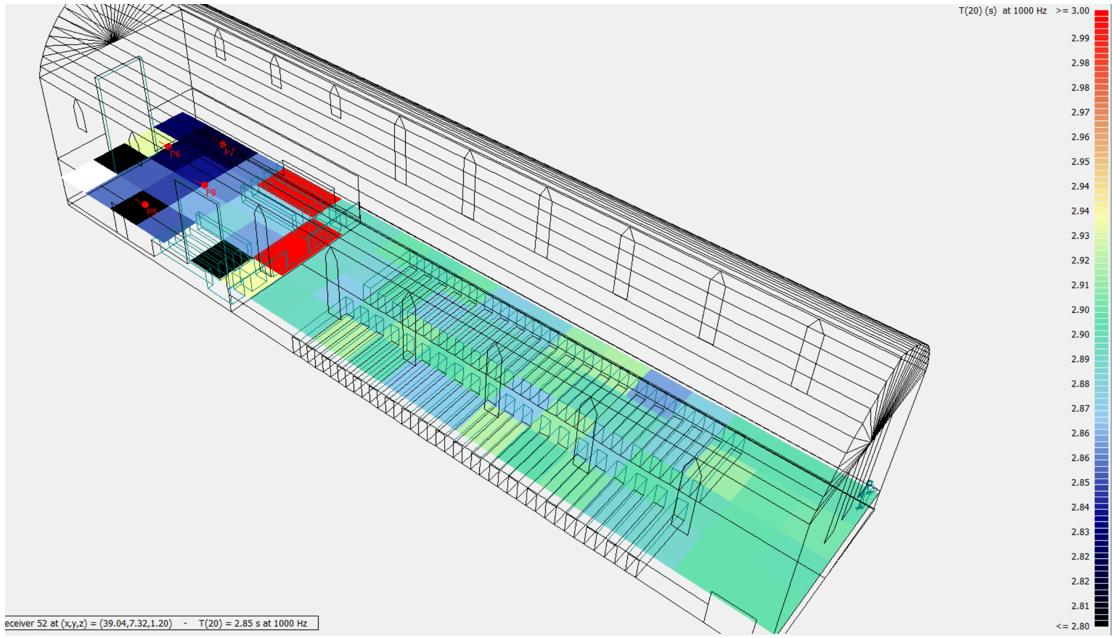


Figure 116 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 1000Hz

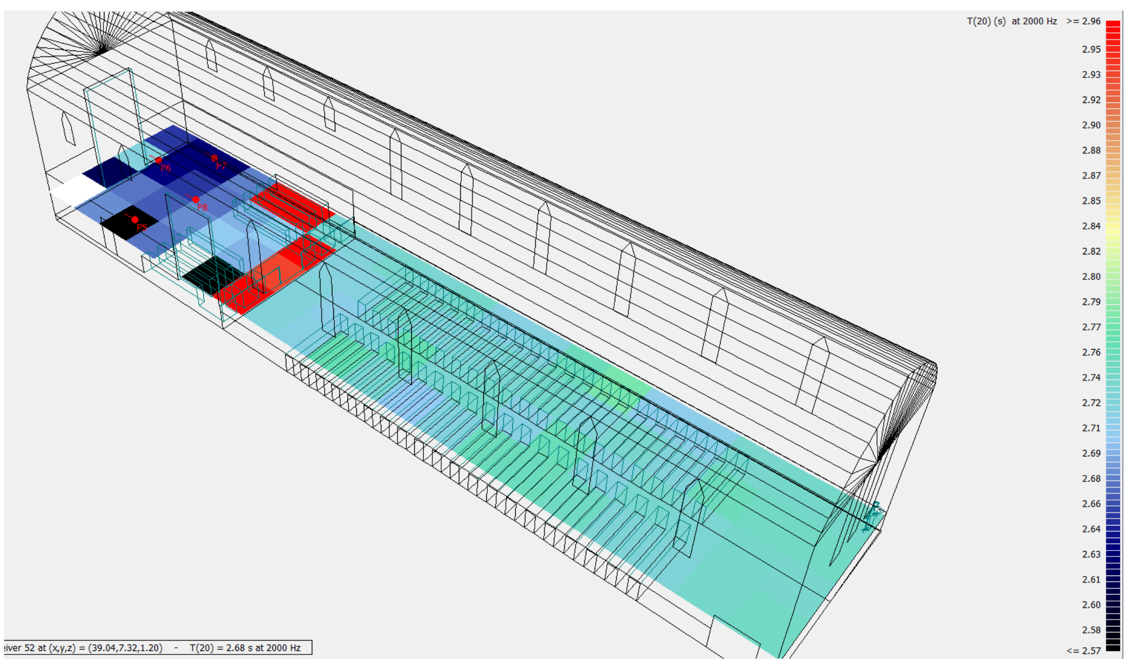


Figure 117 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 2000Hz

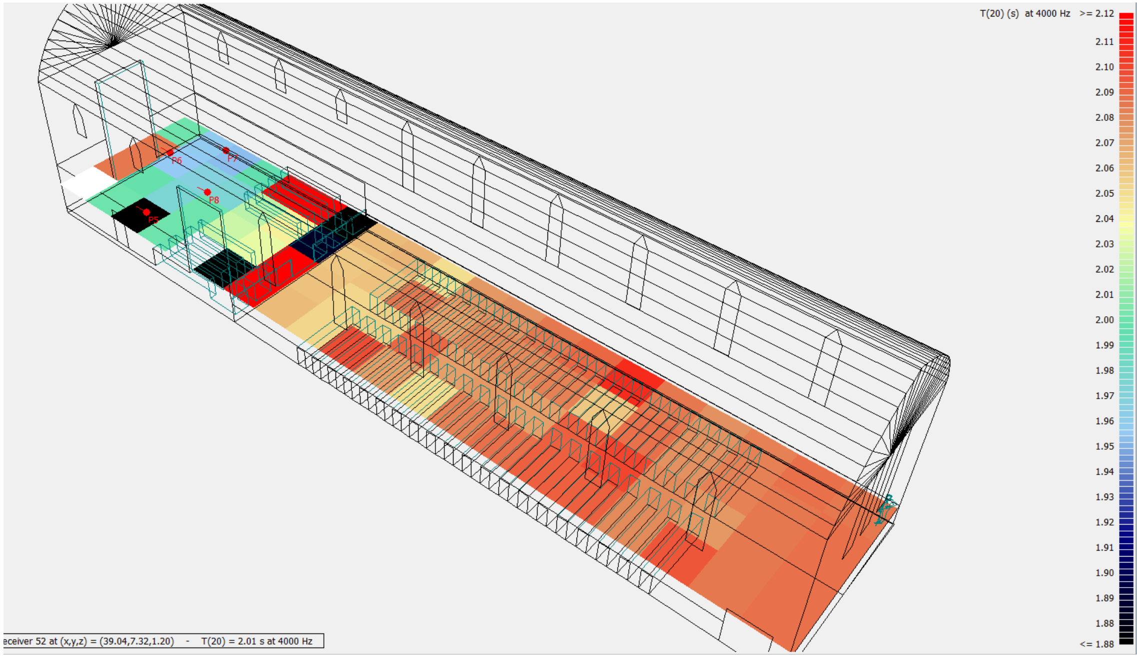


Figure 118 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 4000Hz

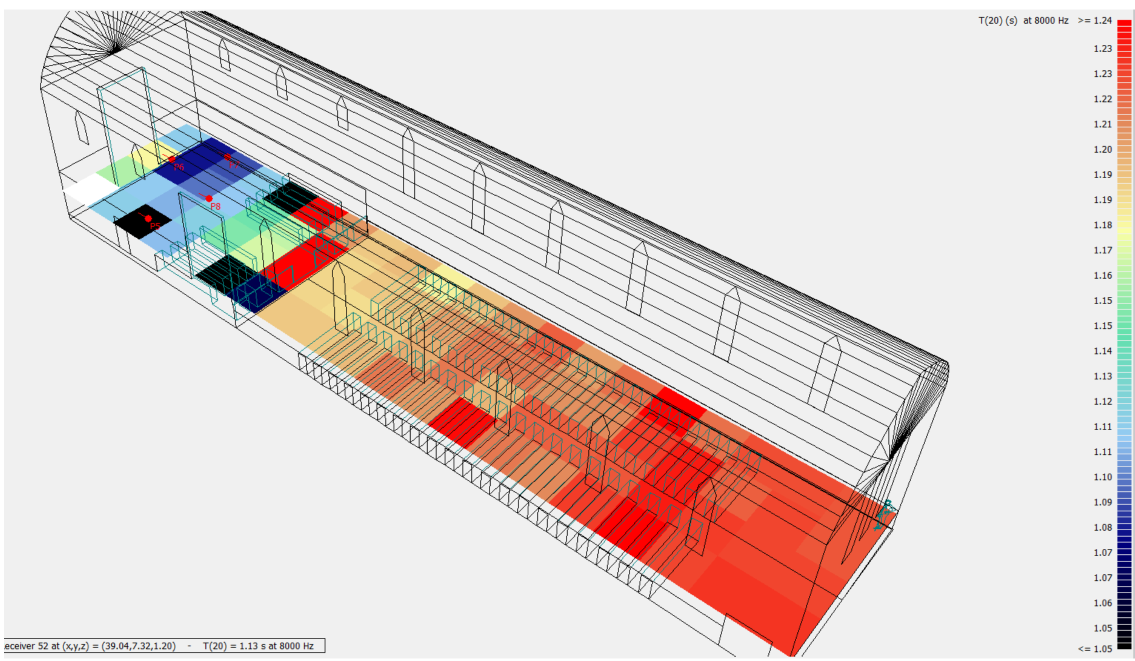


Figure 119 ODEON St. Martins - Orchestra / Musical Ensemble Location RT – 8000Hz

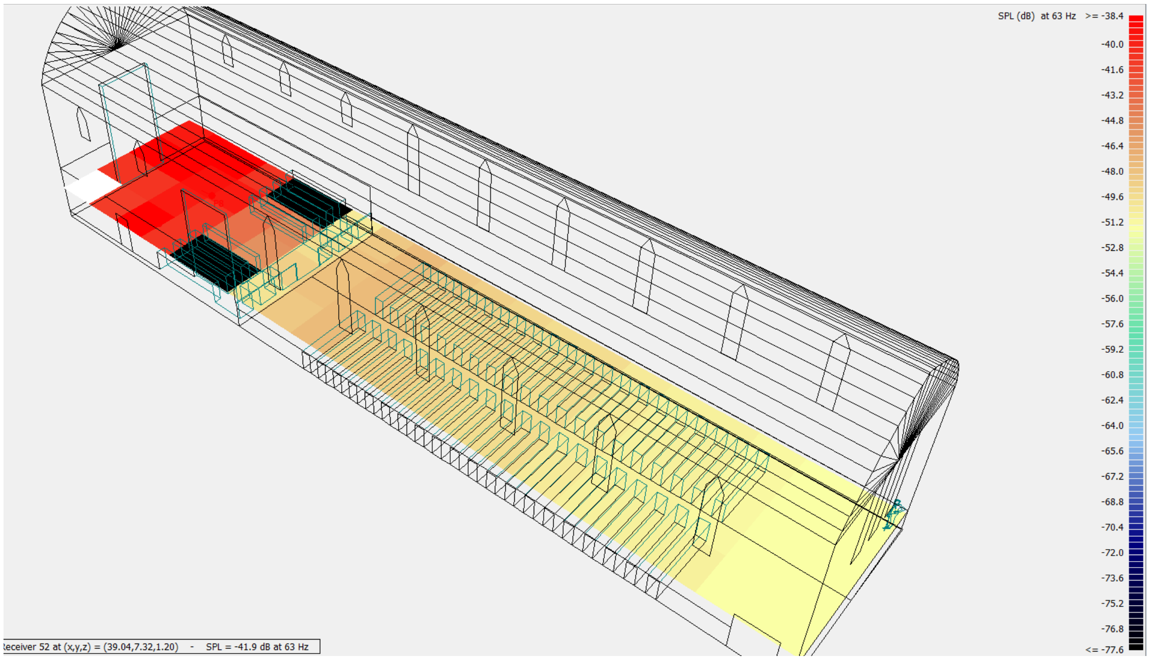


Figure 120 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 63Hz

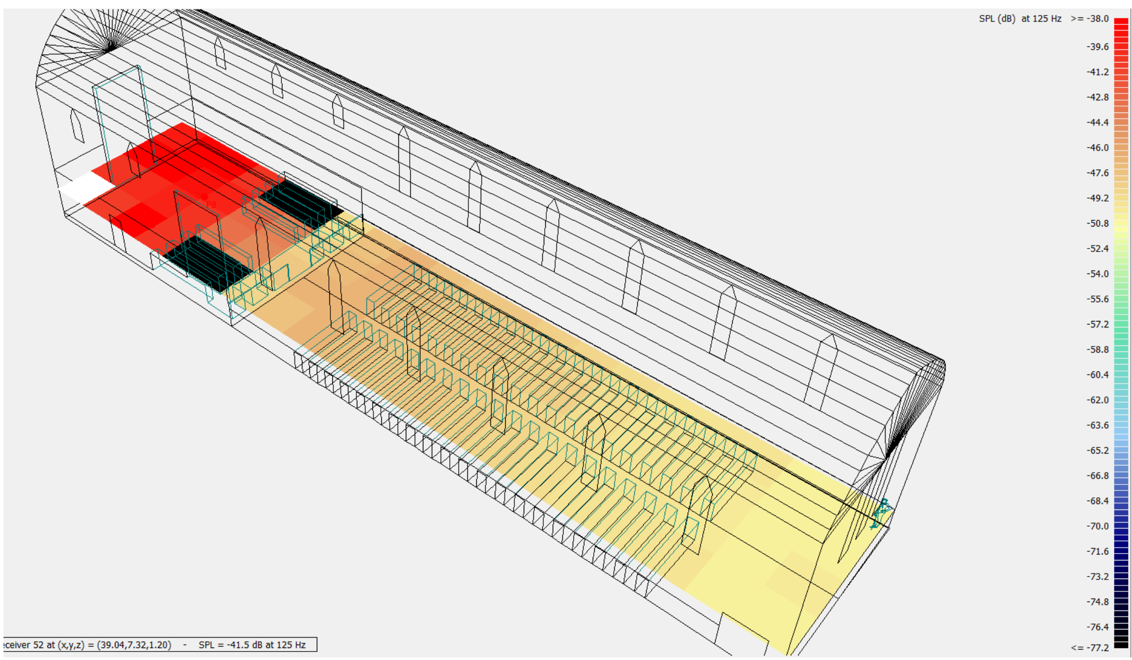


Figure 121 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 125Hz

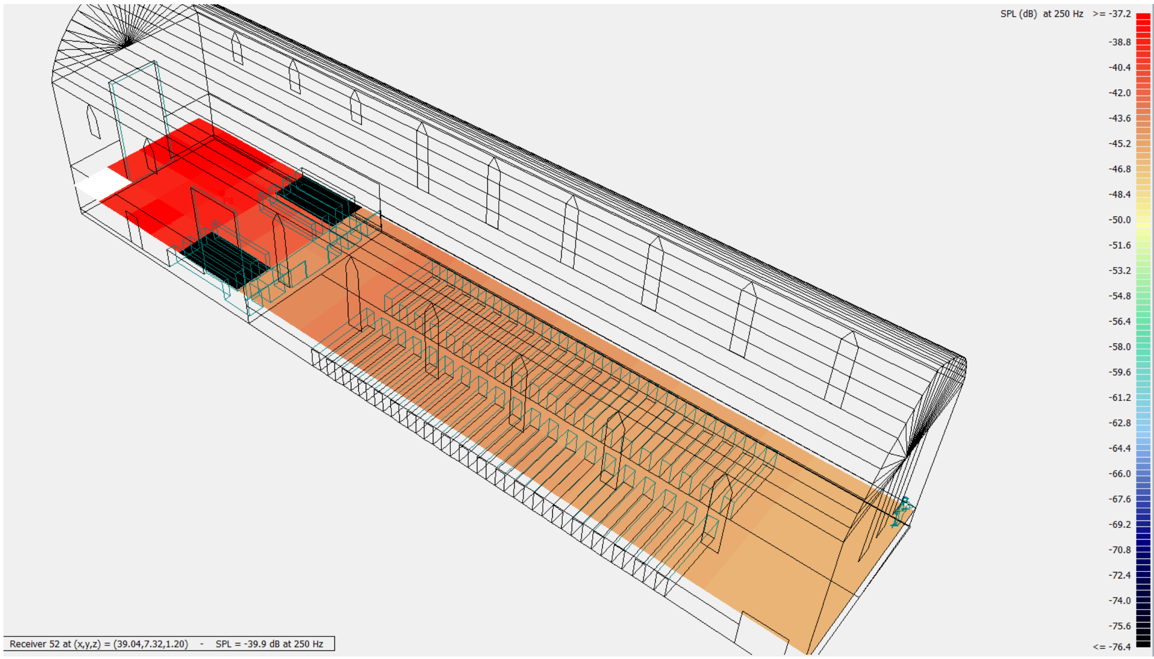


Figure 122 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 250Hz

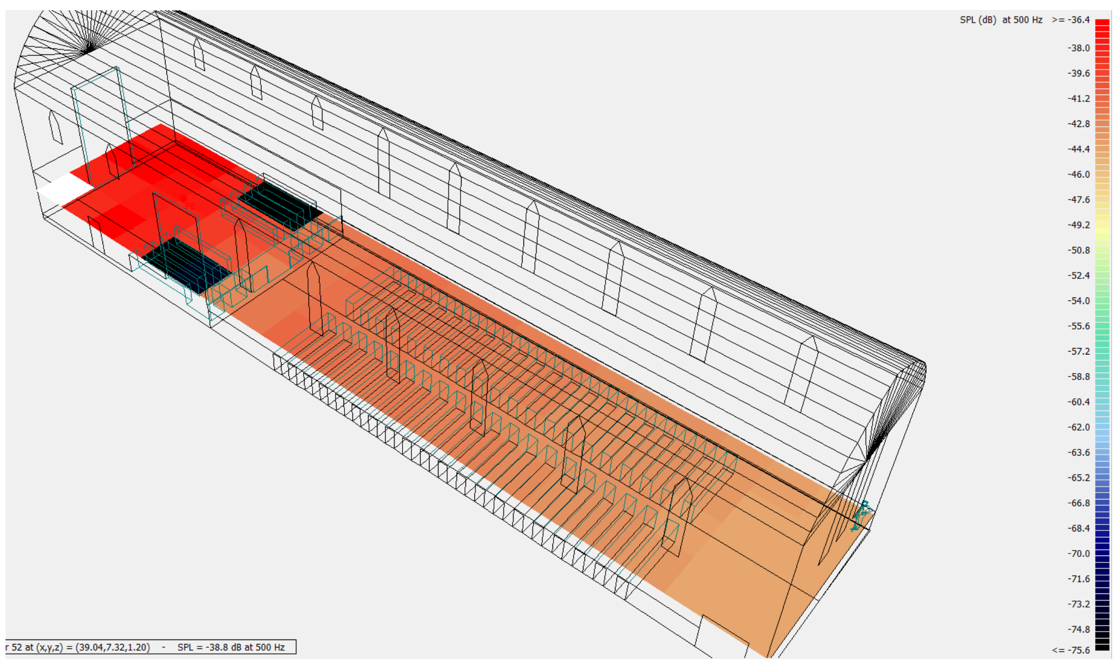


Figure 123 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 500Hz

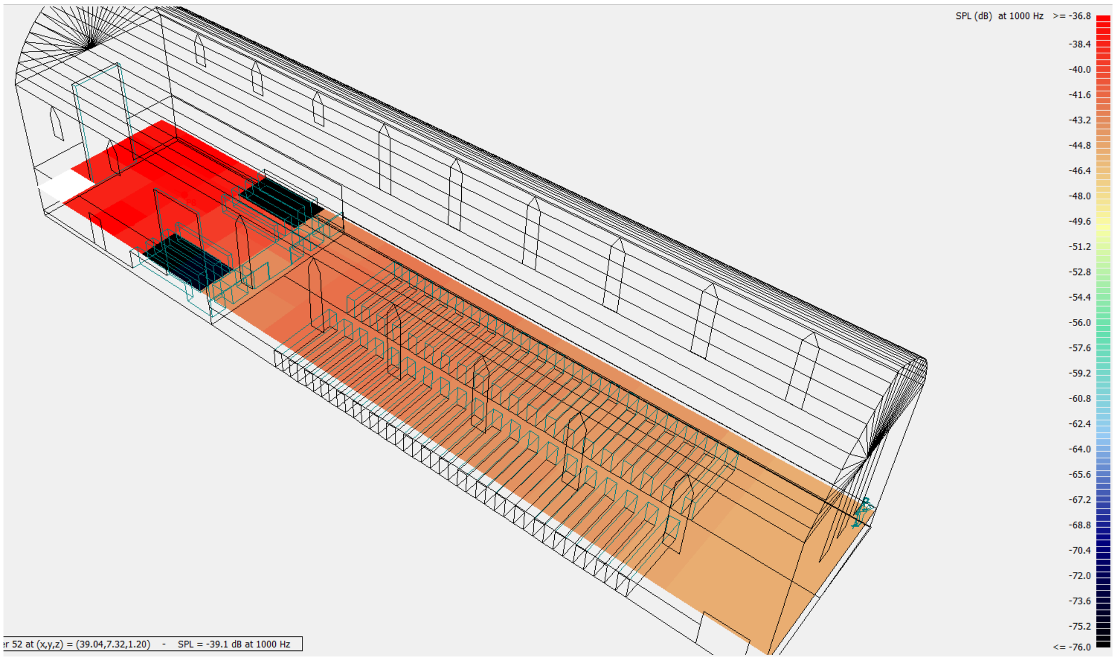


Figure 124 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 1000Hz

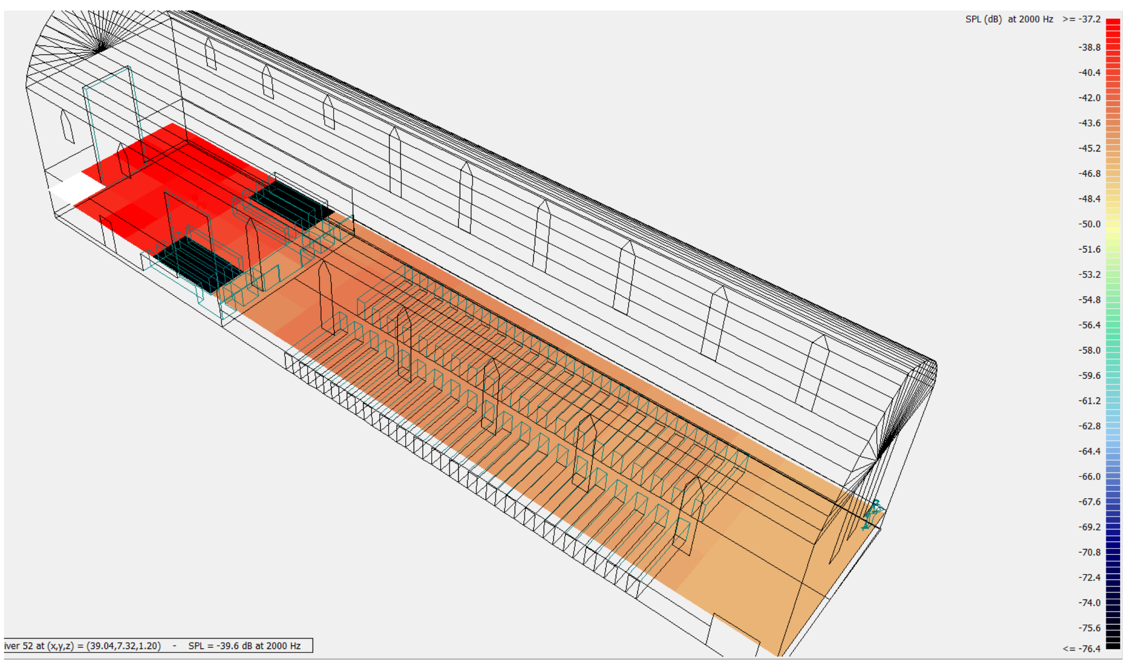


Figure 125 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 2000Hz

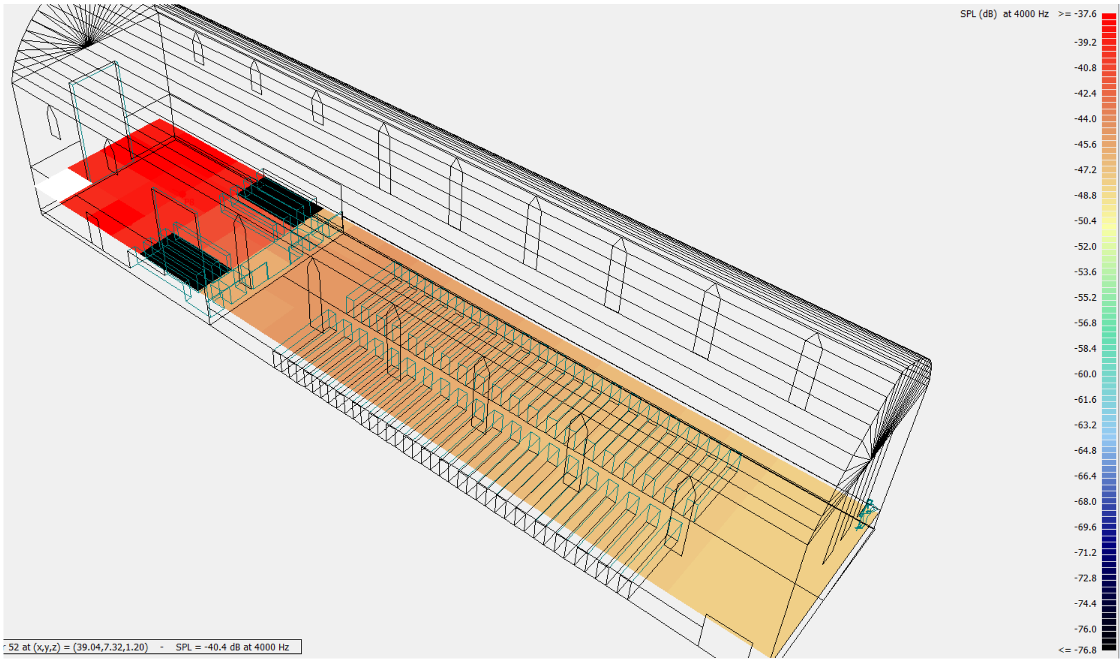


Figure 126 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 4000Hz

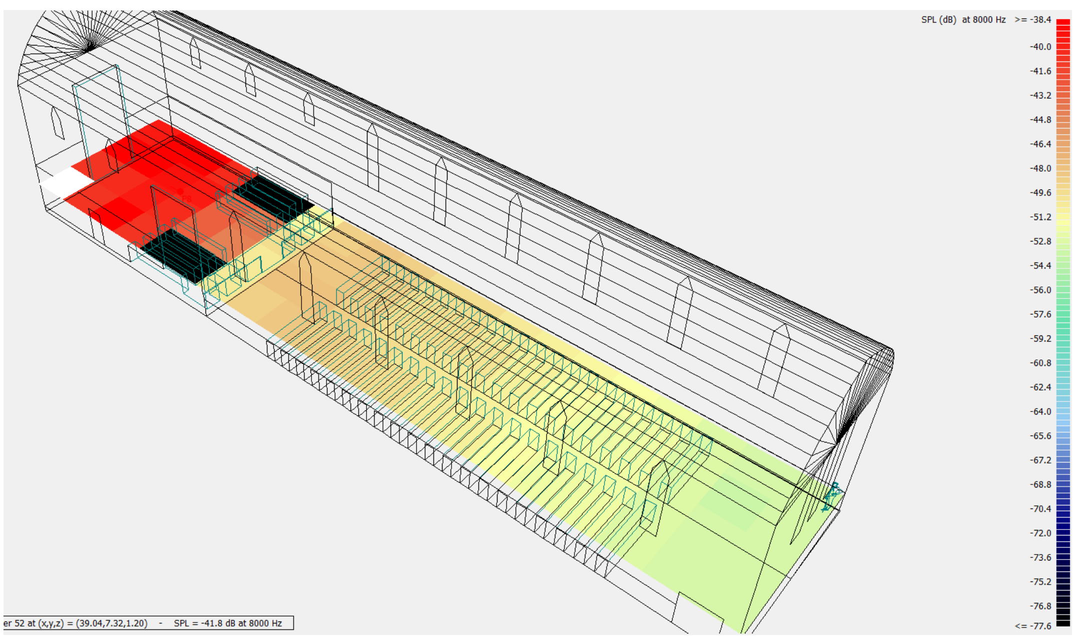


Figure 127 ODEON St. Martins - Orchestra / Musical Ensemble Location SPL – 8000Hz

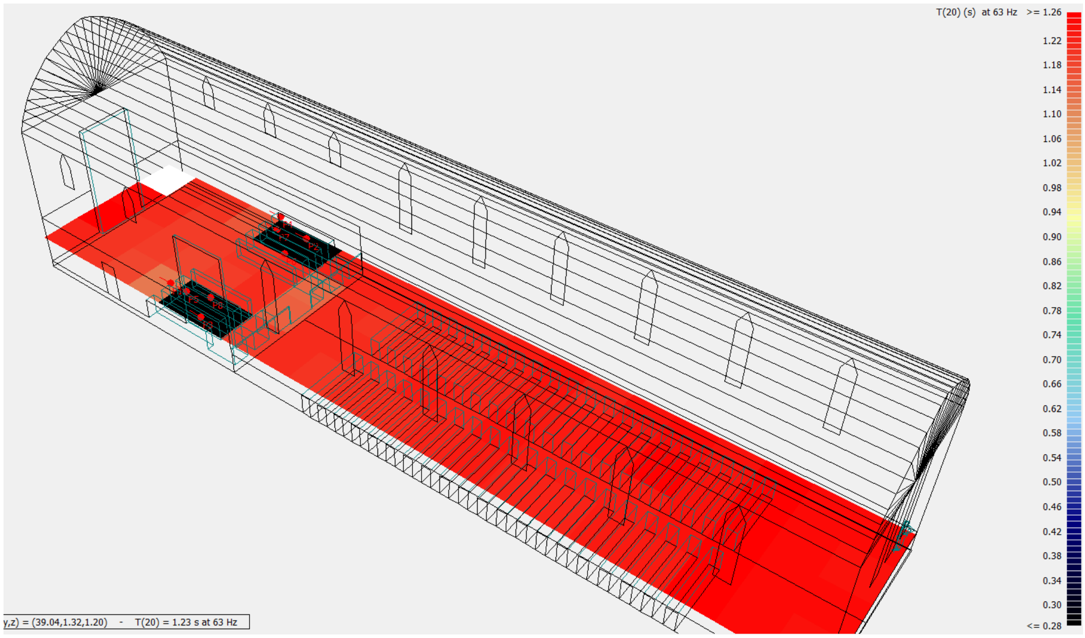


Figure 128 ODEON St. Martins - Choir Location RT – 63Hz

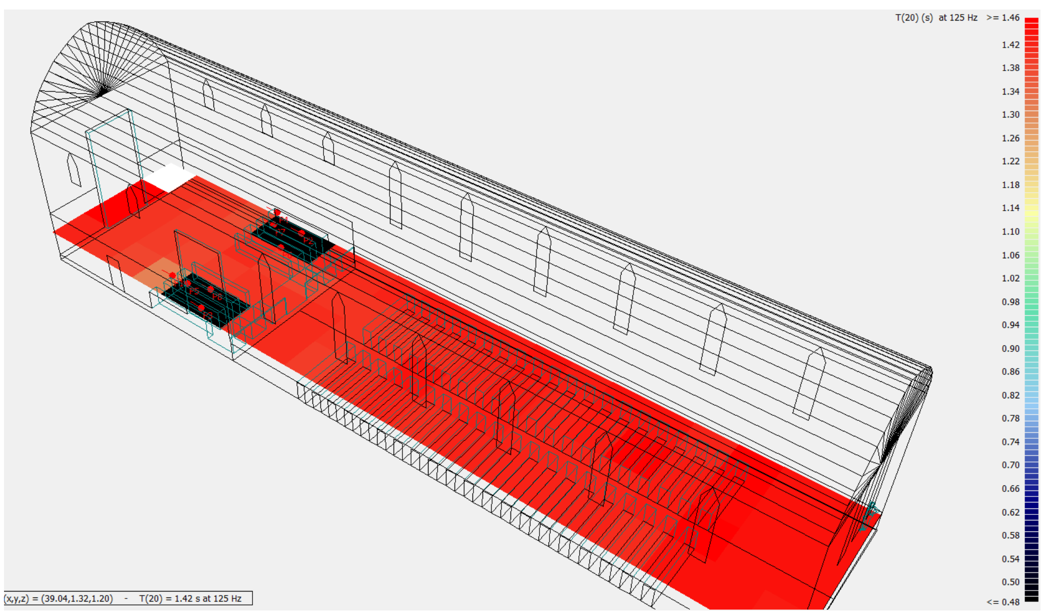


Figure 129 ODEON St. Martins - Choir Location RT – 125Hz

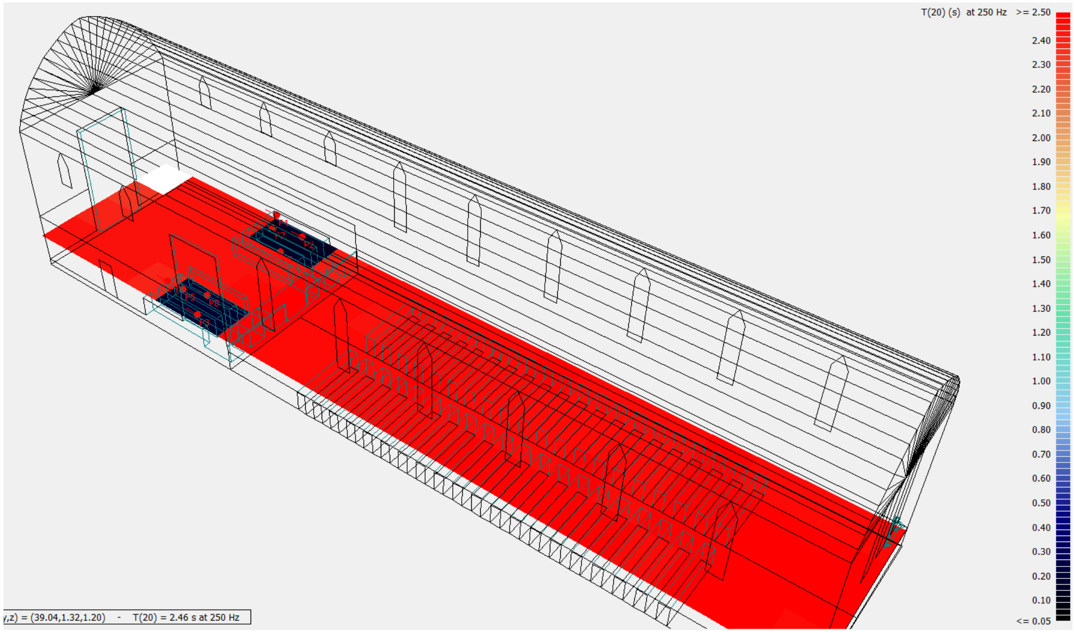


Figure 130 ODEON St. Martins - Choir Location RT – 250Hz

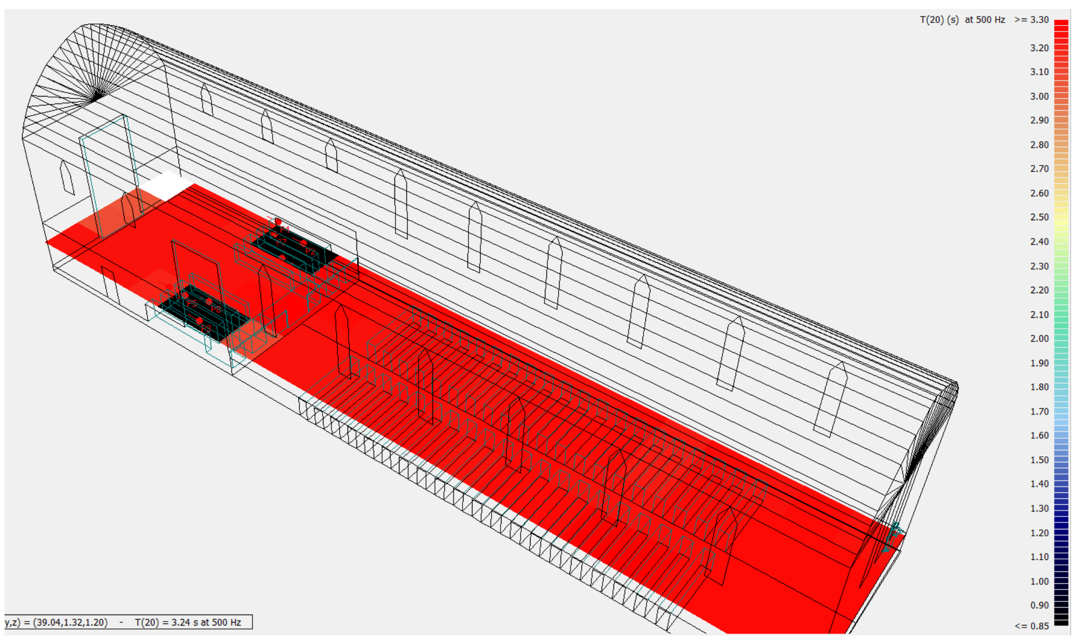


Figure 131 ODEON St. Martins - Choir Location RT – 500Hz

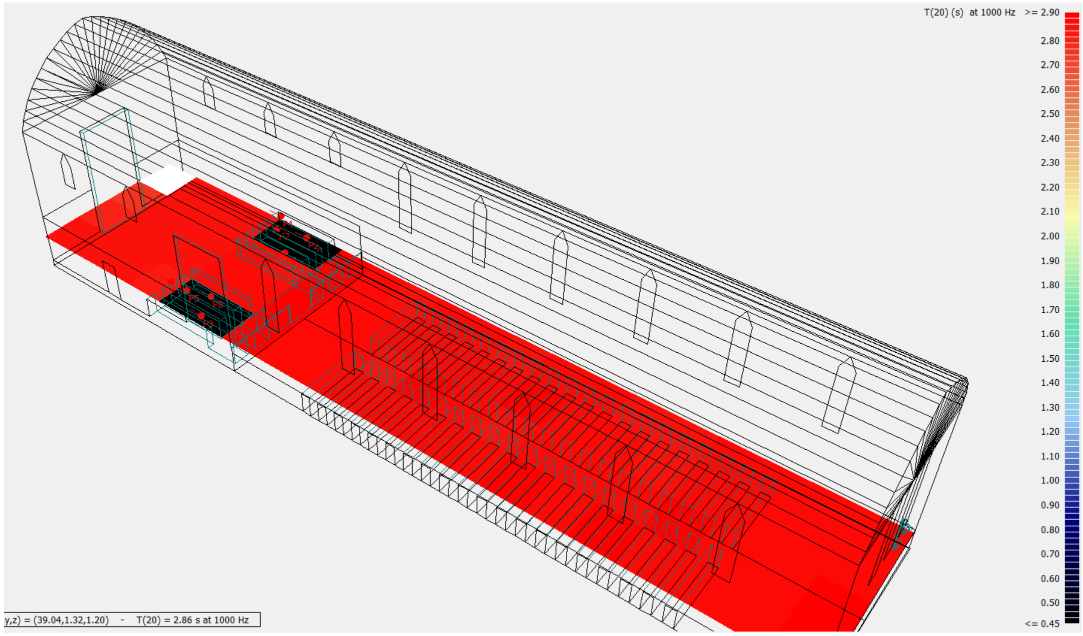


Figure 132 ODEON St. Martins - Choir Location RT – 1000Hz

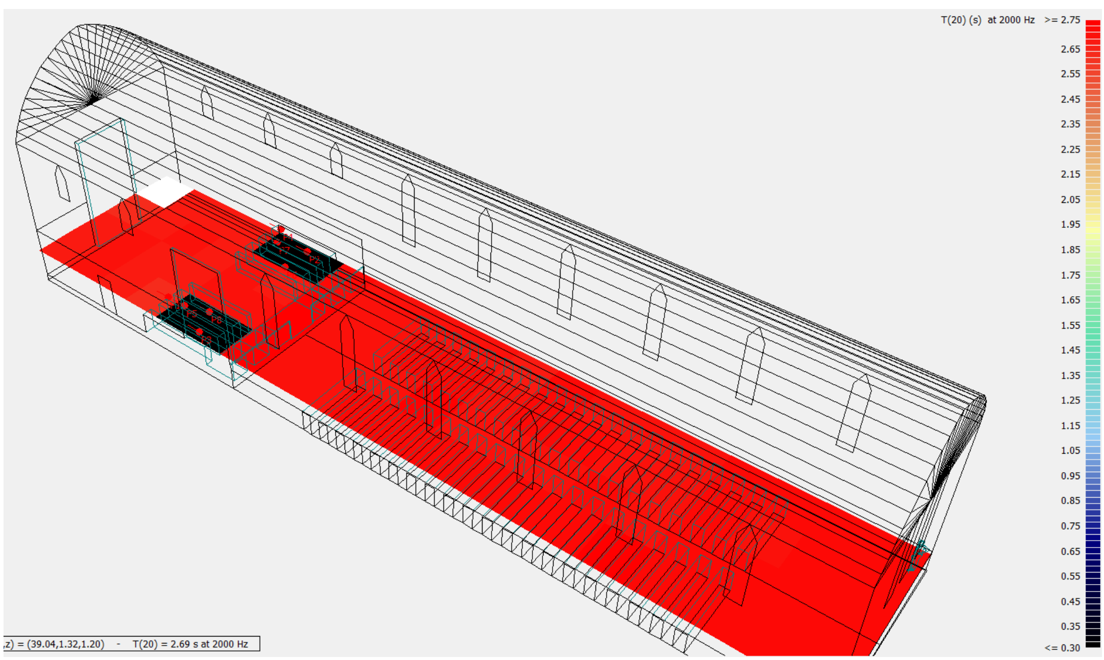


Figure 133 ODEON St. Martins - Choir Location RT – 2000Hz

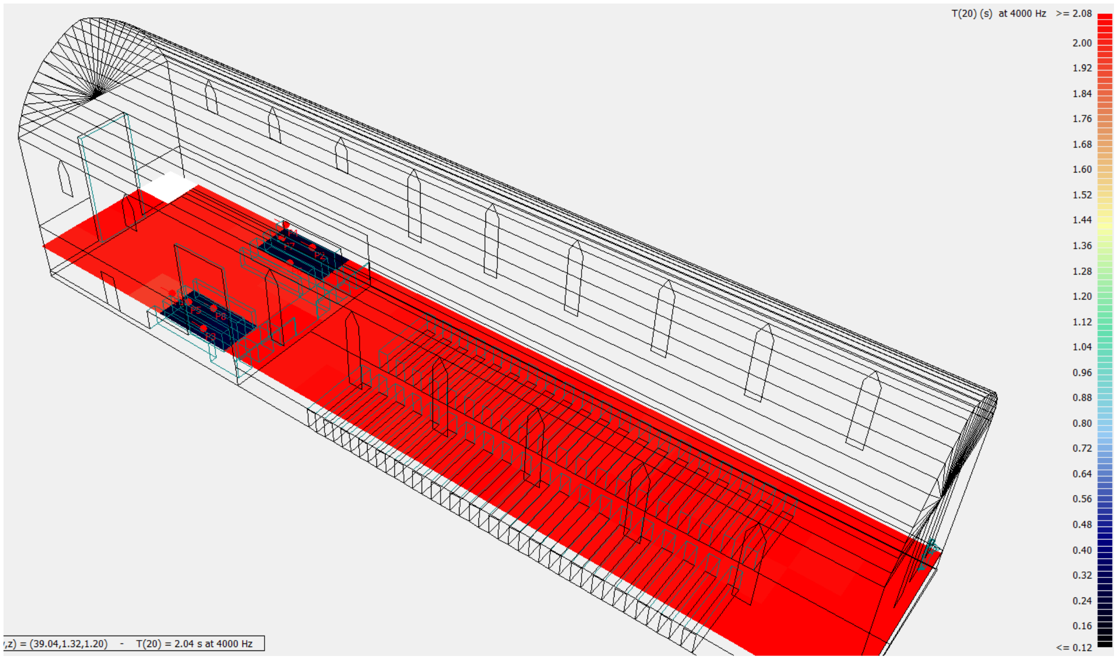


Figure 134 ODEON St. Martins - Choir Location RT – 4000Hz

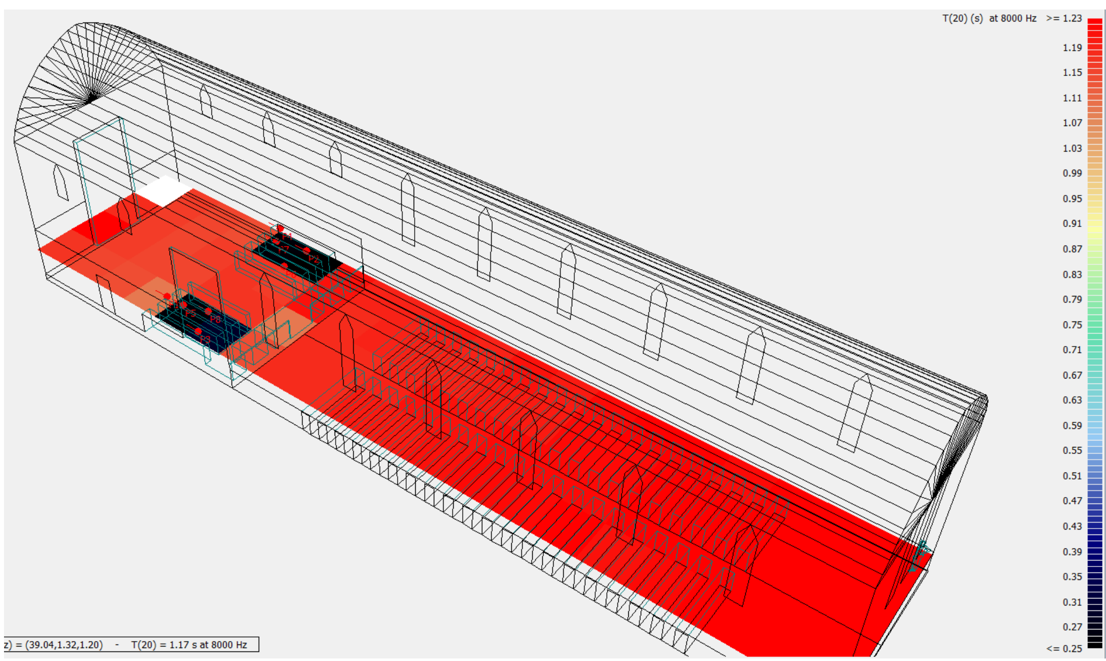


Figure 135 ODEON St. Martins - Choir Location RT – 8000Hz

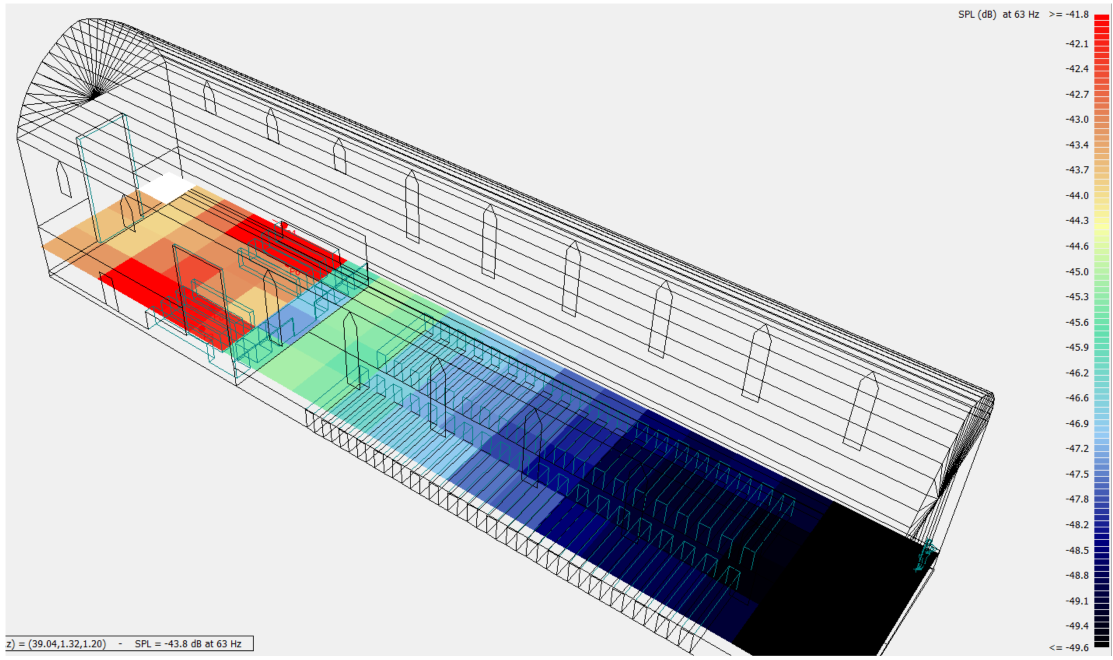


Figure 136 ODEON St. Martins - Choir Location SPL – 63Hz

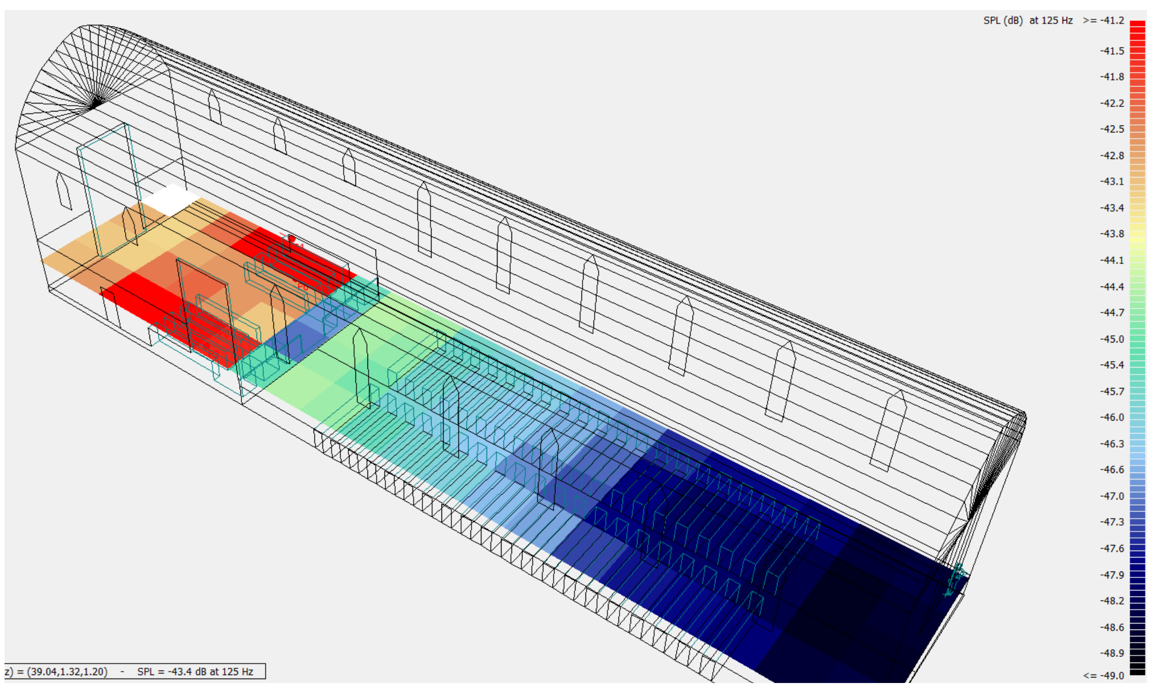


Figure 137 ODEON St. Martins - Choir Location SPL – 125Hz

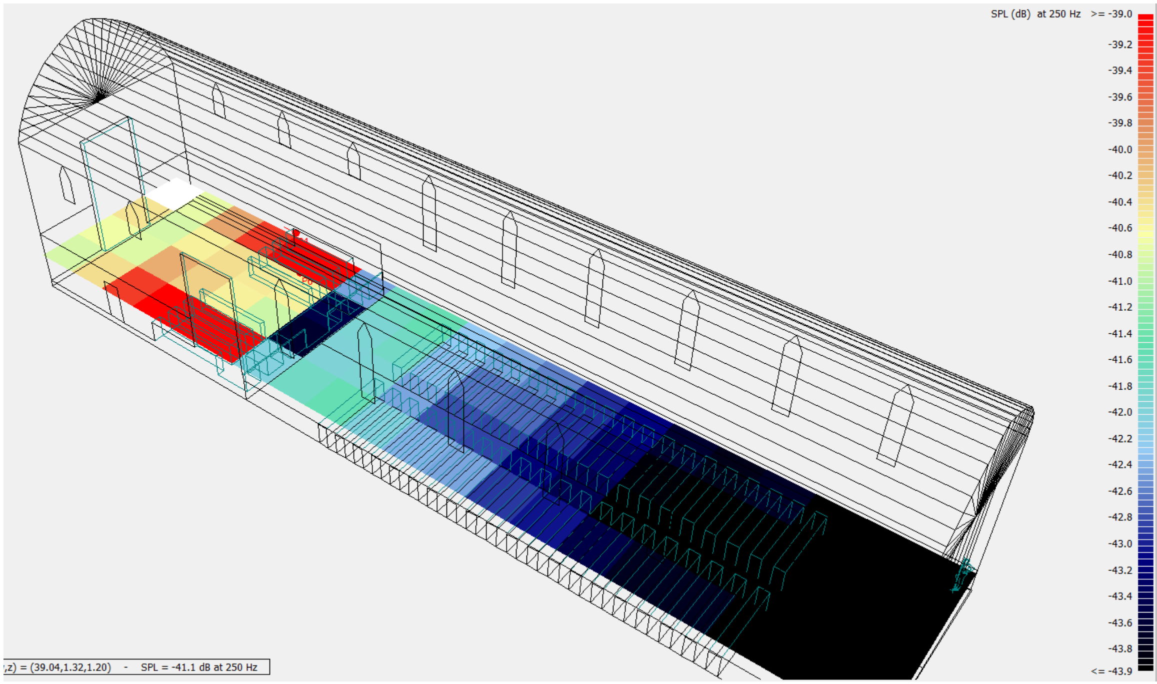


Figure 138 ODEON St. Martins - Choir Location SPL – 250Hz

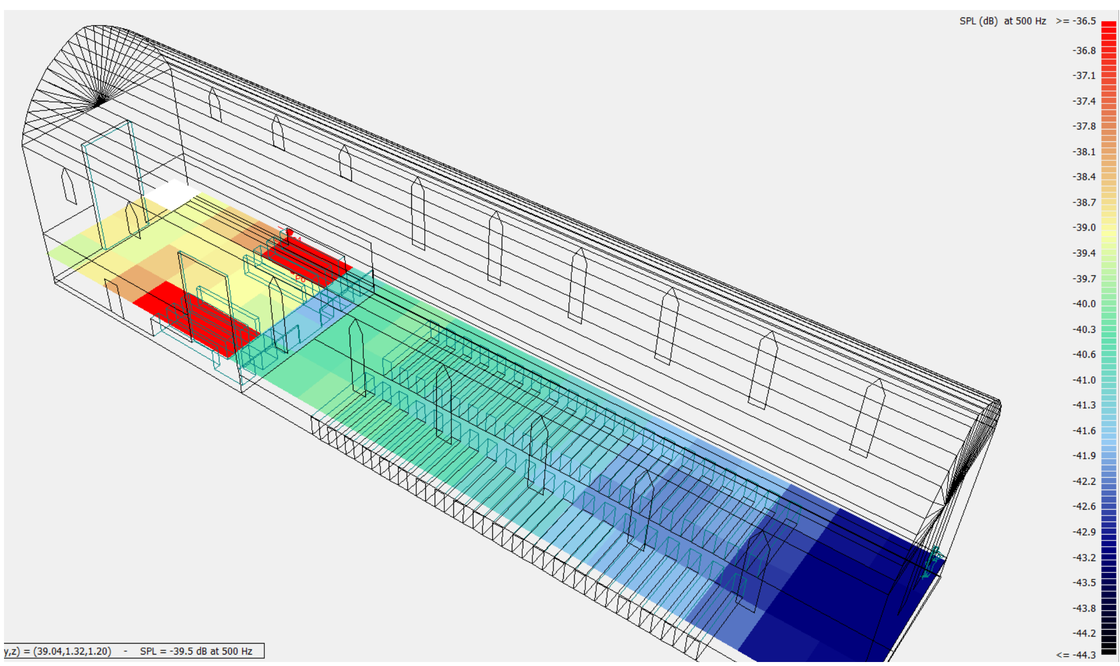


Figure 139 ODEON St. Martins - Choir Location SPL – 500Hz

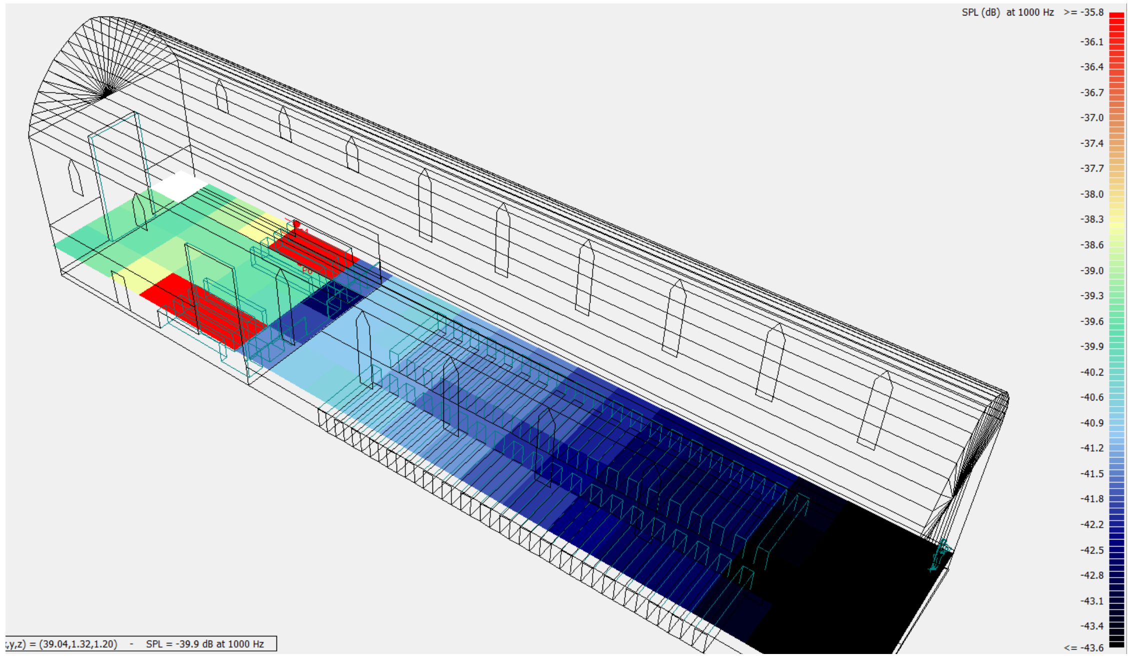


Figure 140 ODEON St. Martins - Choir Location SPL – 1000Hz

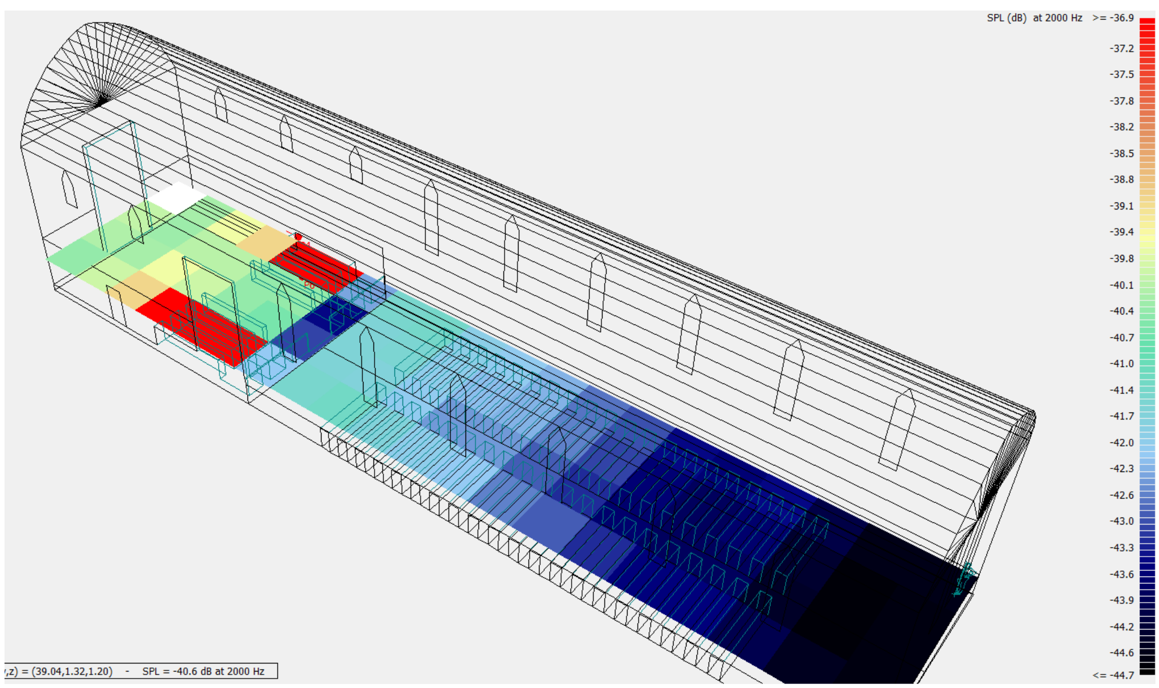


Figure 141 ODEON St. Martins - Choir Location SPL – 2000Hz

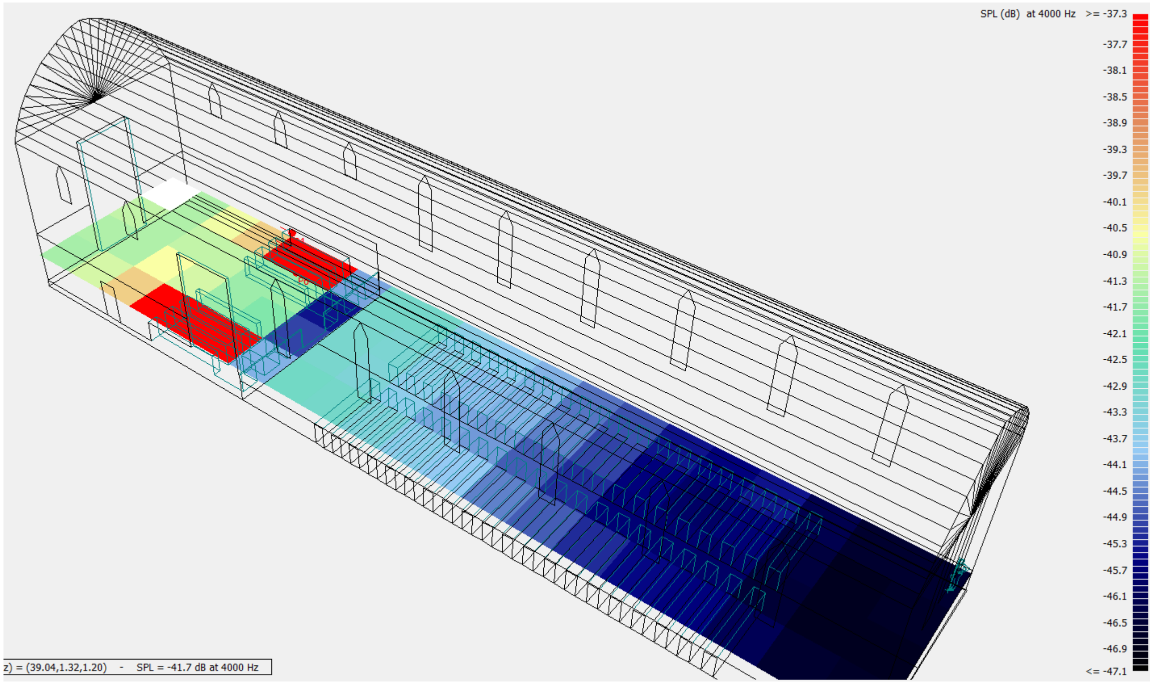


Figure 142 ODEON St. Martins - Choir Location SPL – 4000Hz

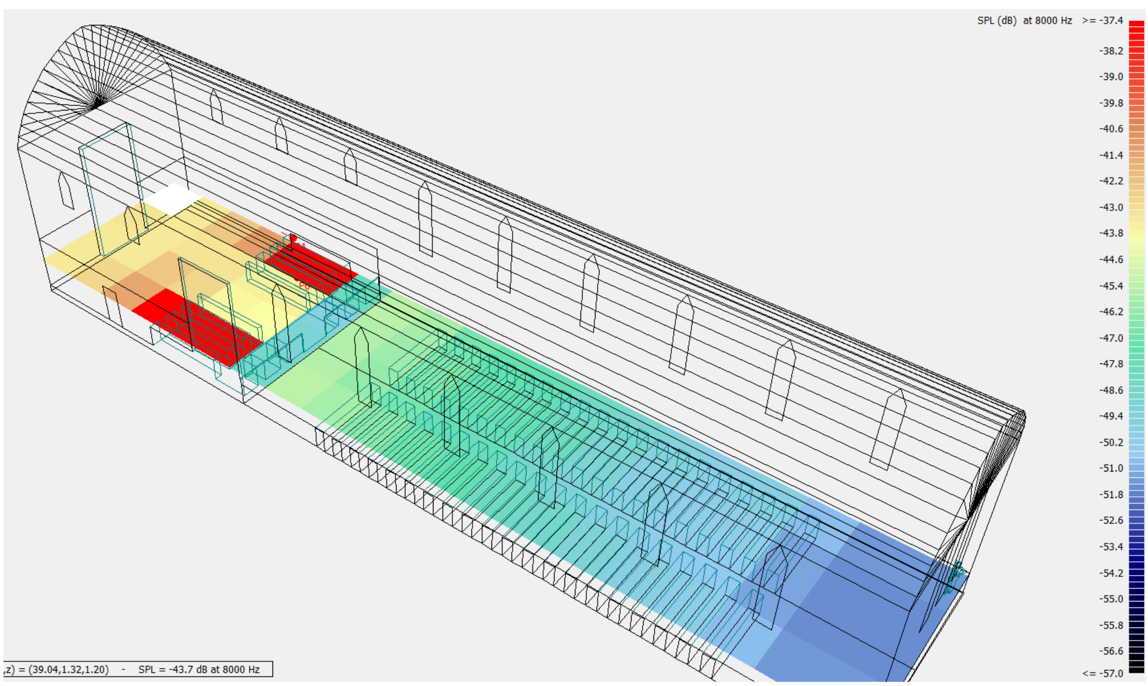


Figure 143 ODEON St. Martins - Choir Location SPL – 8000Hz

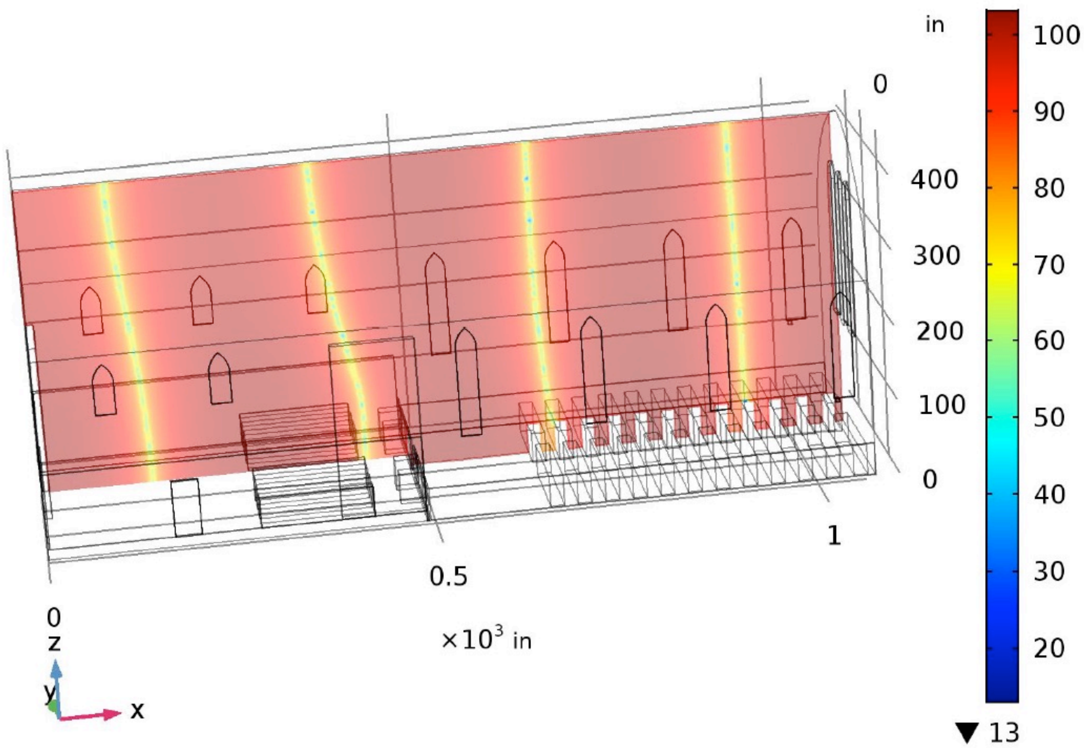


Figure 144: St. Martins – One source 25 Hz

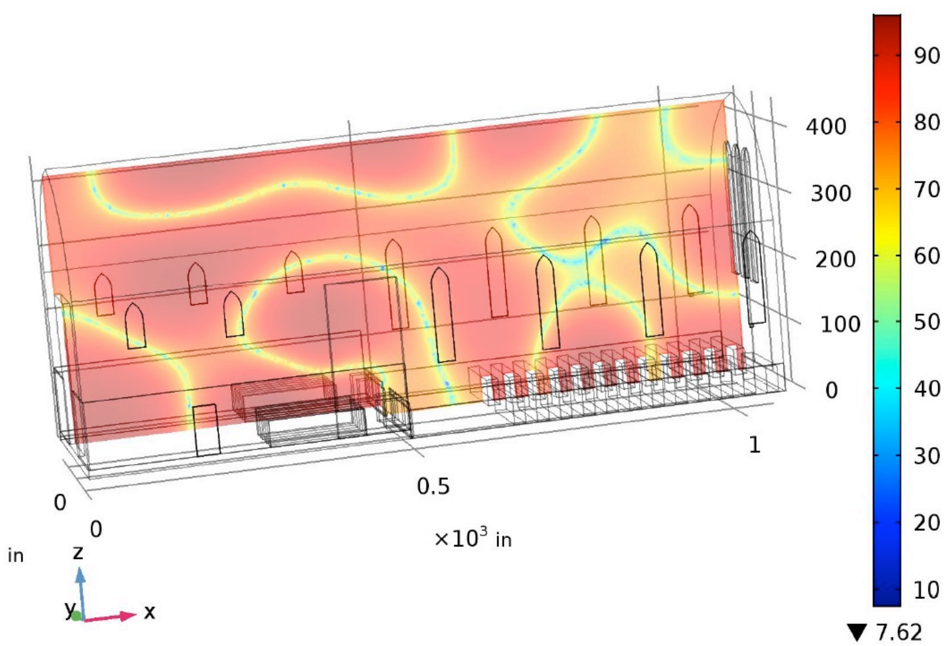


Figure 145: St. Martins – One source 50 Hz

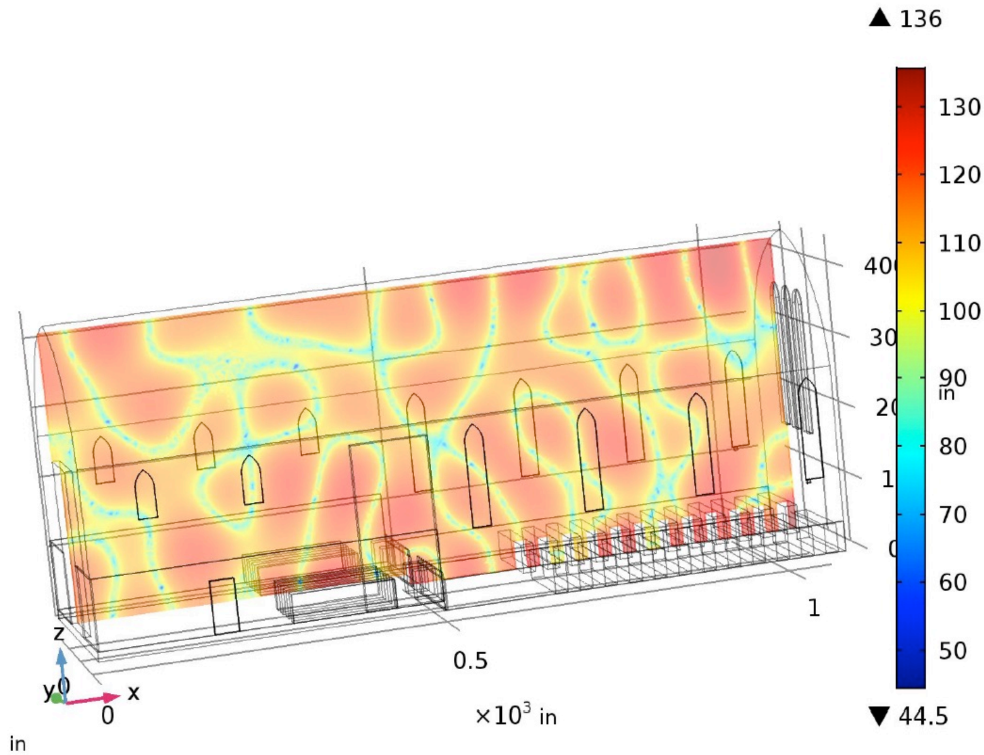


Figure 146: St. Martins – One source 100 Hz

Figure 147: St. Martins – Three sources 25 Hz

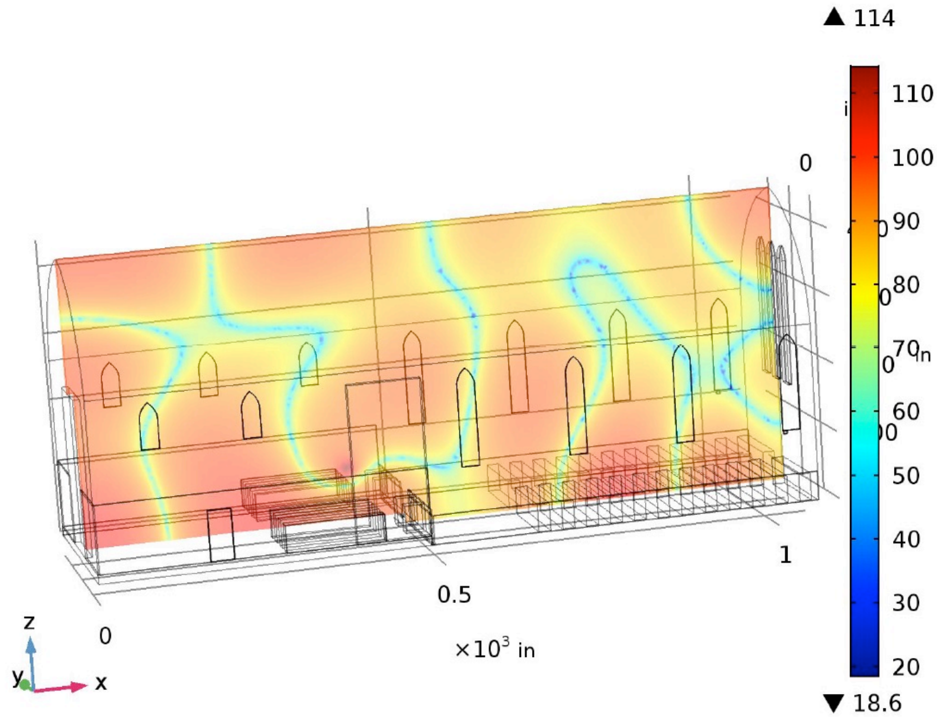


Figure 148: St. Martins – Three sources 50 Hz

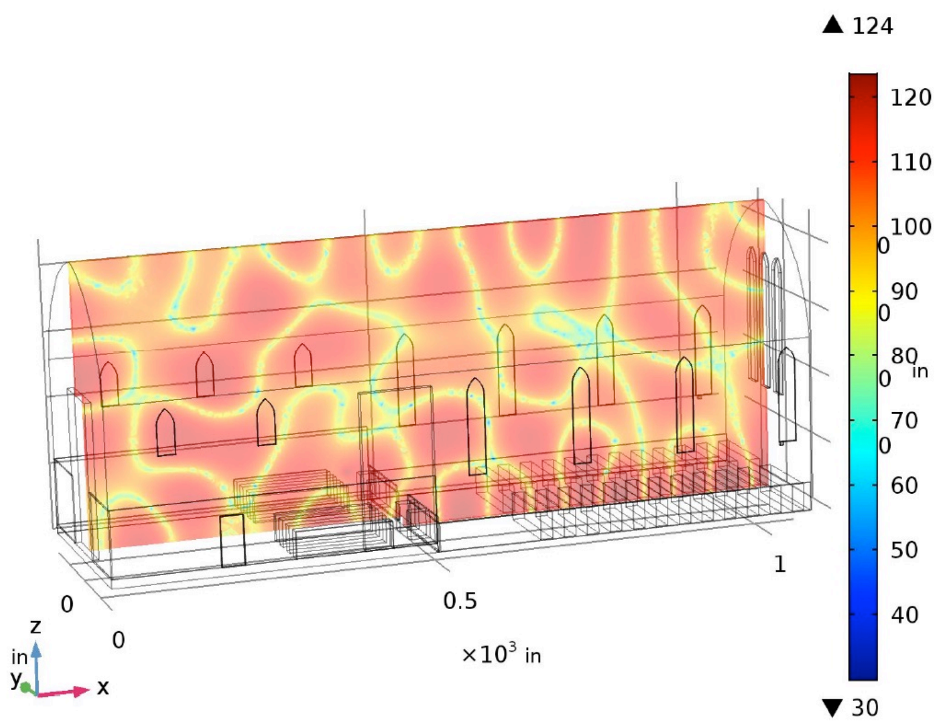


Figure 149: St. Martins – Three sources 100 Hz

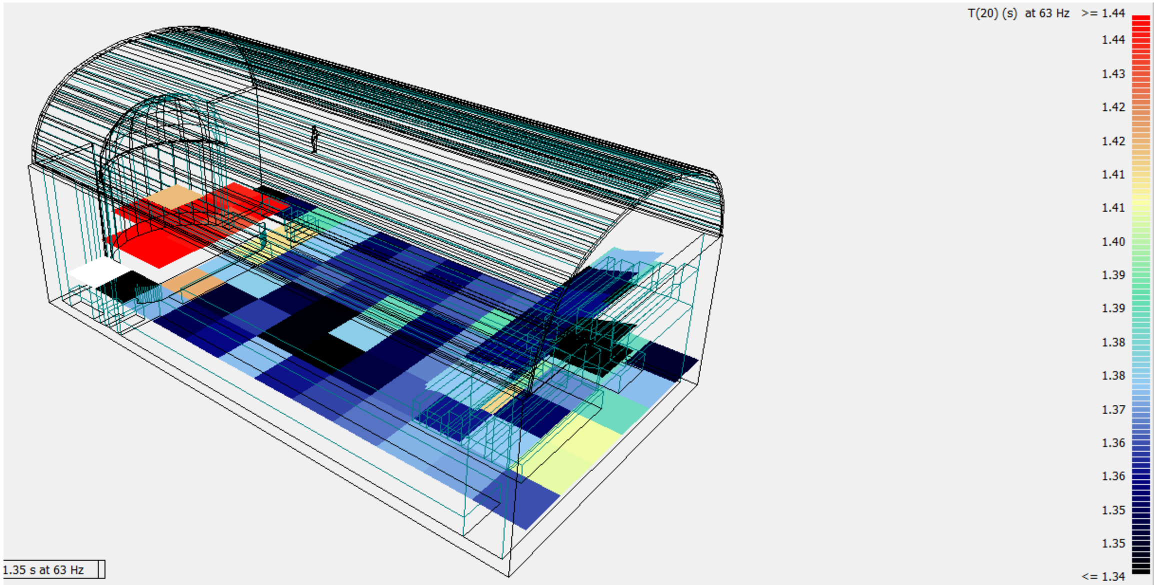


Figure 150 ODEON Wigmore Hall - Source at back of dome RT – 63Hz

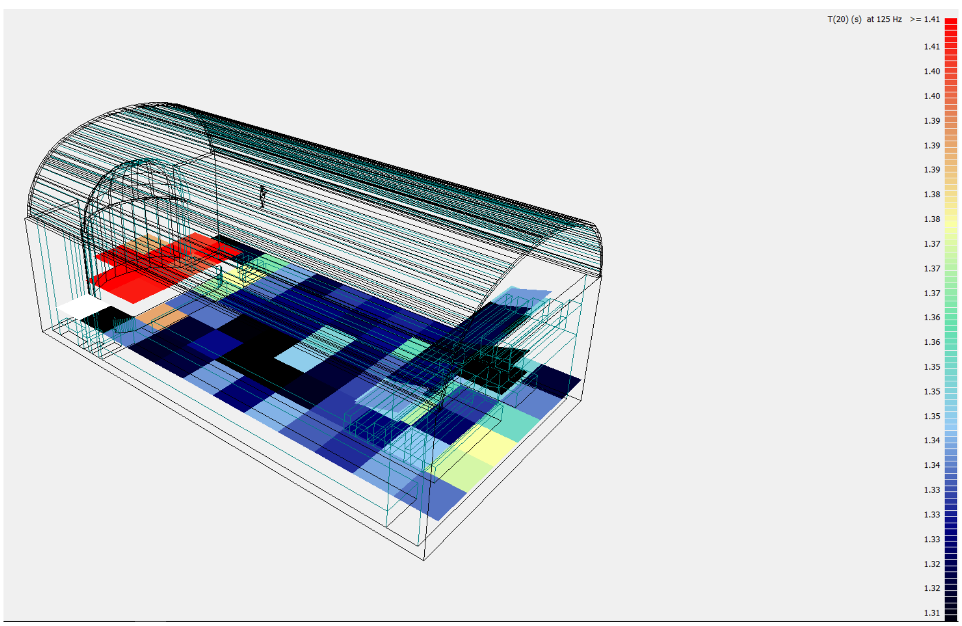


Figure 151 ODEON Wigmore Hall - Source at back of dome RT – 125Hz

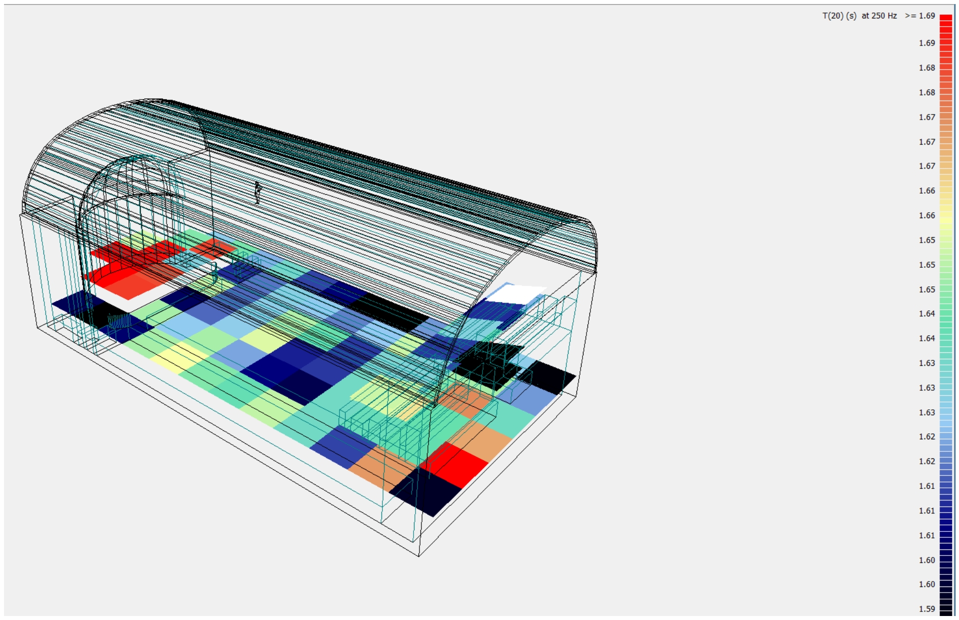


Figure 152 ODEON Wigmore Hall - Source at back of dome RT – 250Hz

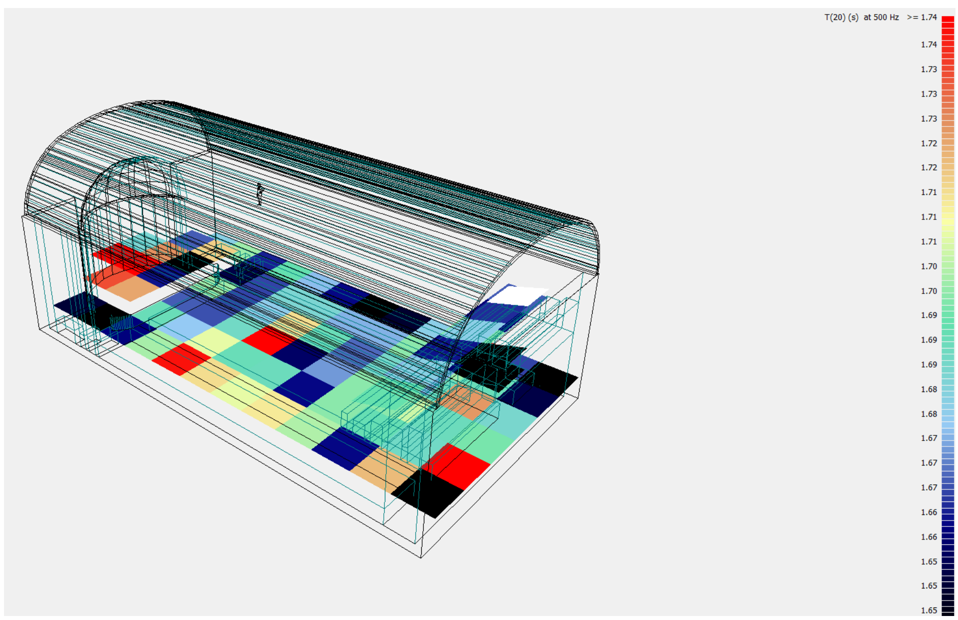


Figure 153 ODEON Wigmore Hall - Source at back of dome RT – 500Hz

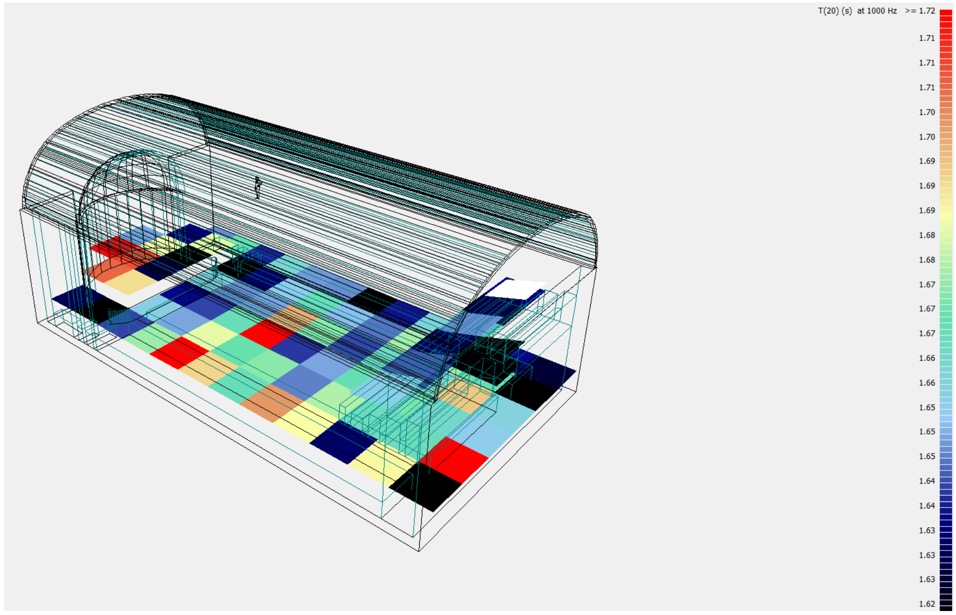


Figure 154 ODEON Wigmore Hall - Source at back of dome RT – 1000Hz

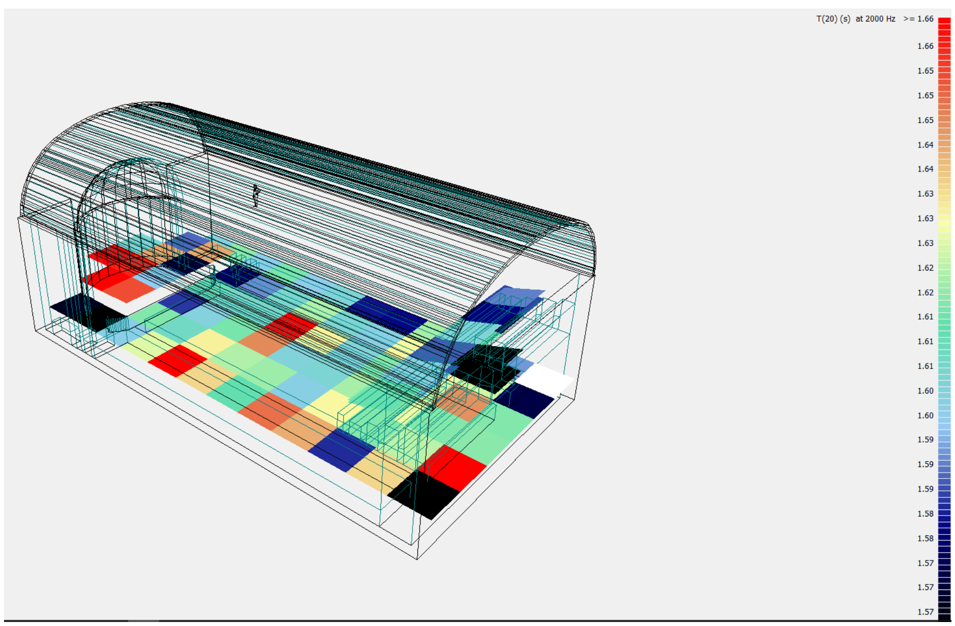


Figure 155 ODEON Wigmore Hall - Source at back of dome RT – 2000Hz

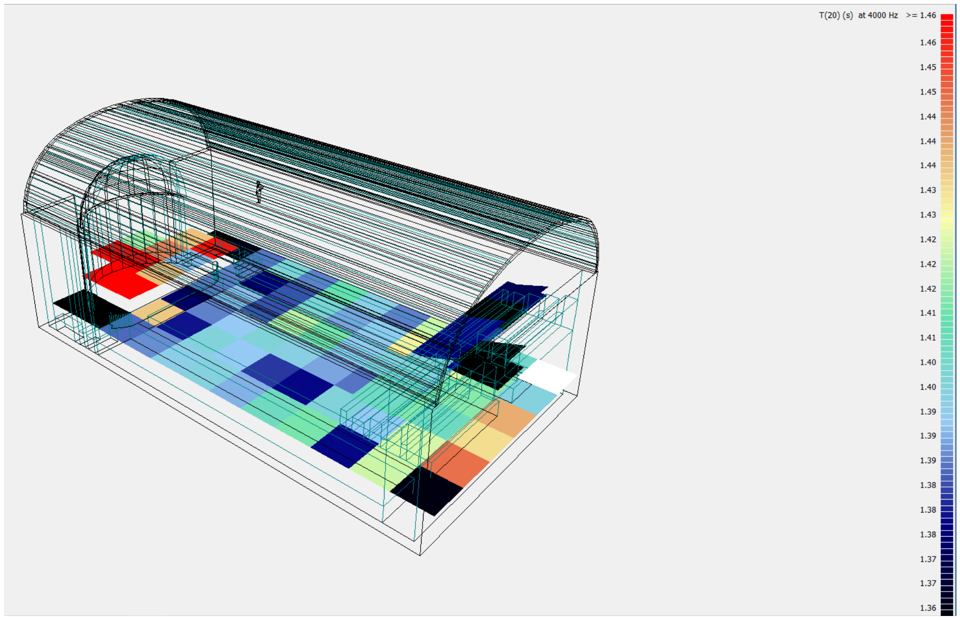


Figure 156 ODEON Wigmore Hall - Source at back of dome RT – 4000Hz

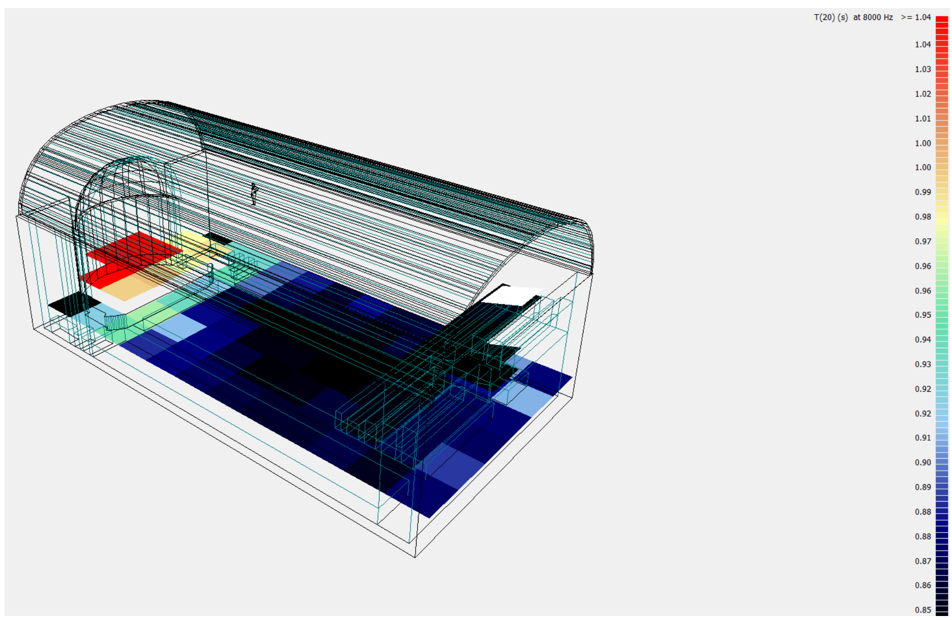


Figure 157 ODEON Wigmore Hall - Source at back of dome RT – 8000Hz

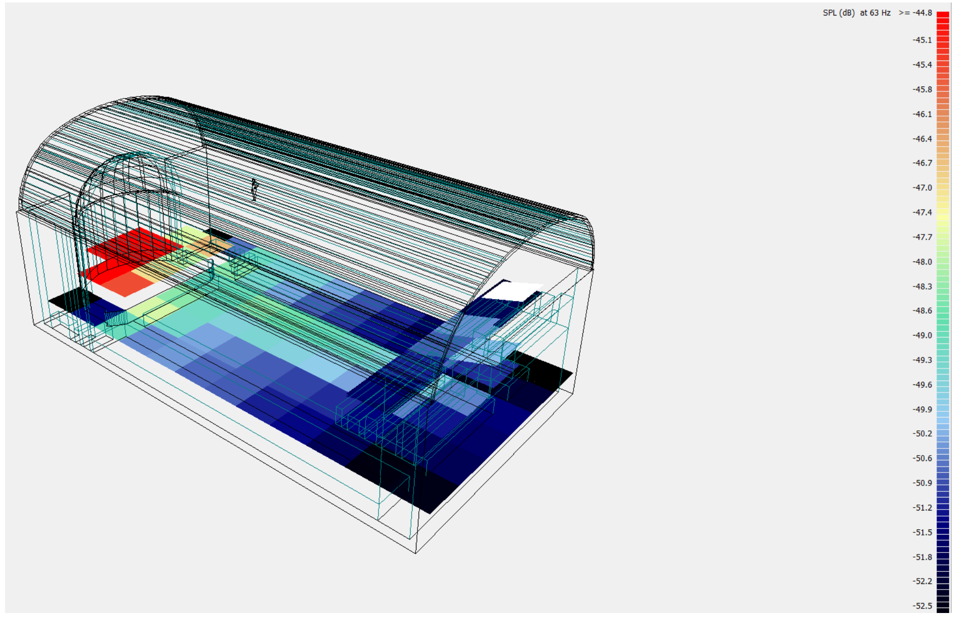


Figure 158 ODEON Wigmore Hall - Source at back of dome SPL – 63Hz

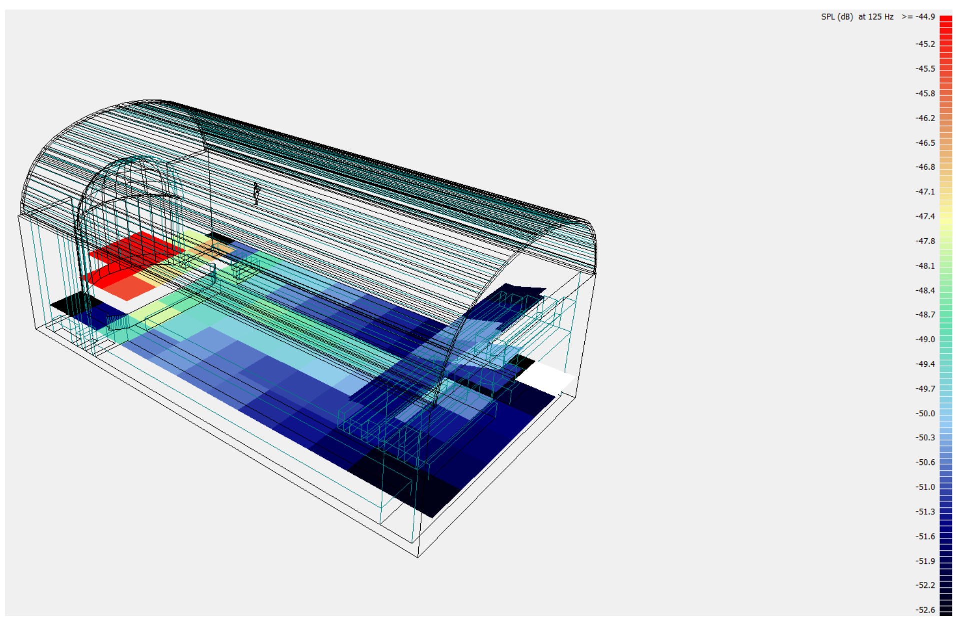


Figure 159 ODEON Wigmore Hall - Source at back of dome SPL – 125Hz

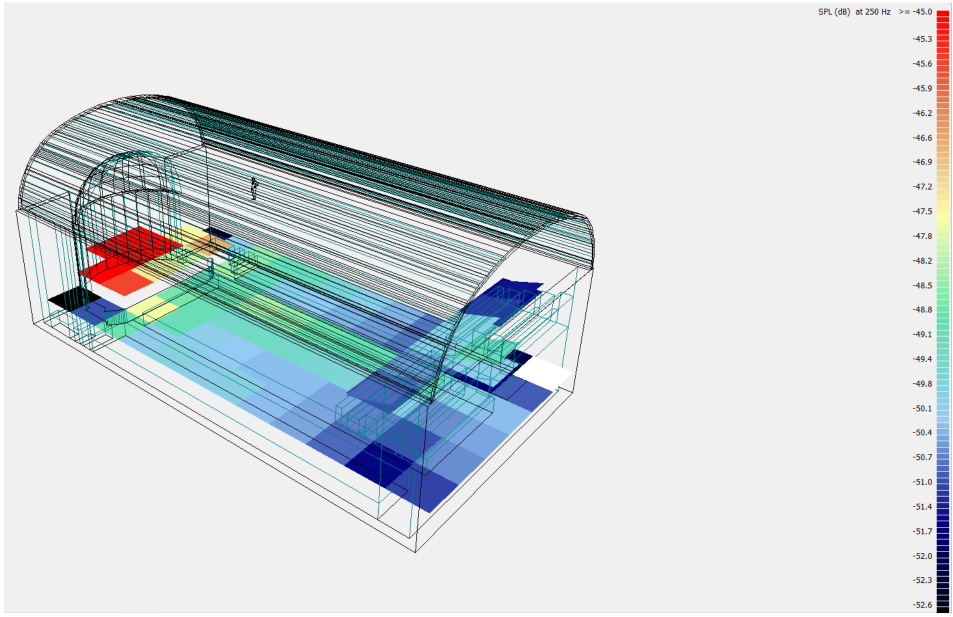


Figure 160 ODEON Wigmore Hall - Source at back of dome SPL – 250Hz

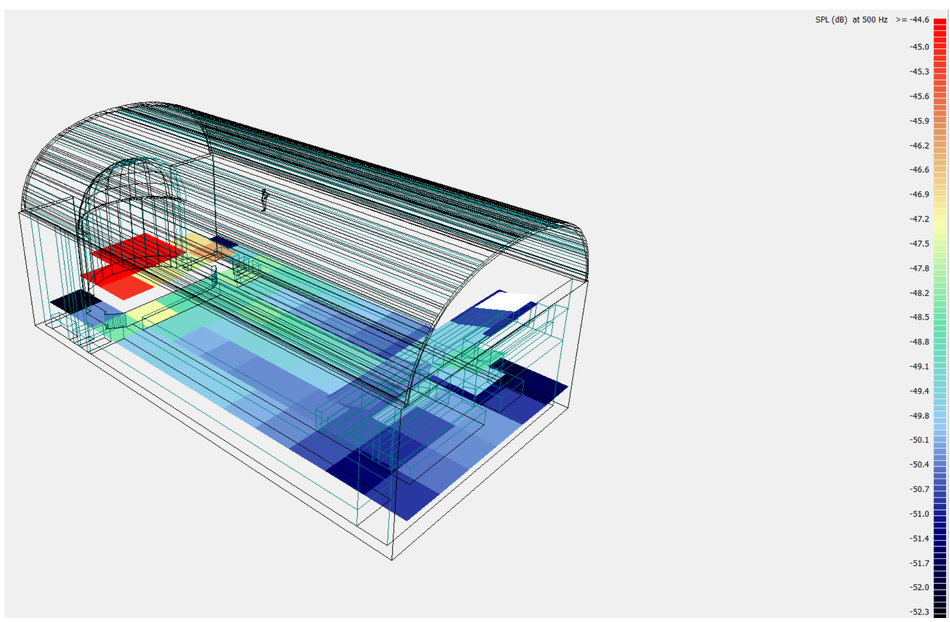


Figure 161 ODEON Wigmore Hall - Source at back of dome SPL – 500Hz

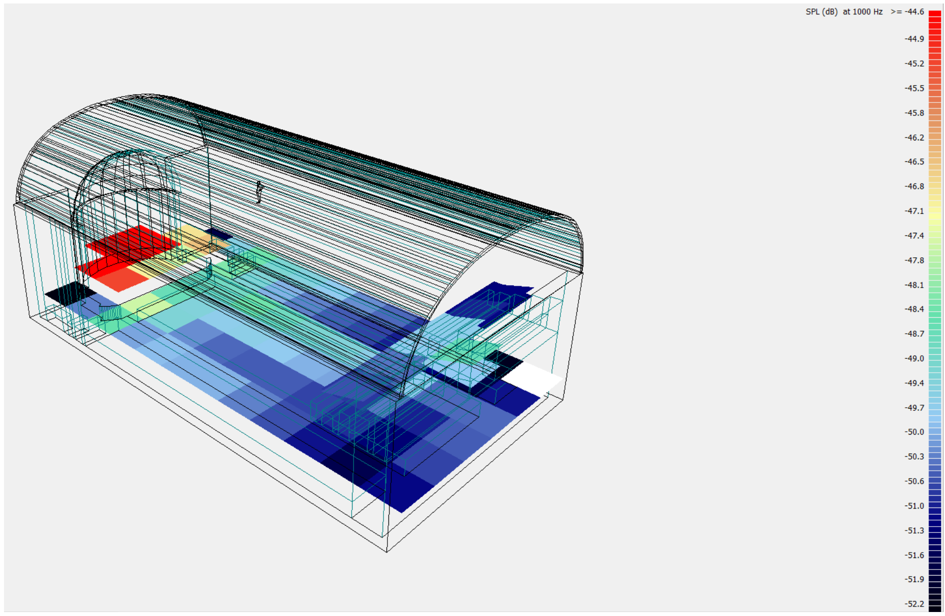


Figure 162 ODEON Wigmore Hall - Source at back of dome SPL – 1000Hz

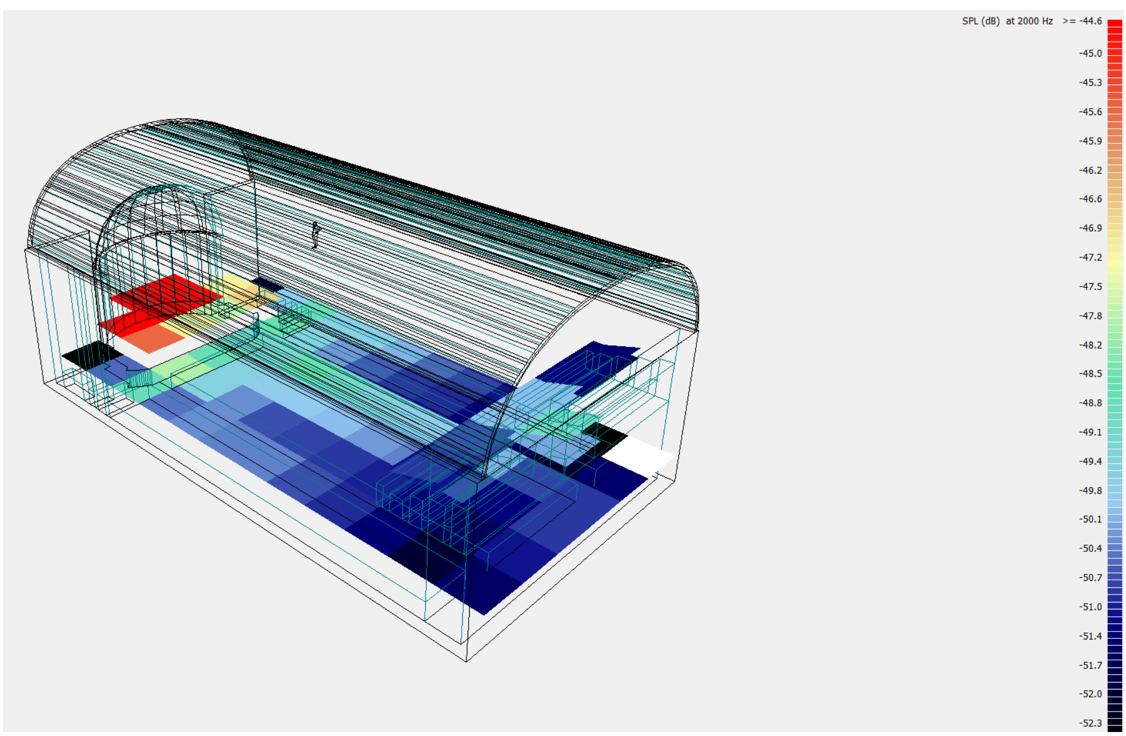


Figure 163 ODEON Wigmore Hall - Source at back of dome SPL – 2000Hz

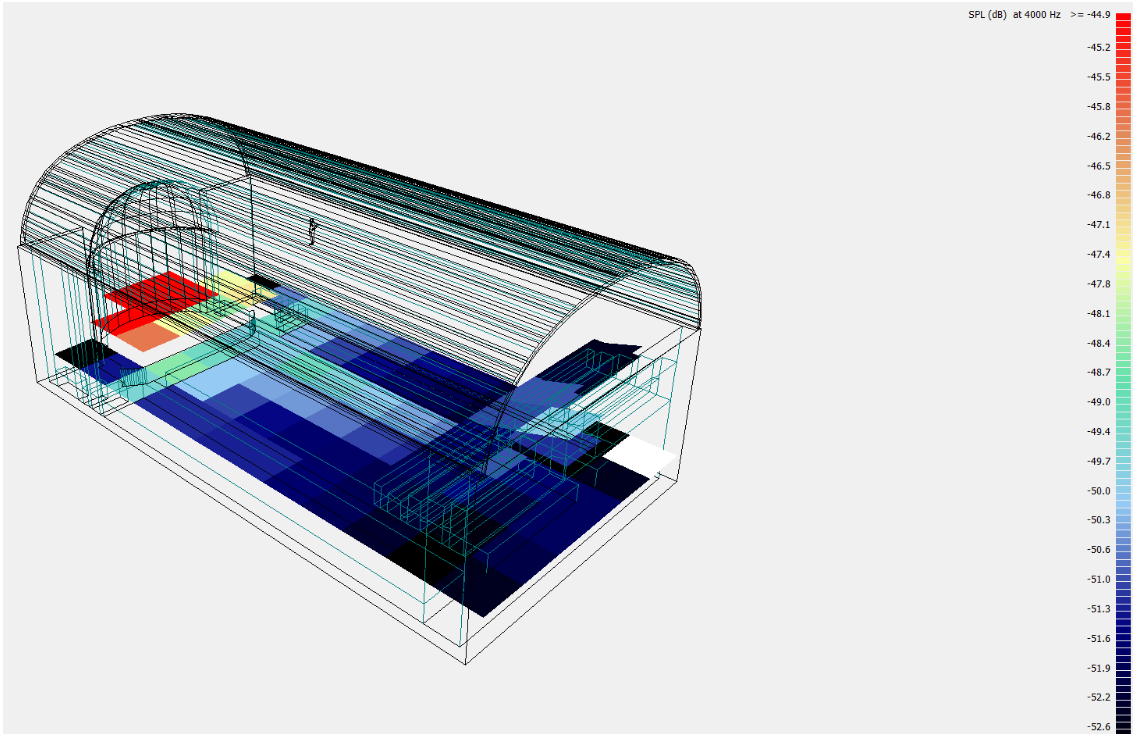


Figure 164 ODEON Wigmore Hall - Source at back of dome SPL – 4000Hz

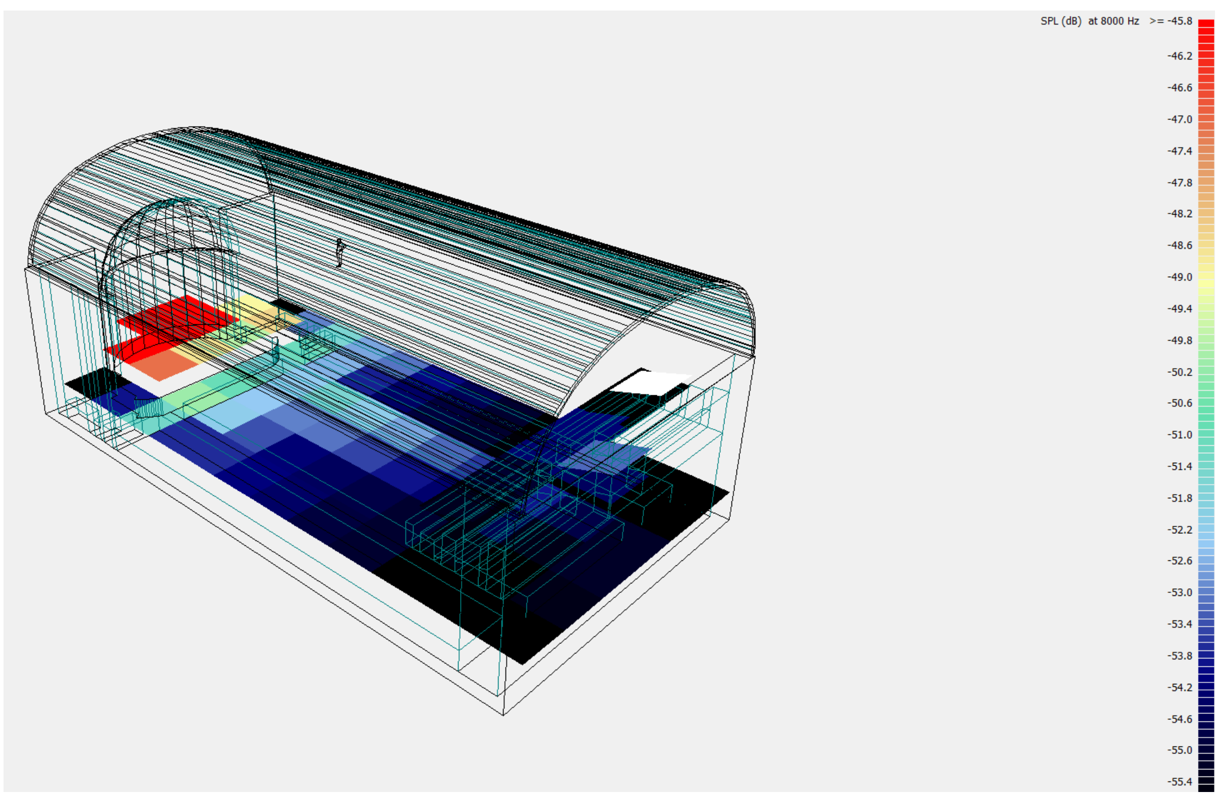


Figure 165 ODEON Wigmore Hall - Source at back of dome SPL – 8000Hz

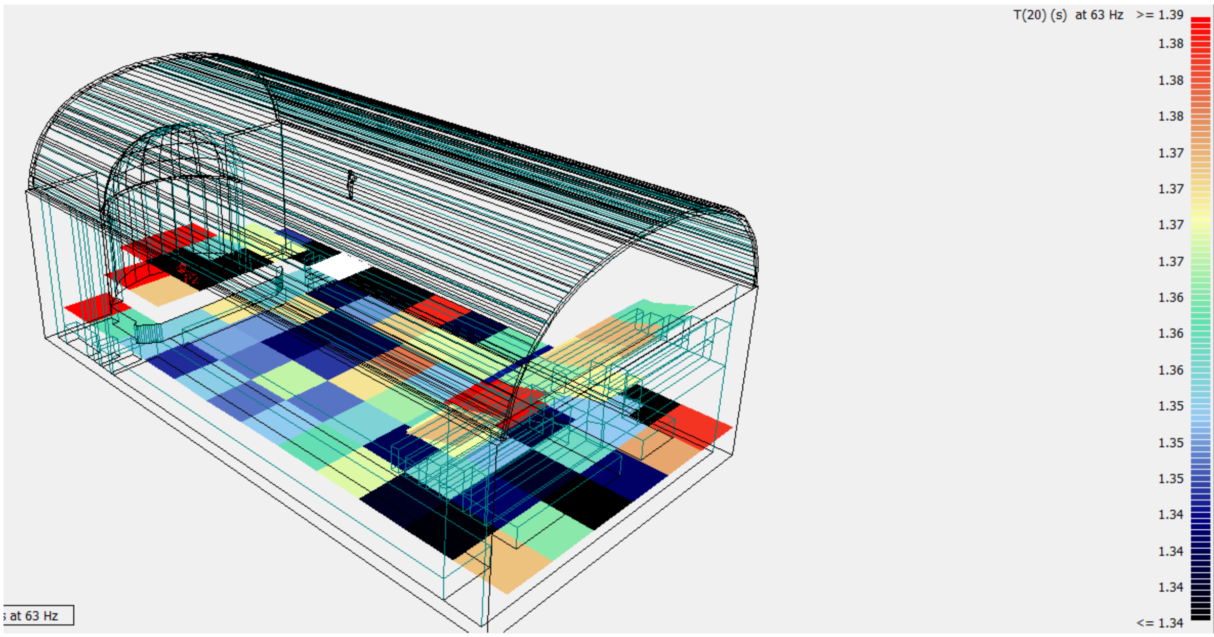


Figure 166 ODEON Wigmore Hall - Source in middle of stage RT – 63Hz

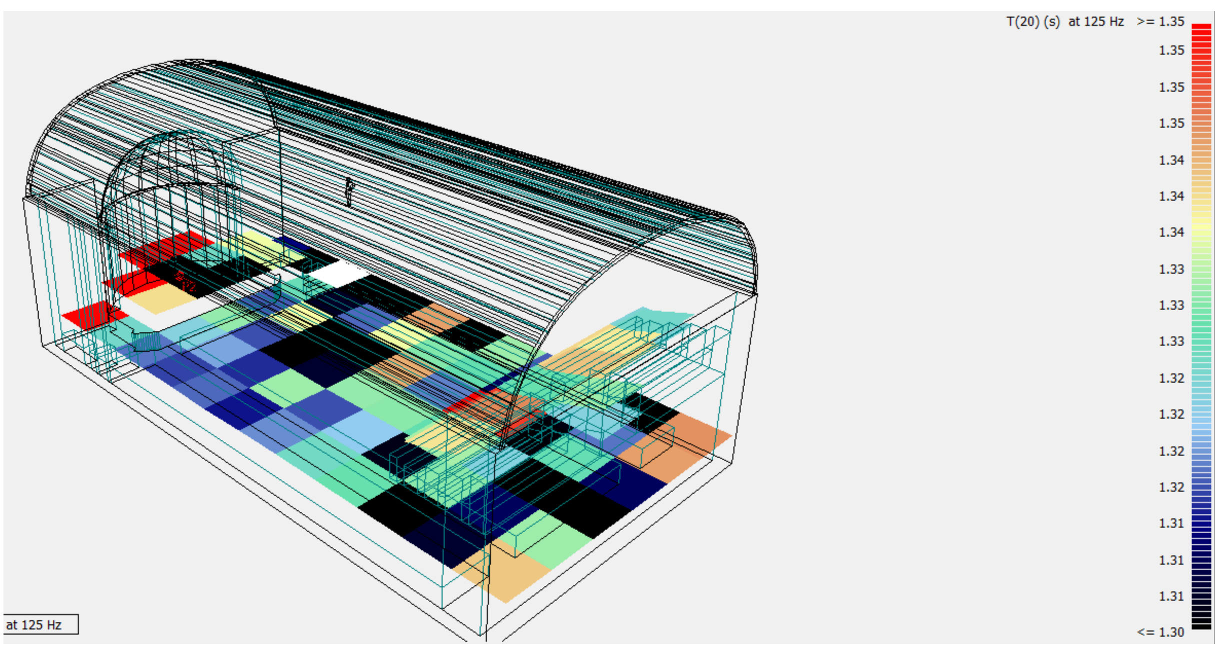


Figure 167 ODEON Wigmore Hall - Source in middle of stage RT – 125Hz

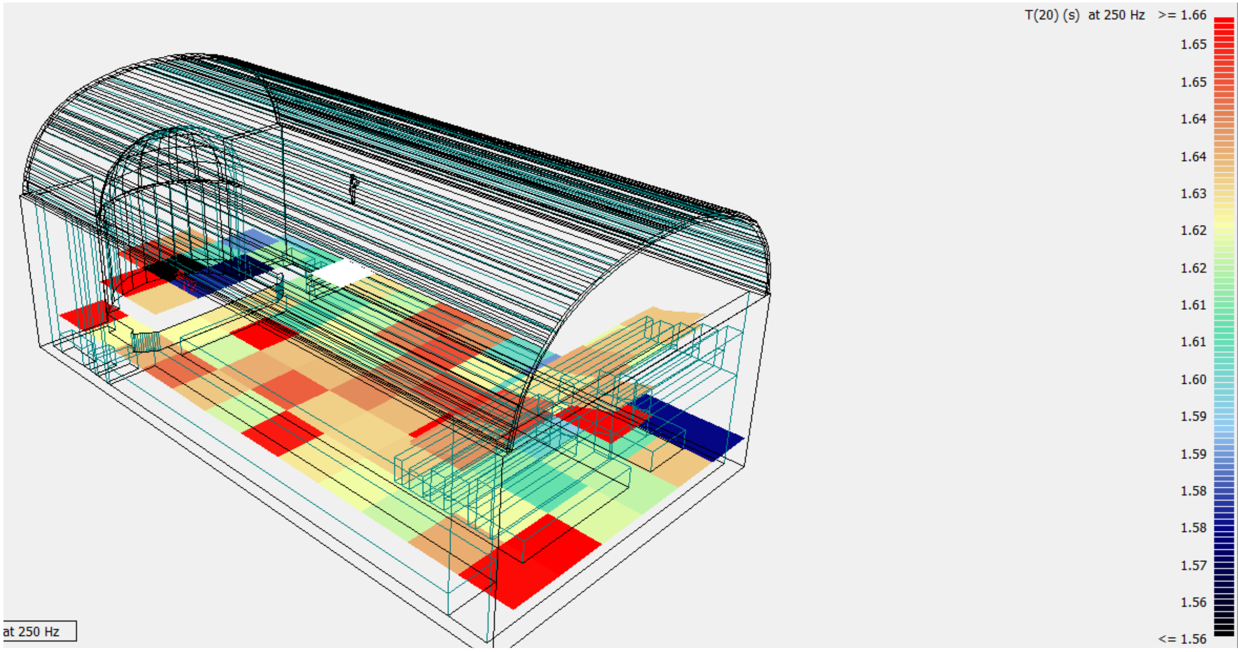


Figure 168 ODEON Wigmore Hall - Source in middle of stage RT – 250Hz

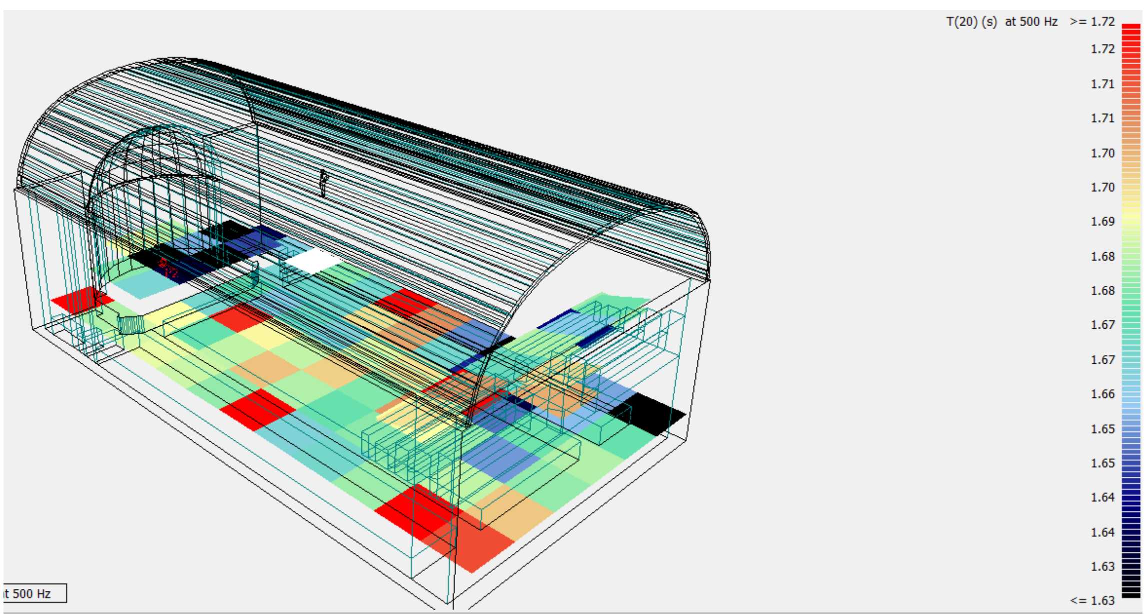


Figure 169 ODEON Wigmore Hall - Source in middle of stage RT– 500Hz

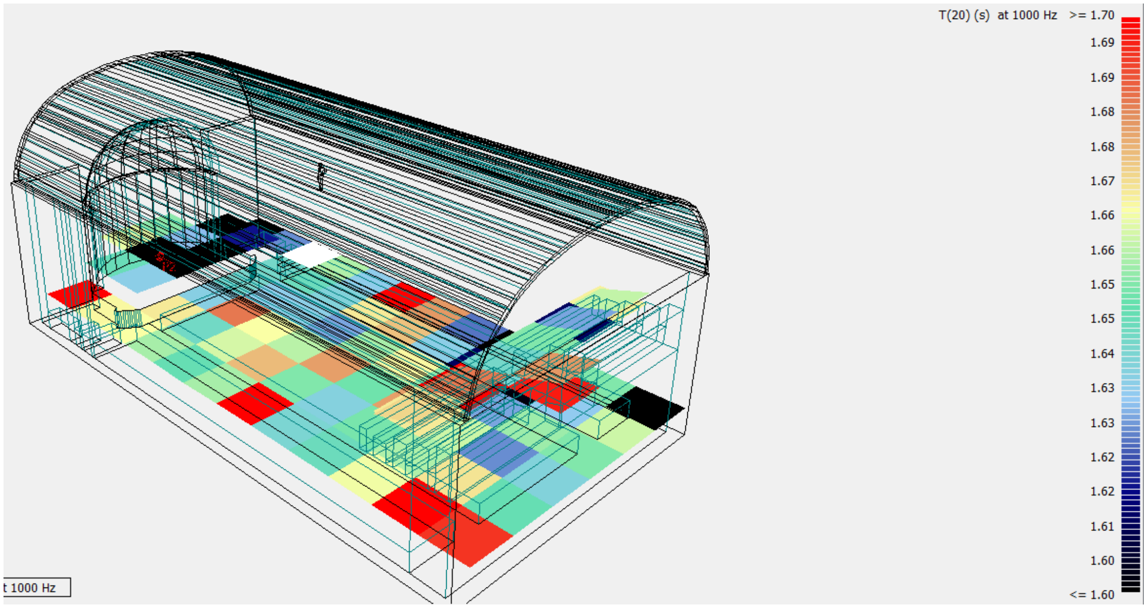


Figure 170 ODEON Wigmore Hall - Source in middle of stage RT – 1000Hz

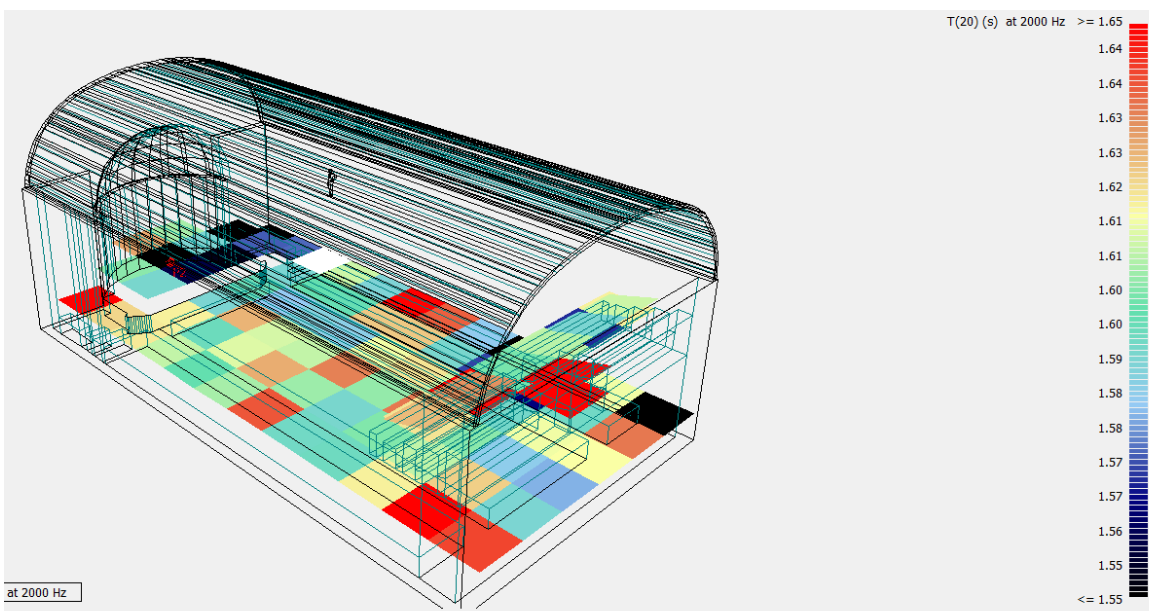


Figure 171 ODEON Wigmore Hall - Source in middle of stage RT – 2000Hz

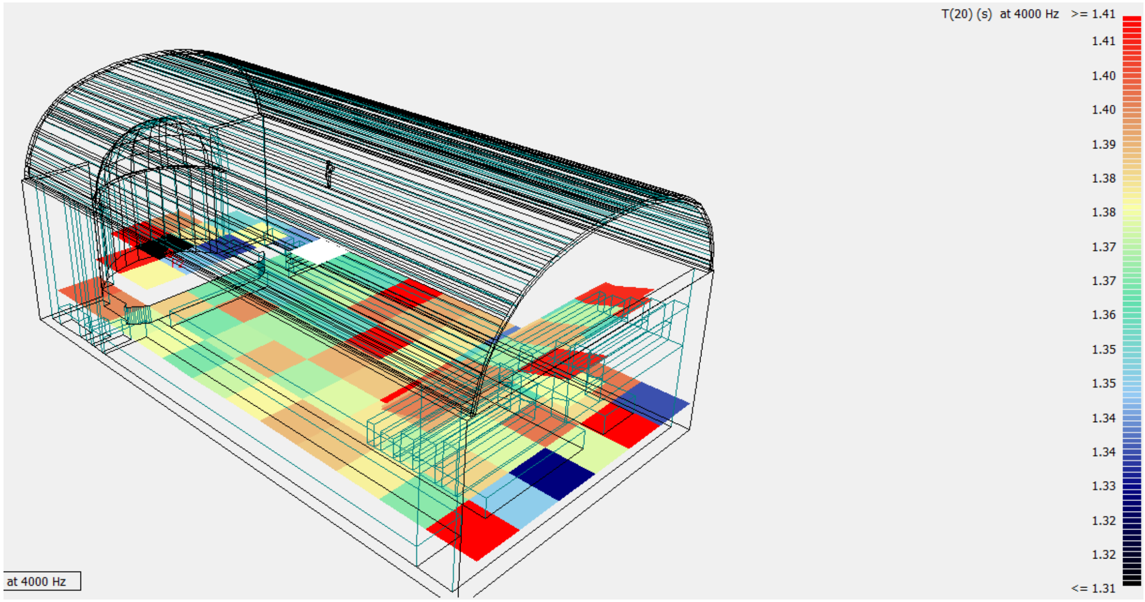


Figure 172 ODEON Wigmore Hall - Source in middle of stage RT – 4000Hz

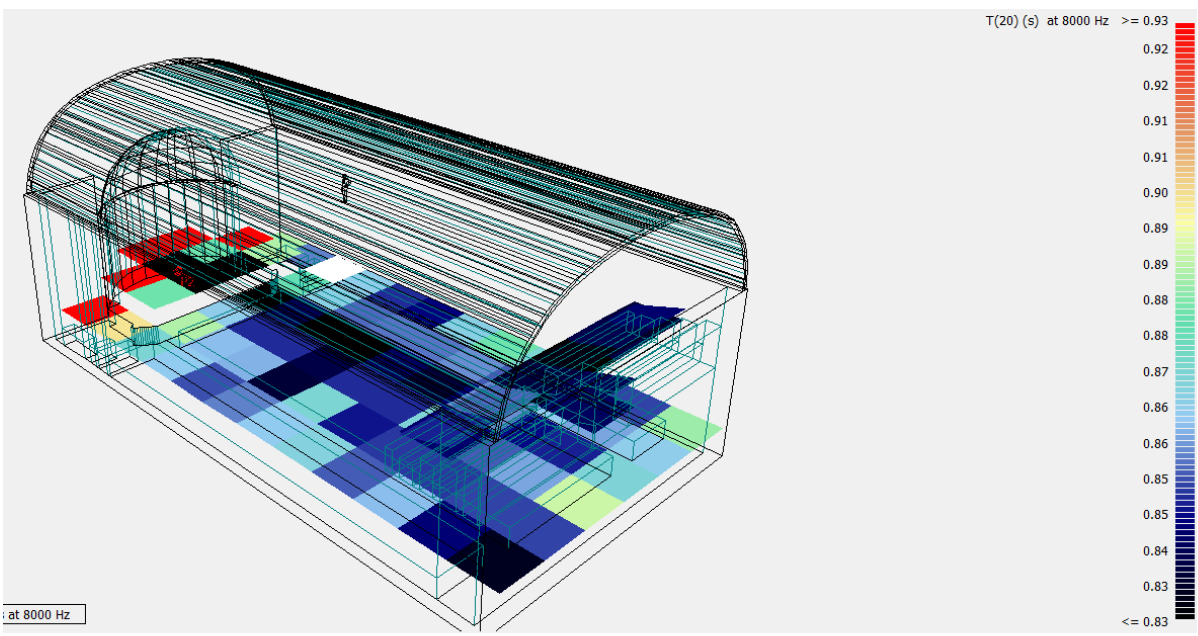


Figure 173 ODEON Wigmore Hall - Source in middle of stage RT – 8000Hz

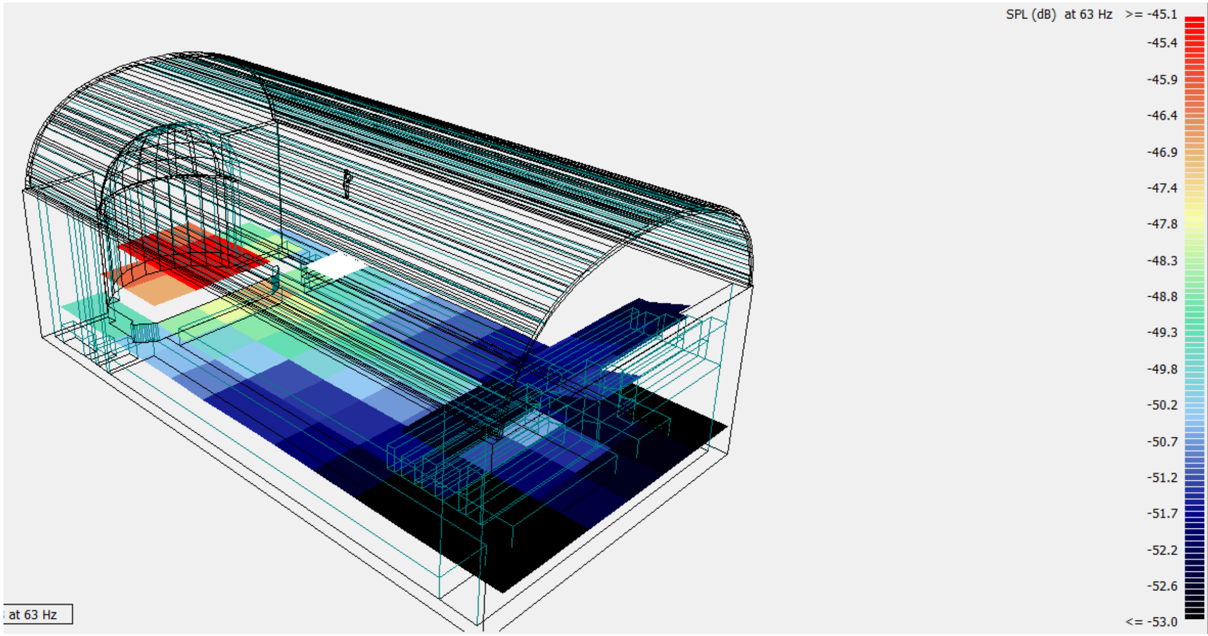


Figure 174 ODEON Wigmore Hall - Source in middle of stage SPL – 63Hz

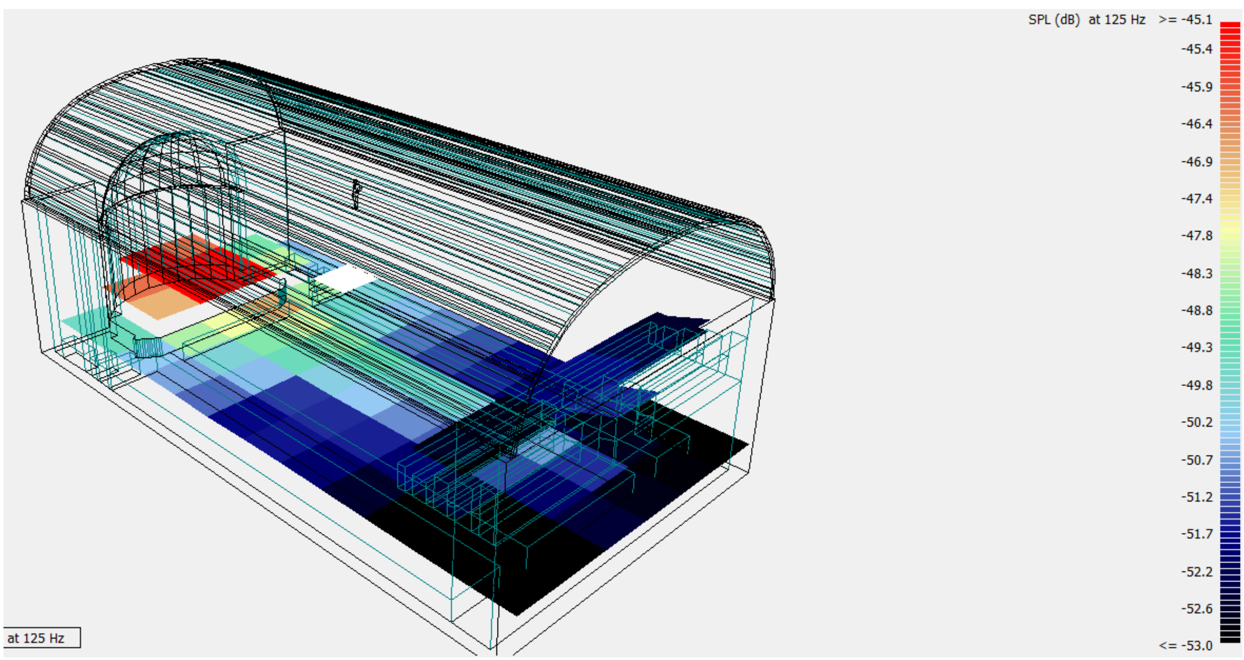


Figure 175 ODEON Wigmore Hall - Source in middle of stage SPL – 125Hz

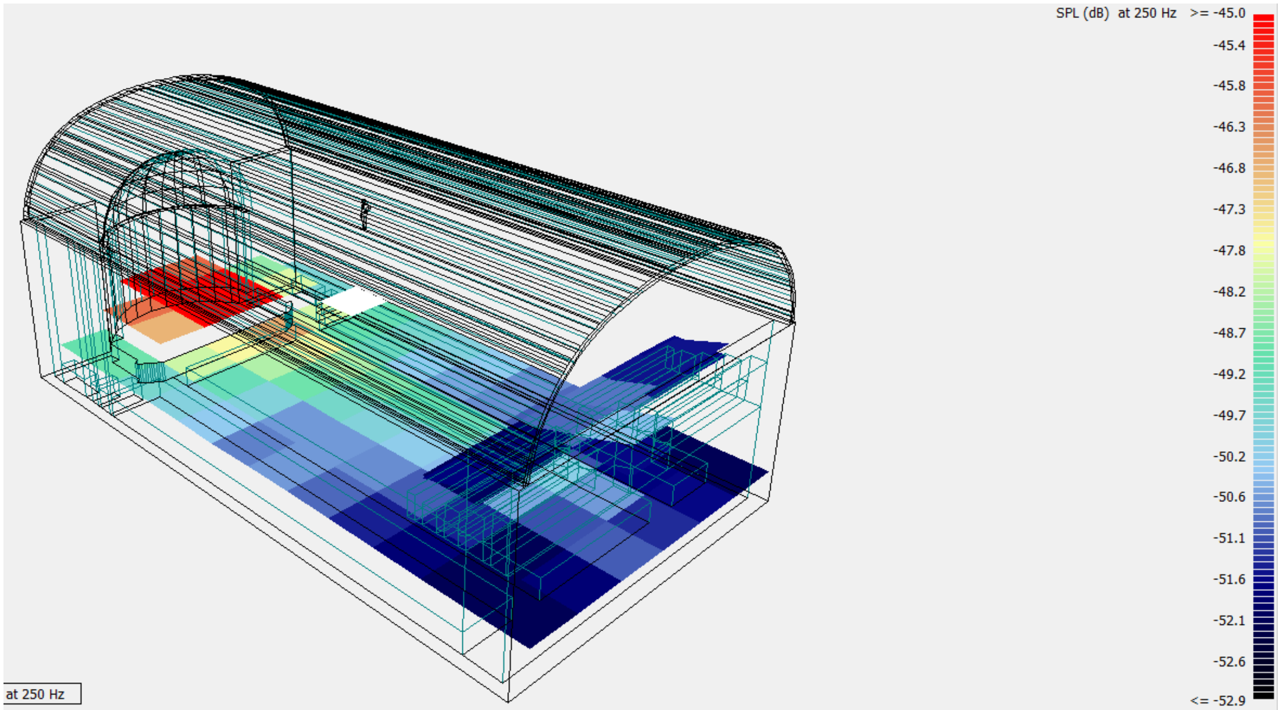


Figure 176 ODEON Wigmore Hall - Source in middle of stage SPL – 250Hz

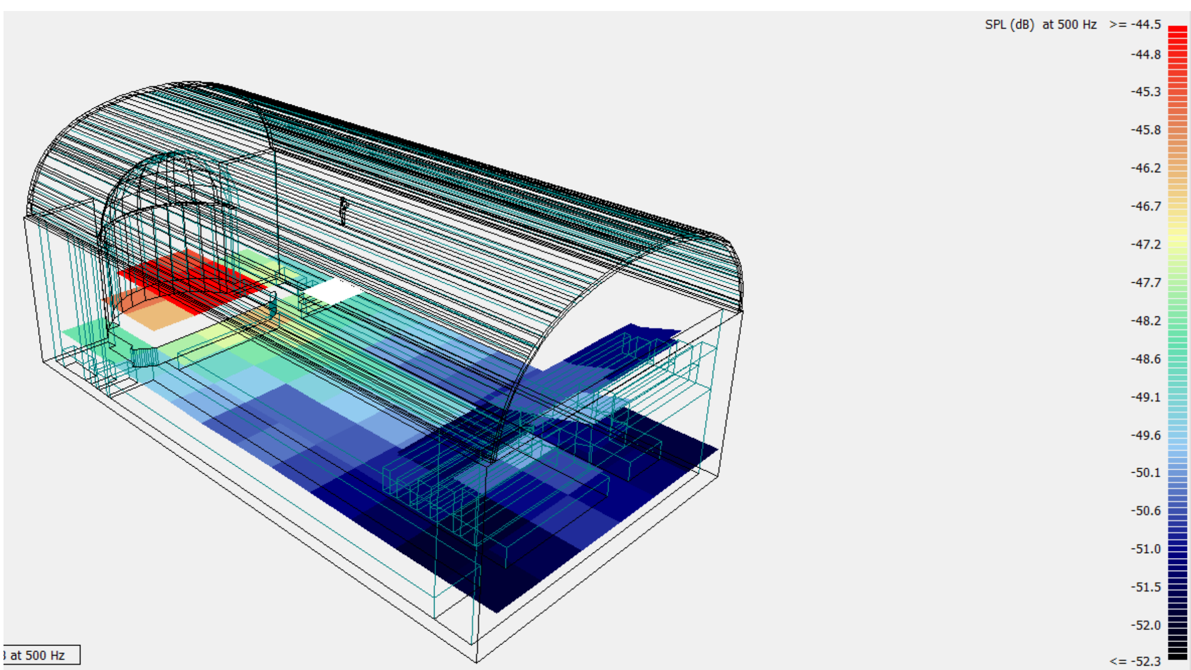


Figure 177 ODEON Wigmore Hall - Source in middle of stage SPL – 500Hz

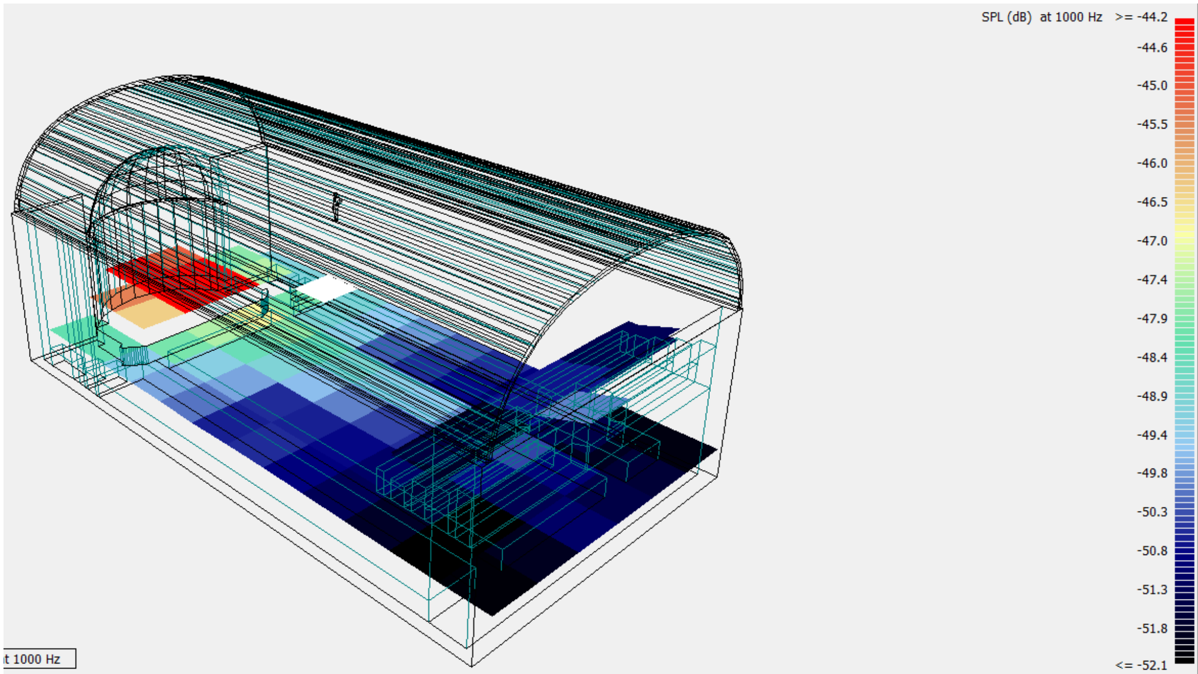


Figure 178 ODEON Wigmore Hall - Source in middle of stage SPL – 1000Hz

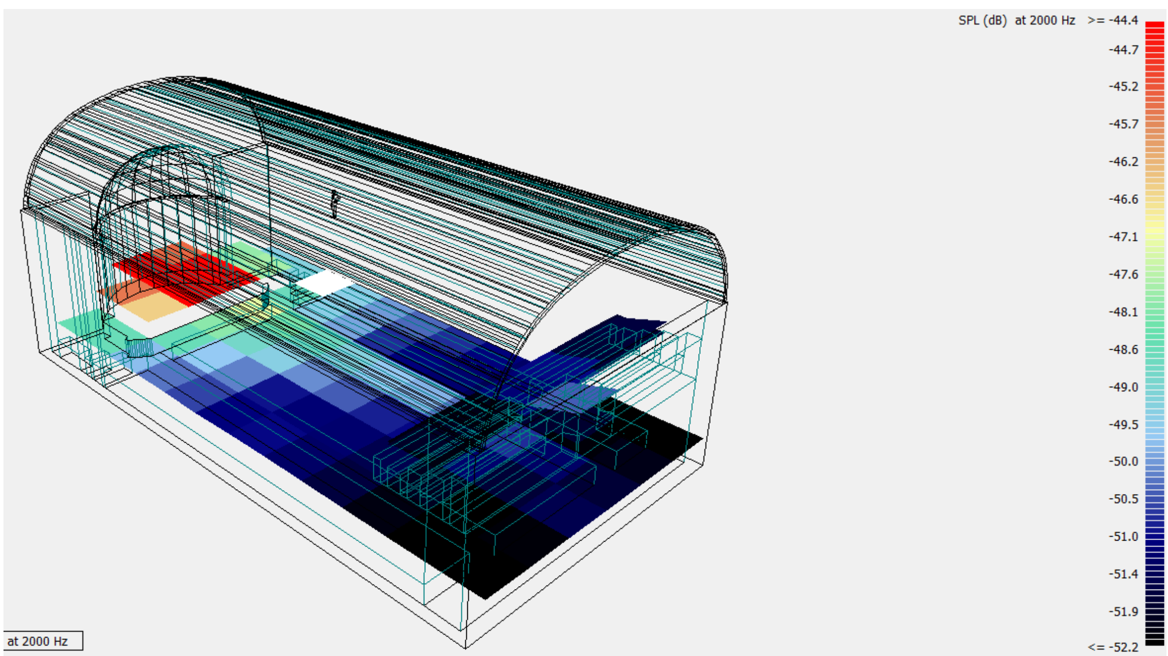


Figure 179 ODEON Wigmore Hall - Source in middle of stage SPL – 2000Hz

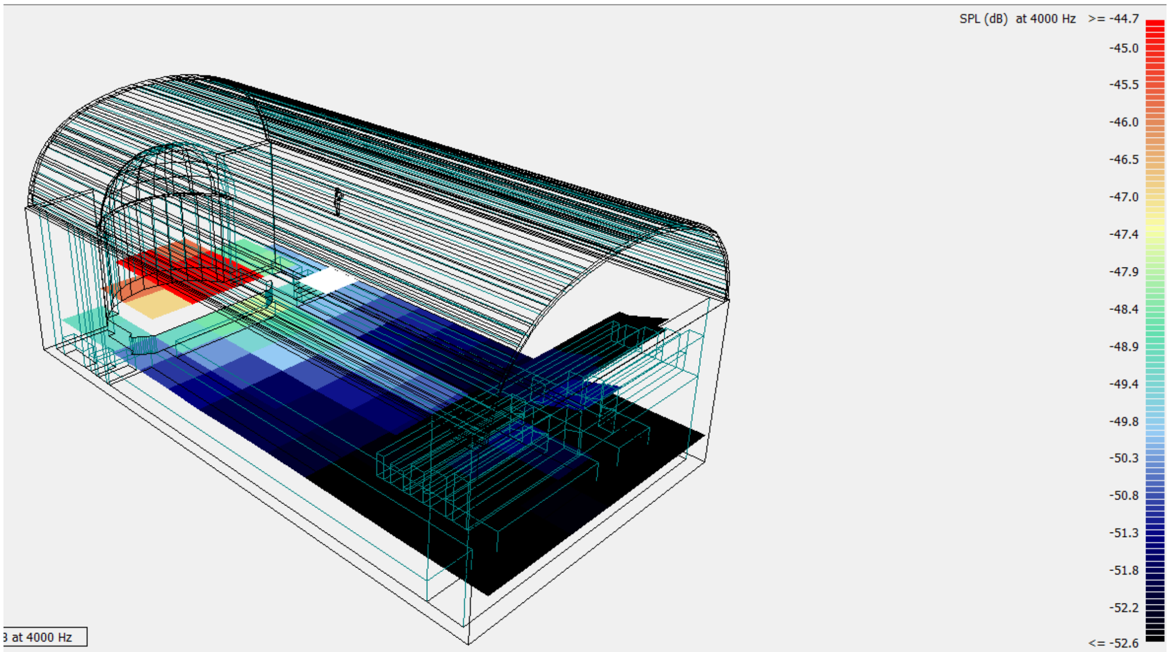


Figure 180 ODEON Wigmore Hall - Source in middle of stage SPL – 4000Hz

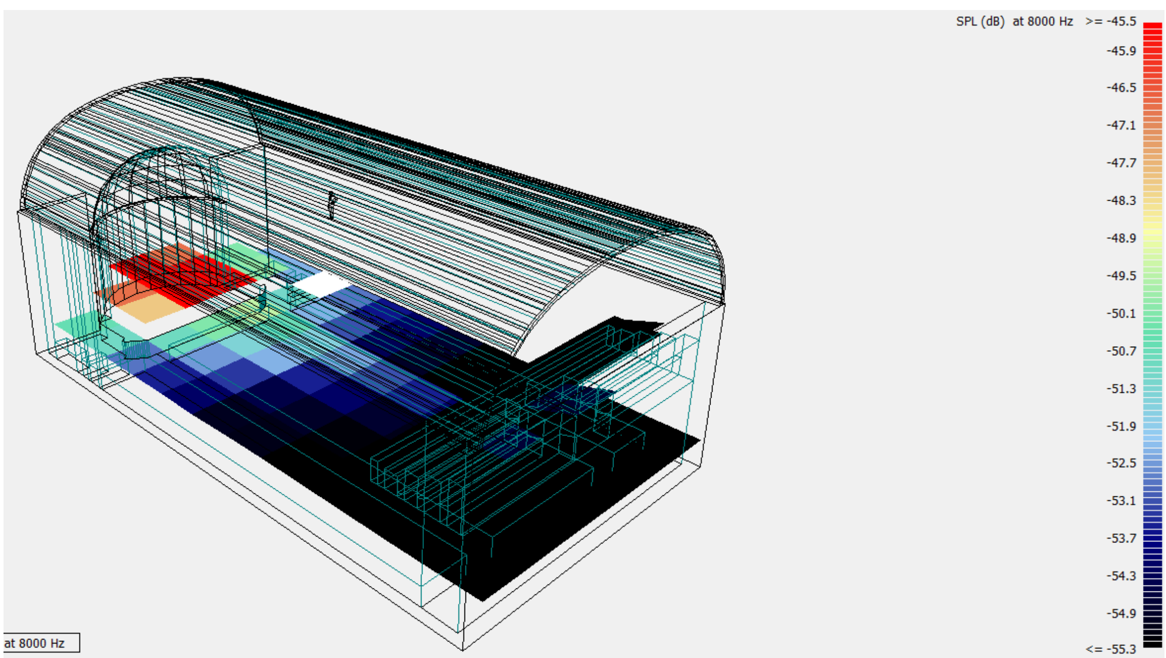


Figure 181 ODEON Wigmore Hall - Source in middle of stage SPL – 8000Hz

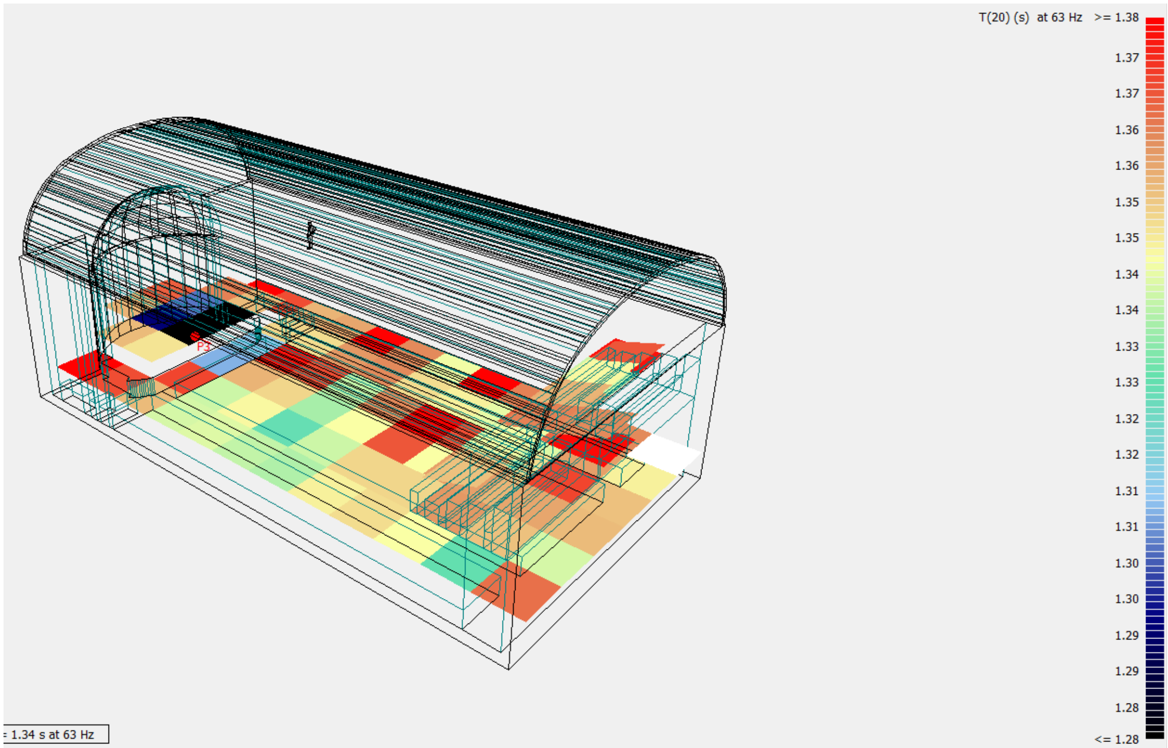


Figure 182 ODEON Wigmore Hall - Source at front stage RT – 63Hz

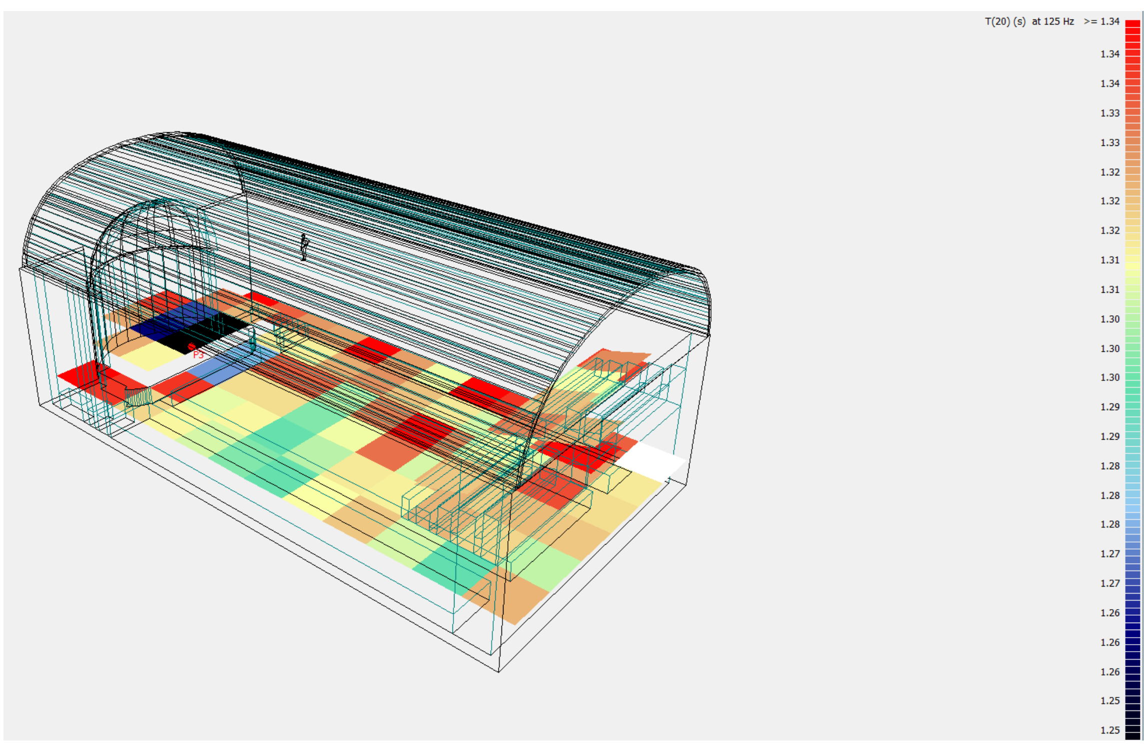


Figure 183 ODEON Wigmore Hall - Source at front stage RT – 125Hz

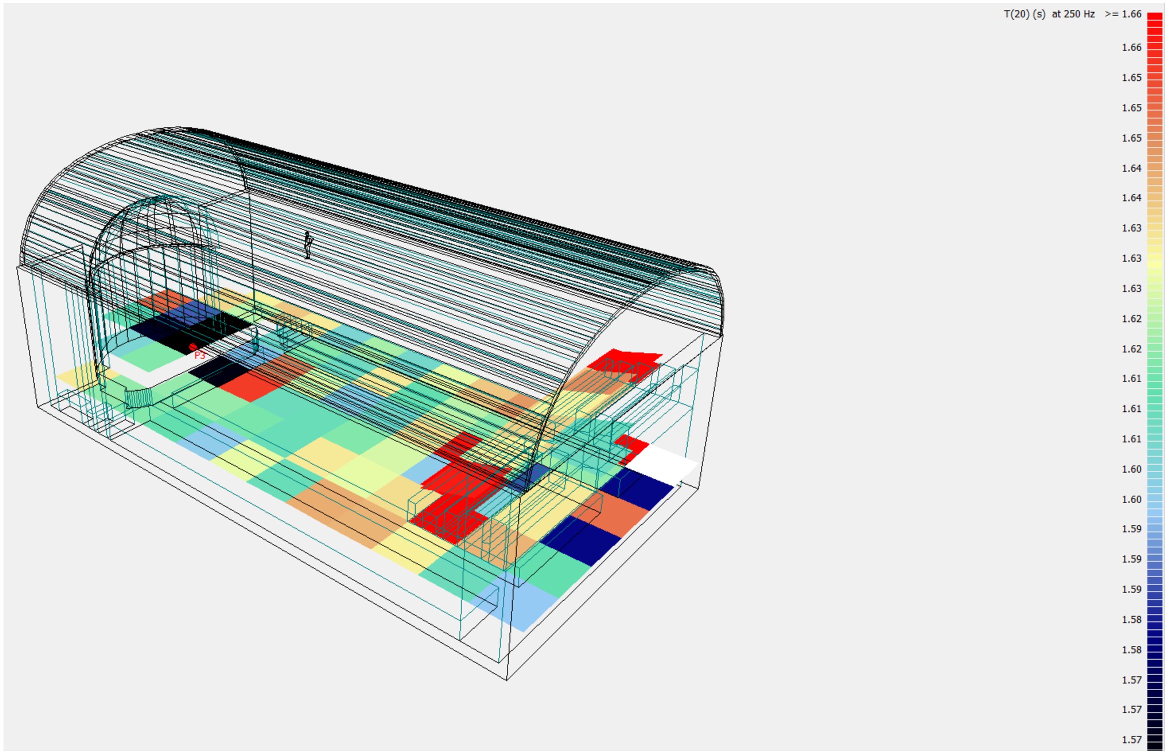


Figure 184 ODEON Wigmore Hall - Source at front stage RT– 250Hz

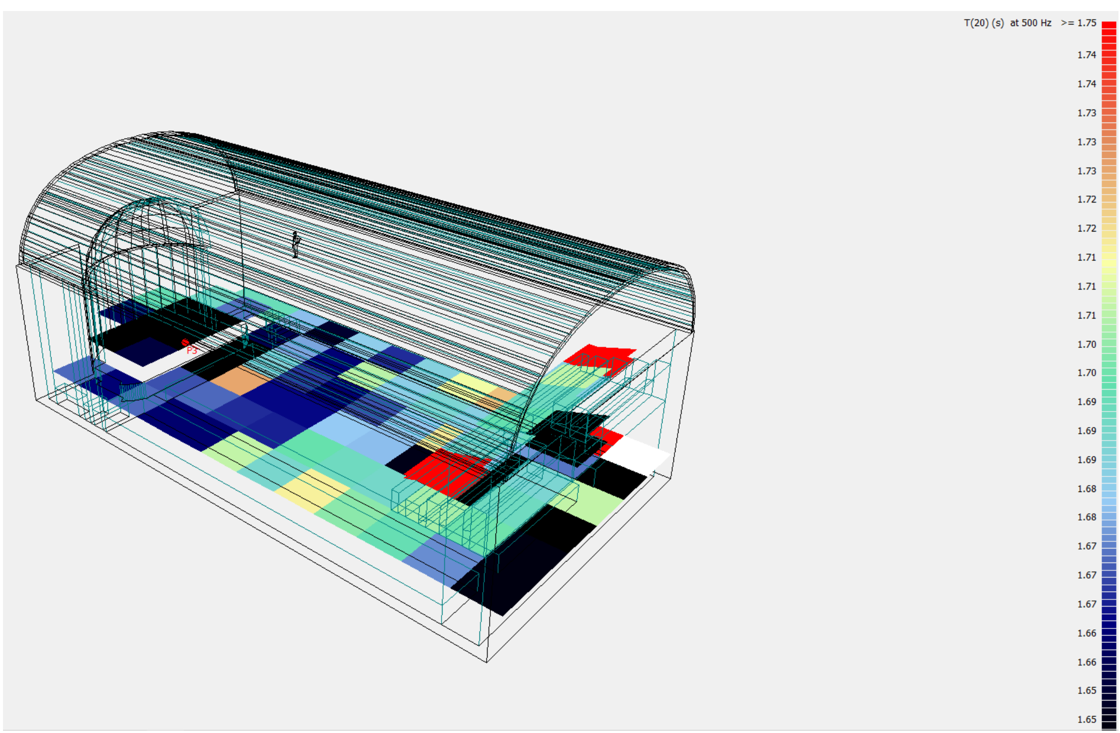


Figure 185 ODEON Wigmore Hall - Source at front stage RT – 500Hz

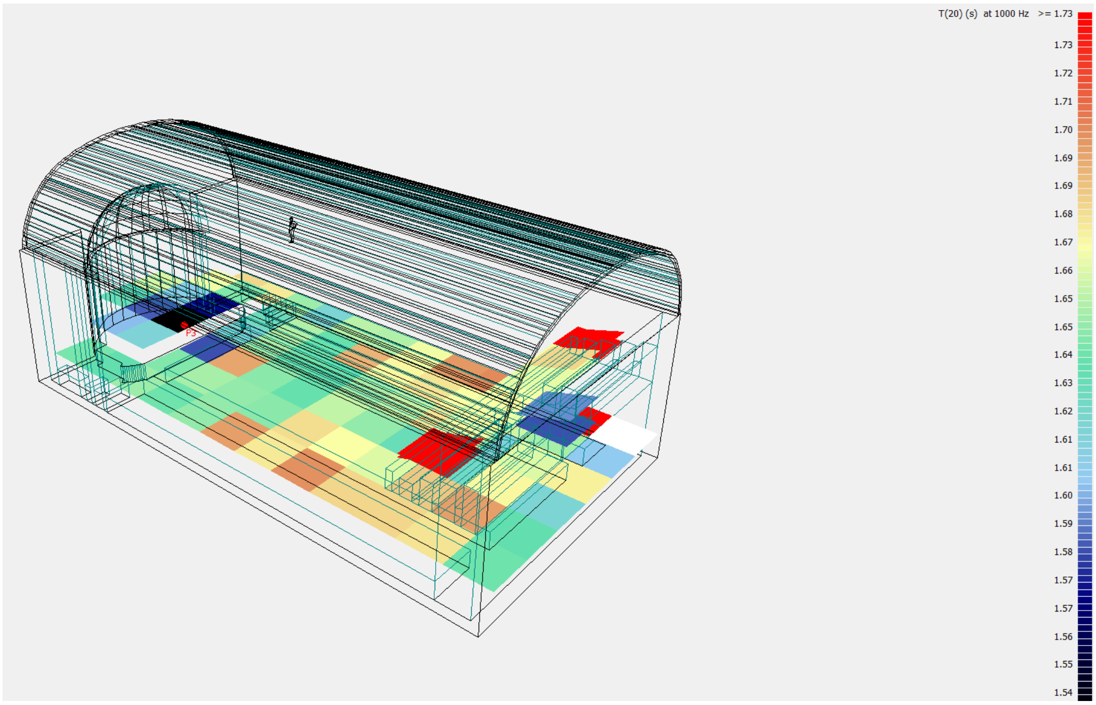


Figure 186 ODEON Wigmore Hall - Source at front stage RT – 1000Hz

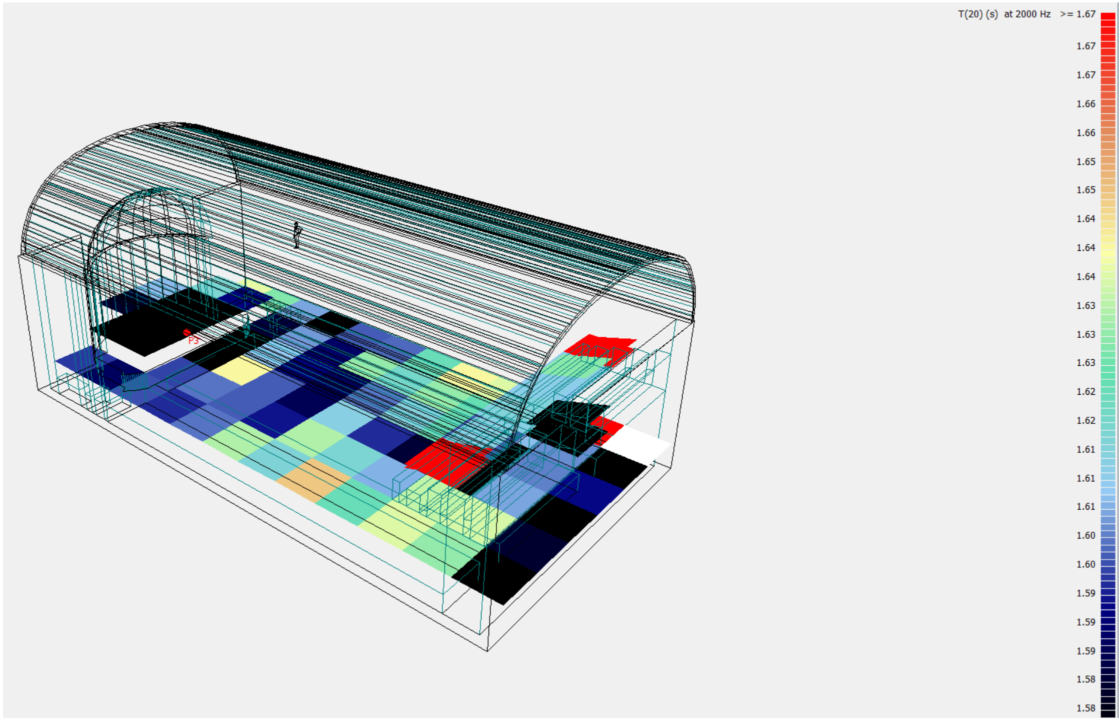


Figure 187 ODEON Wigmore Hall - Source at front stage RT – 2000Hz

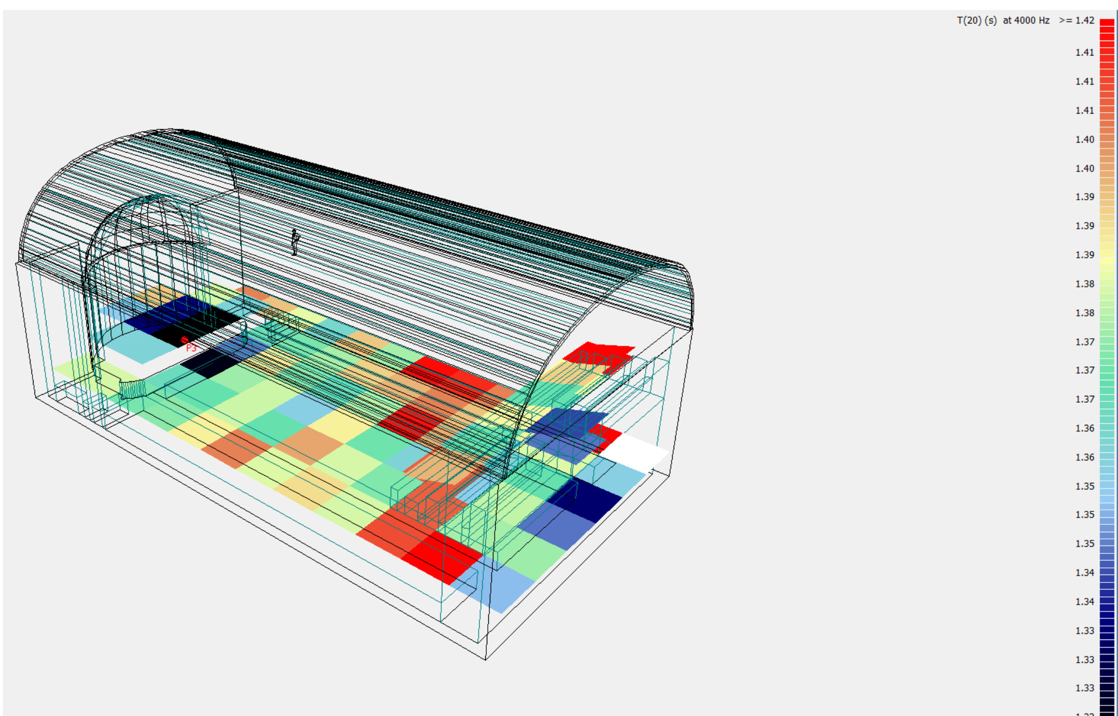


Figure 188 ODEON Wigmore Hall - Source at front stage RT – 4000Hz

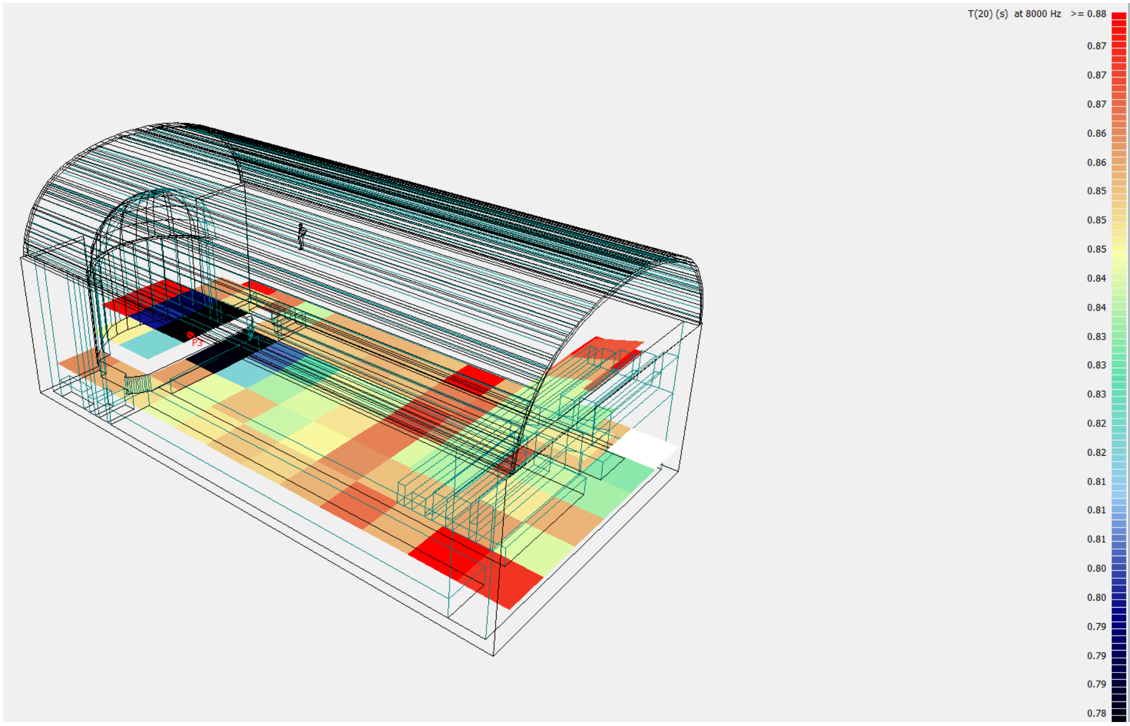


Figure 189 ODEON Wigmore Hall - Source at front stage RT– 8000Hz

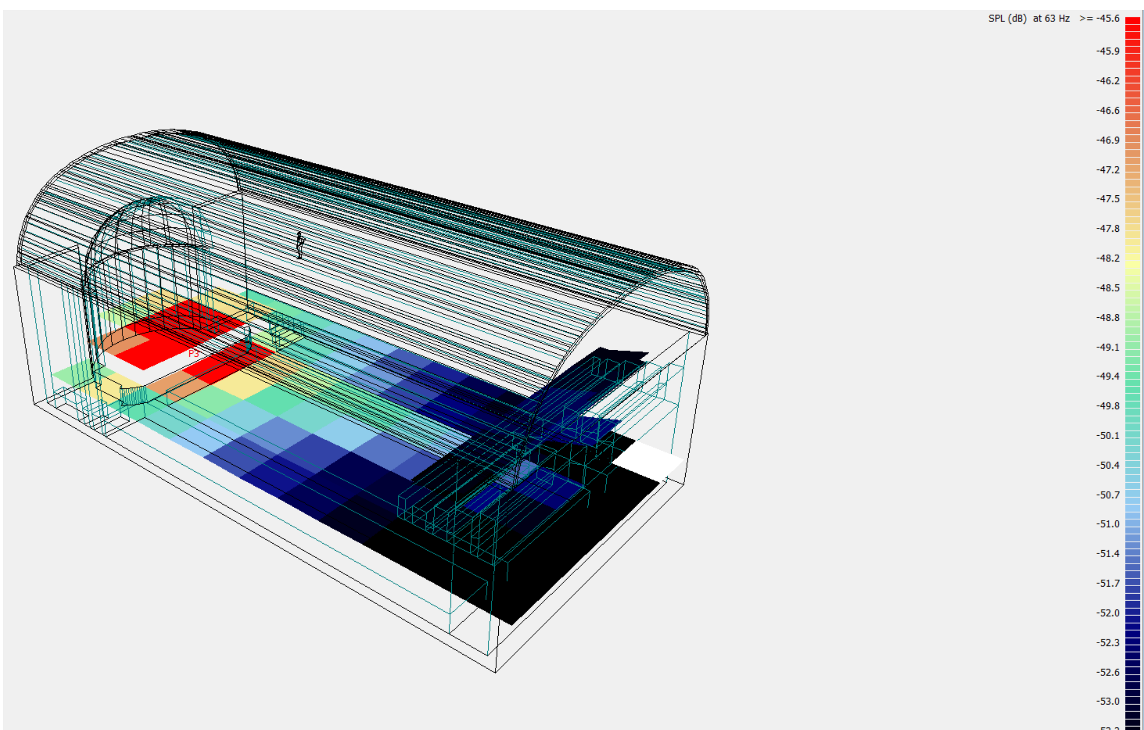


Figure 190 ODEON Wigmore Hall - Source at front stage SPL – 63Hz

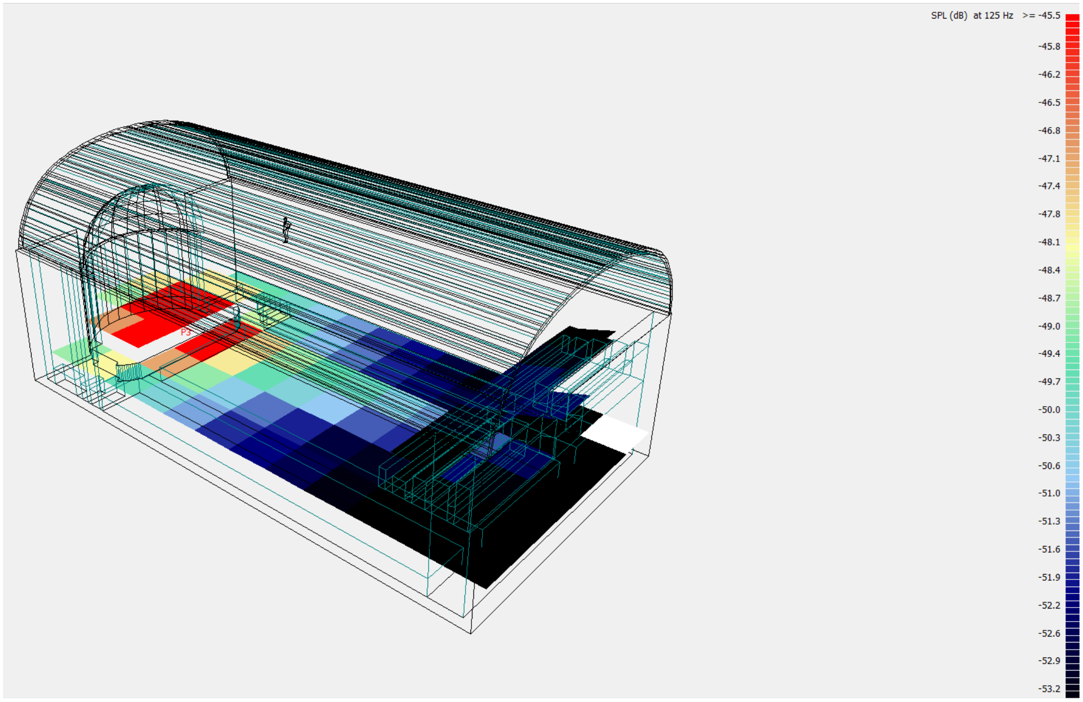


Figure 191 ODEON Wigmore Hall - Source at front stage SPL – 125Hz

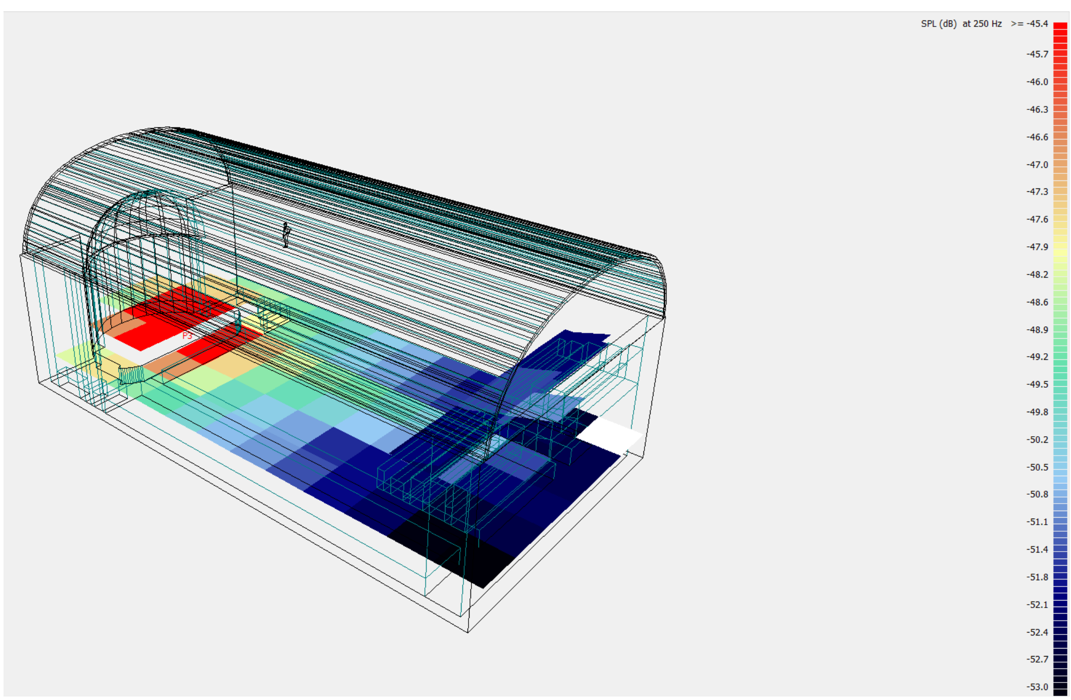


Figure 192 ODEON Wigmore Hall - Source at front stage SPL – 250Hz

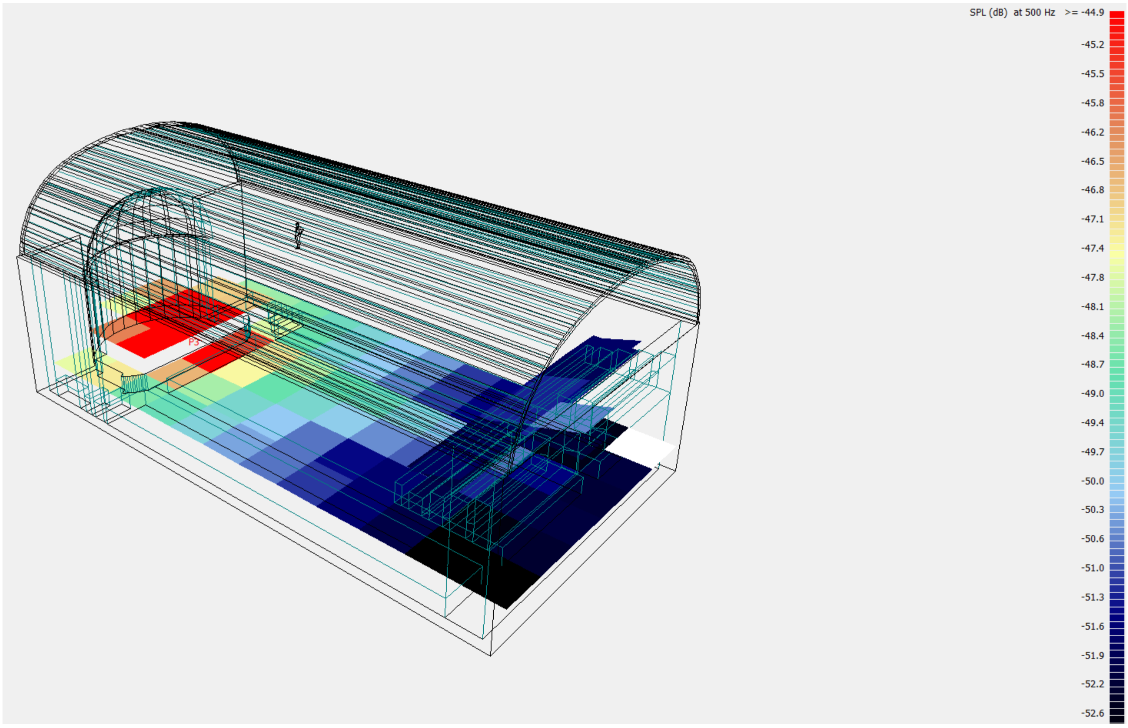


Figure 193 ODEON Wigmore Hall - Source at front stage SPL – 500Hz

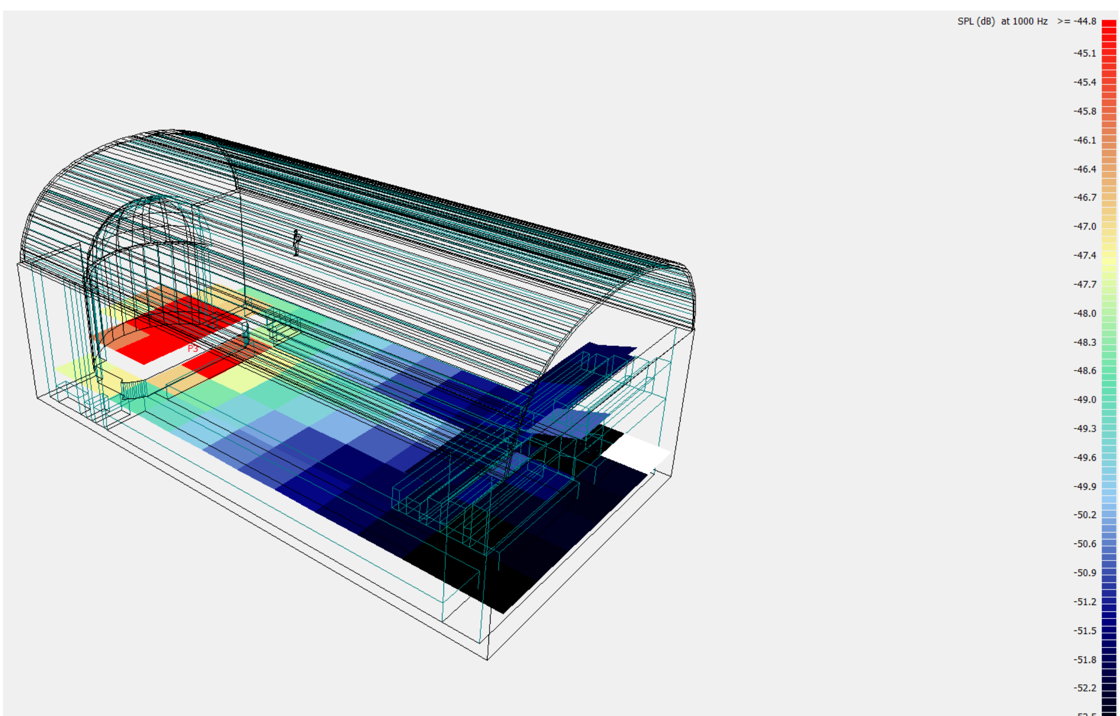


Figure 194 ODEON Wigmore Hall - Source at front stage SPL – 1000Hz

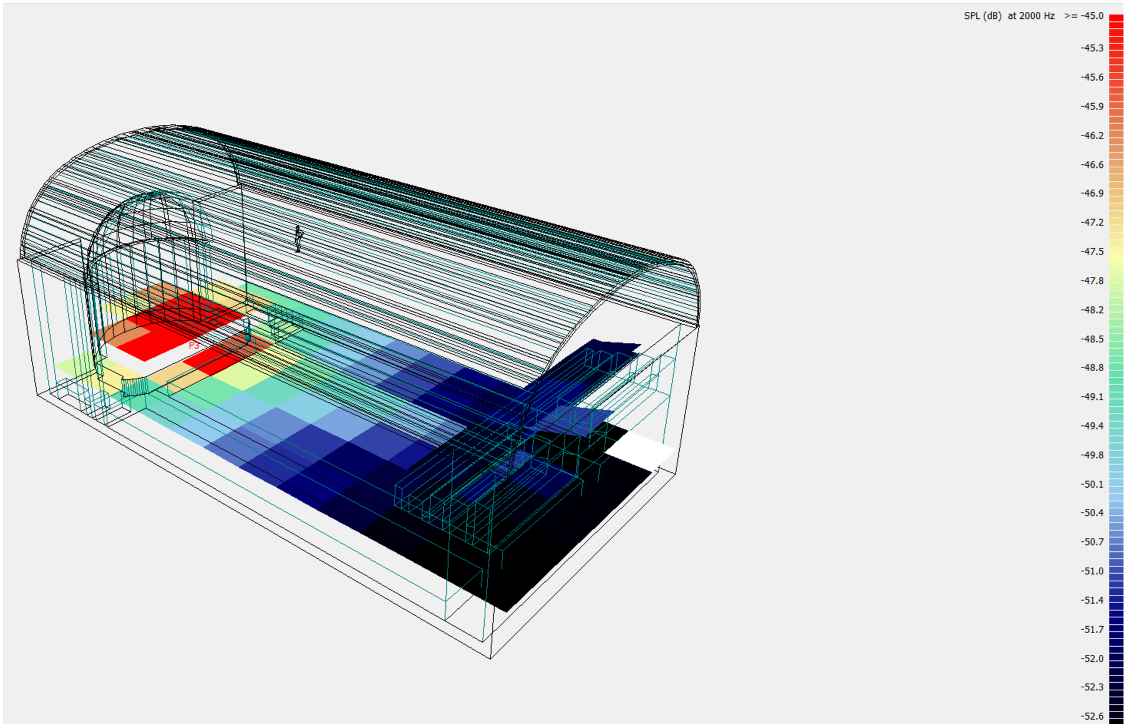


Figure 195 ODEON Wigmore Hall - Source at front stage SPL – 2000Hz

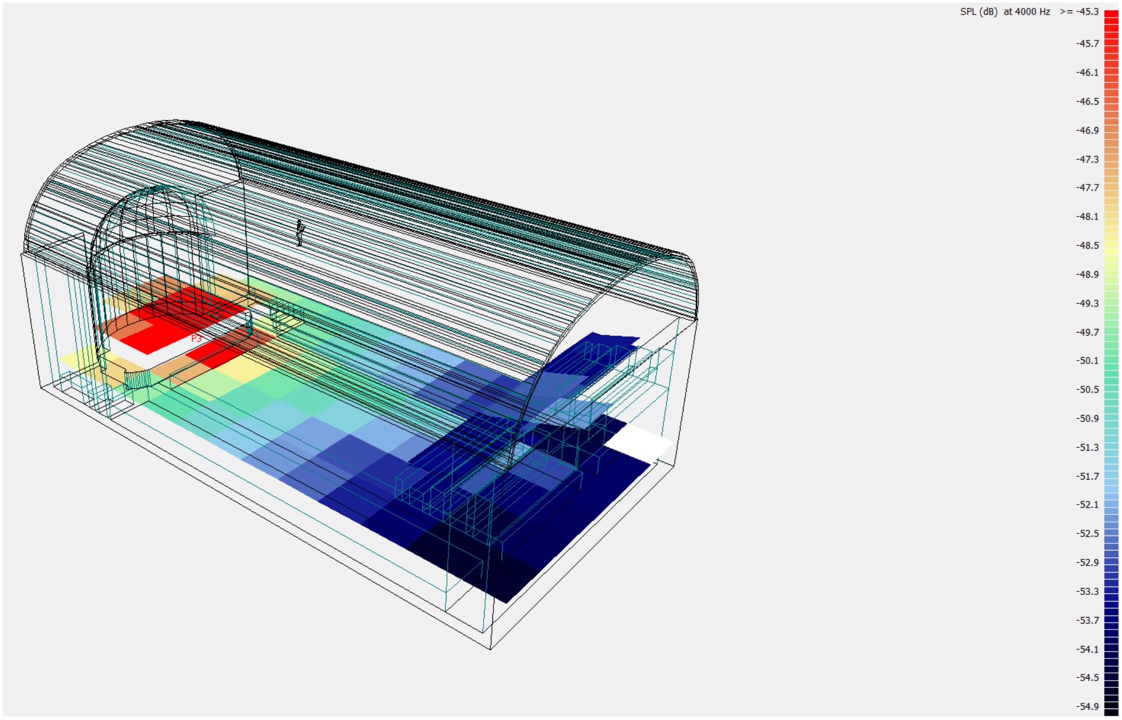


Figure 196 ODEON Wigmore Hall - Source at front stage SPL – 4000Hz

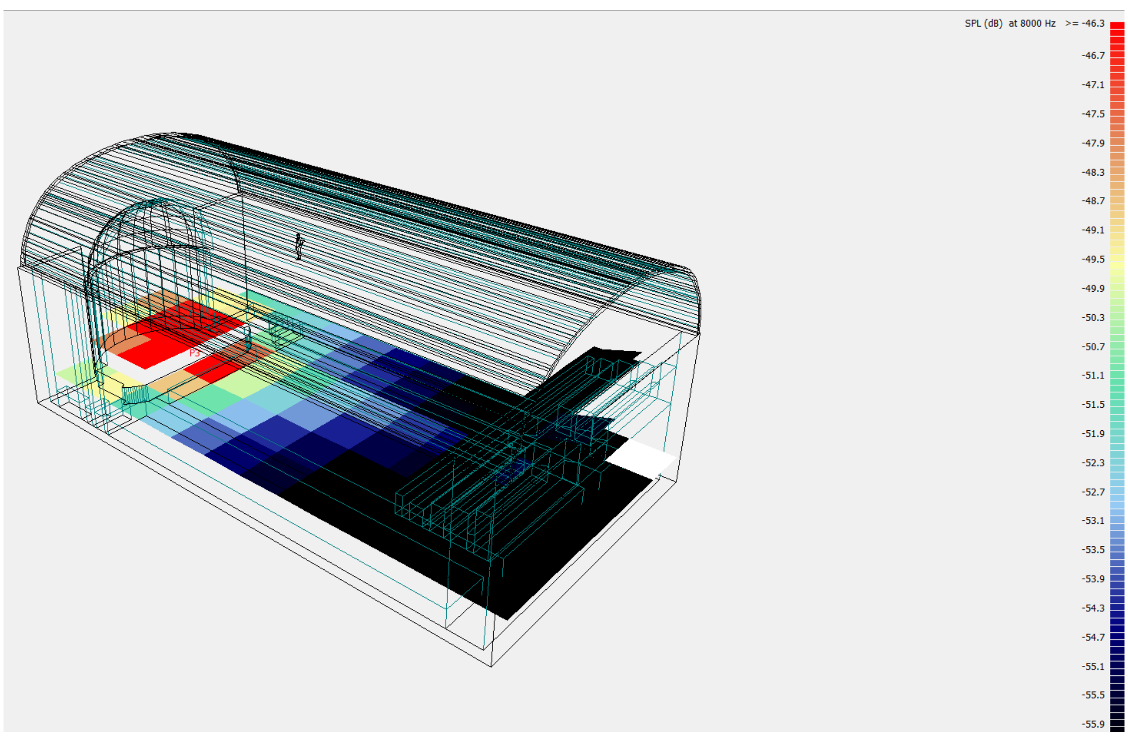


Figure 197 ODEON Wigmore Hall - Source at front stage SPL – 8000Hz

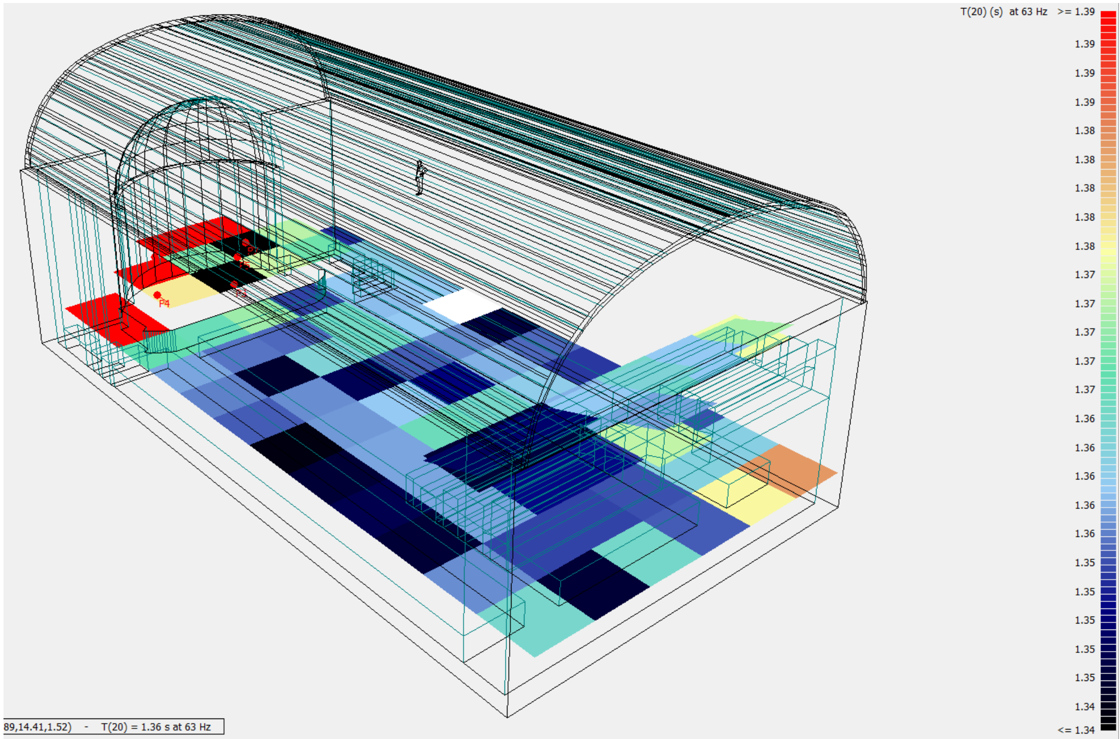


Figure 198 ODEON Wigmore Hall - Source Ensemble on stage RT – 63Hz

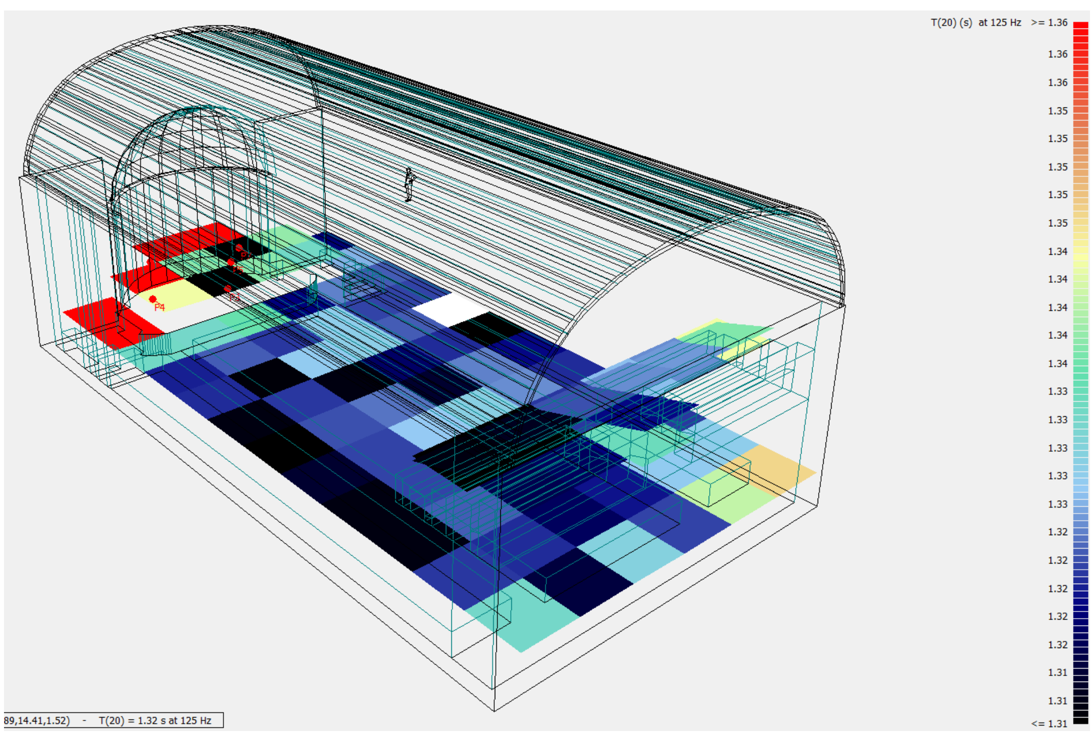


Figure 199 ODEON Wigmore Hall - Source Ensemble on stage RT – 125Hz

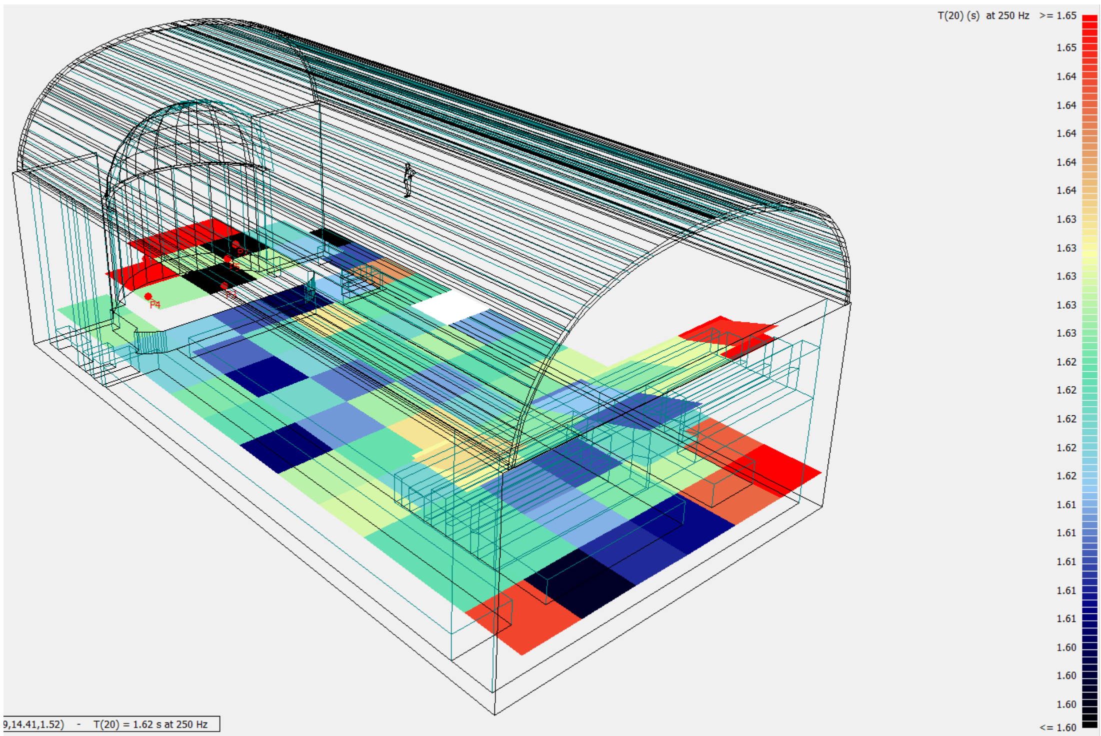


Figure 200 ODEON Wigmore Hall - Source Ensemble on stage RT – 250Hz

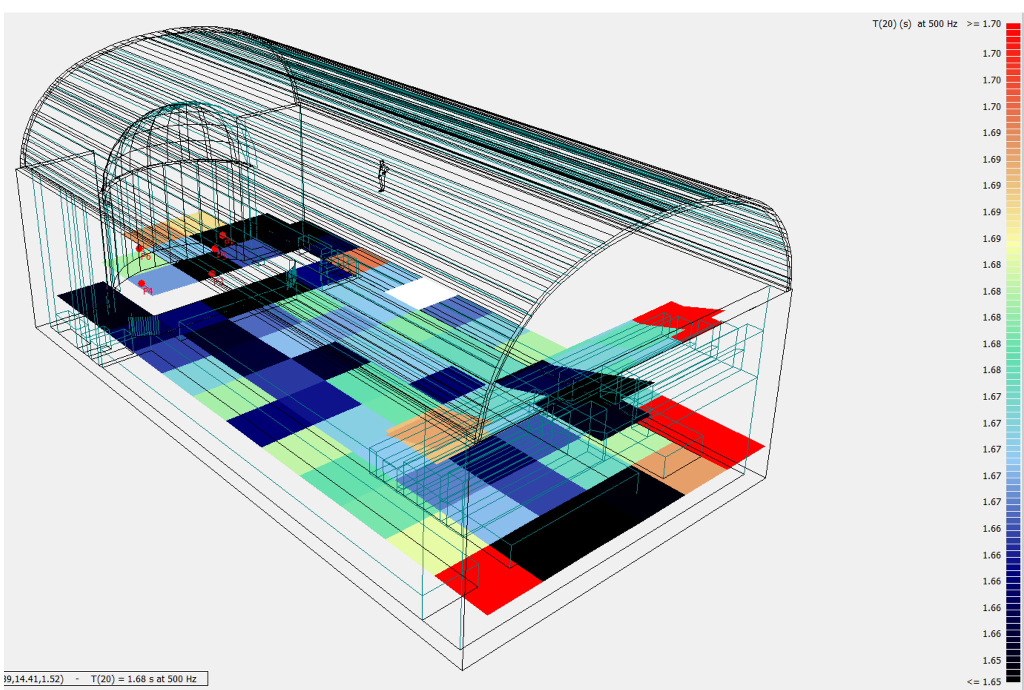


Figure 201 ODEON Wigmore Hall - Source Ensemble on stage RT – 500Hz

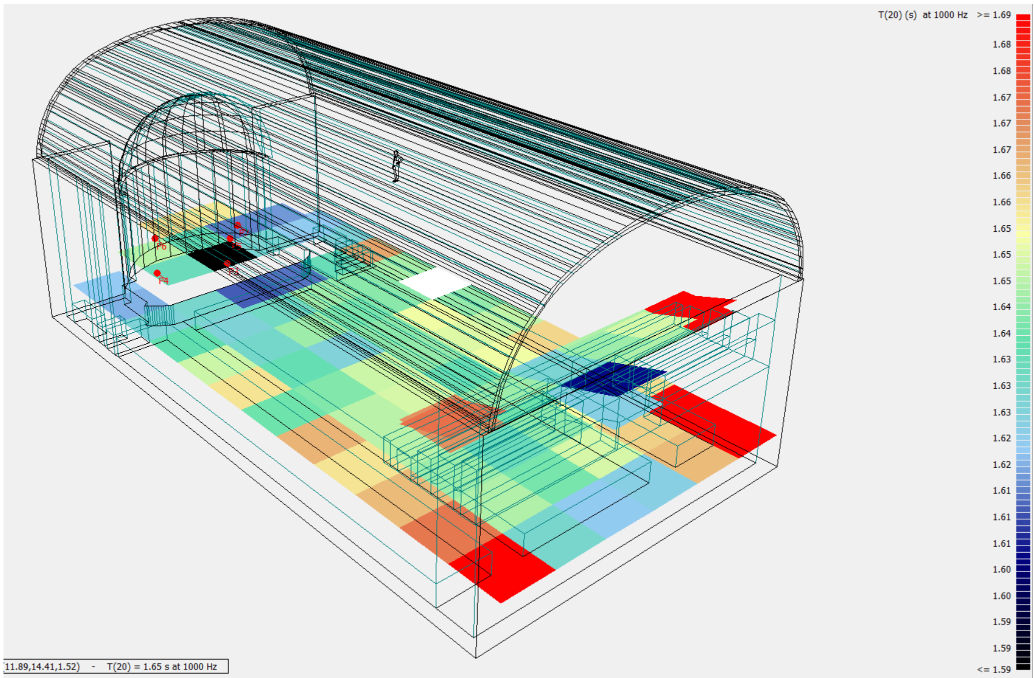


Figure 202 ODEON Wigmore Hall - Source Ensemble on stage RT– 1000Hz

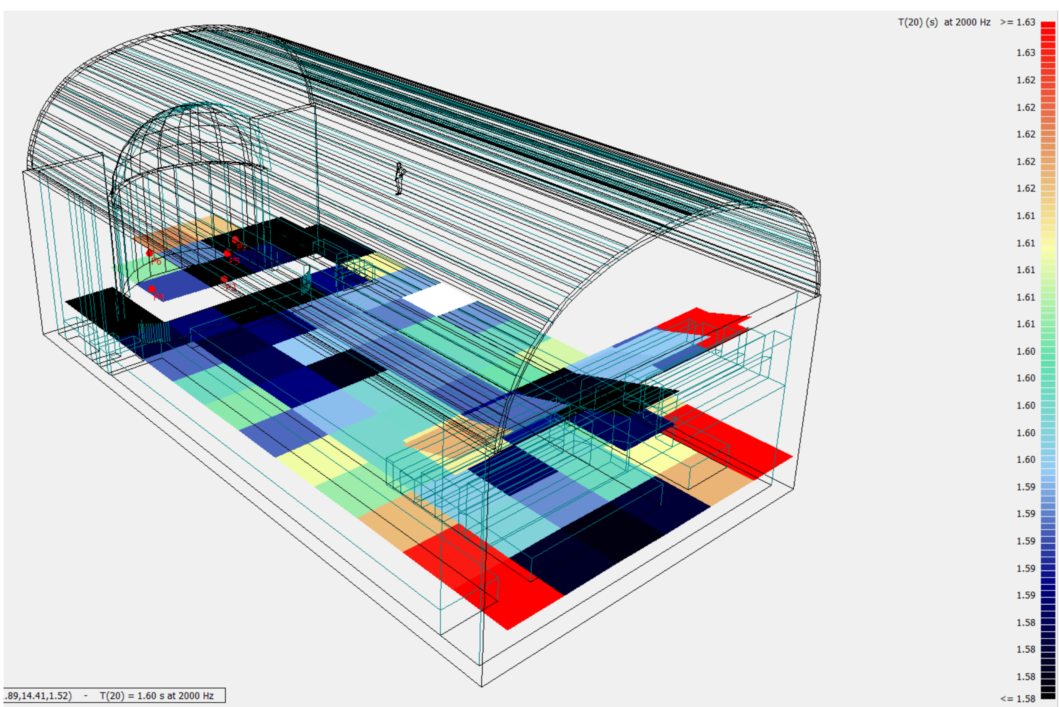


Figure 203 ODEON Wigmore Hall - Source Ensemble on stage RT – 2000Hz

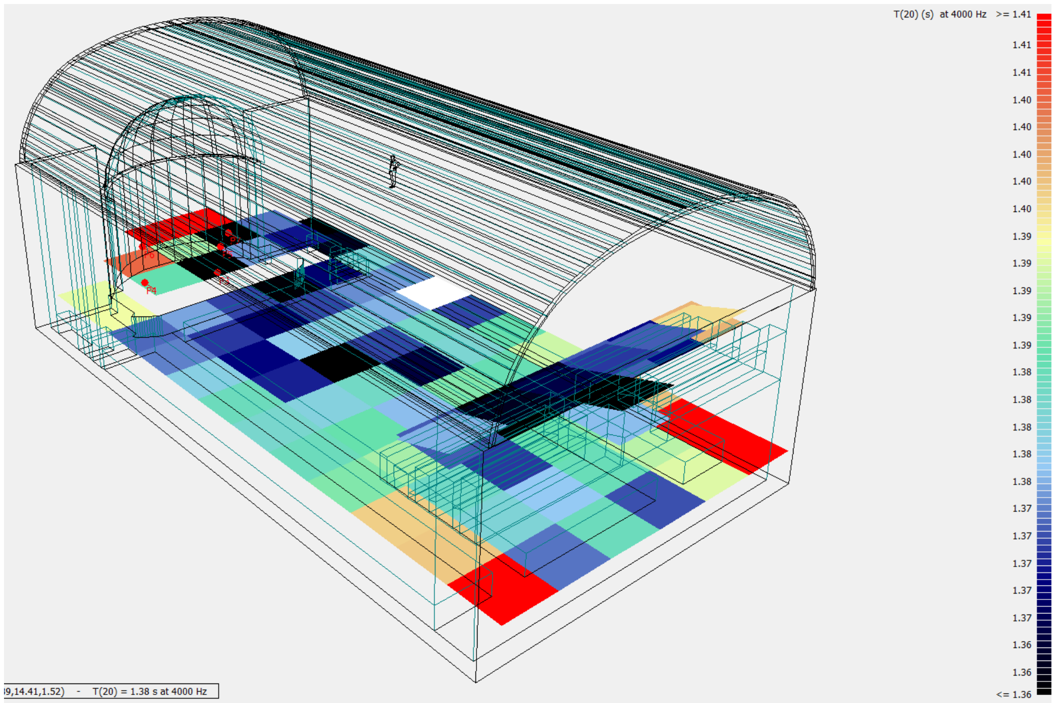


Figure 204 ODEON Wigmore Hall - Source Ensemble on stage RT – 4000Hz

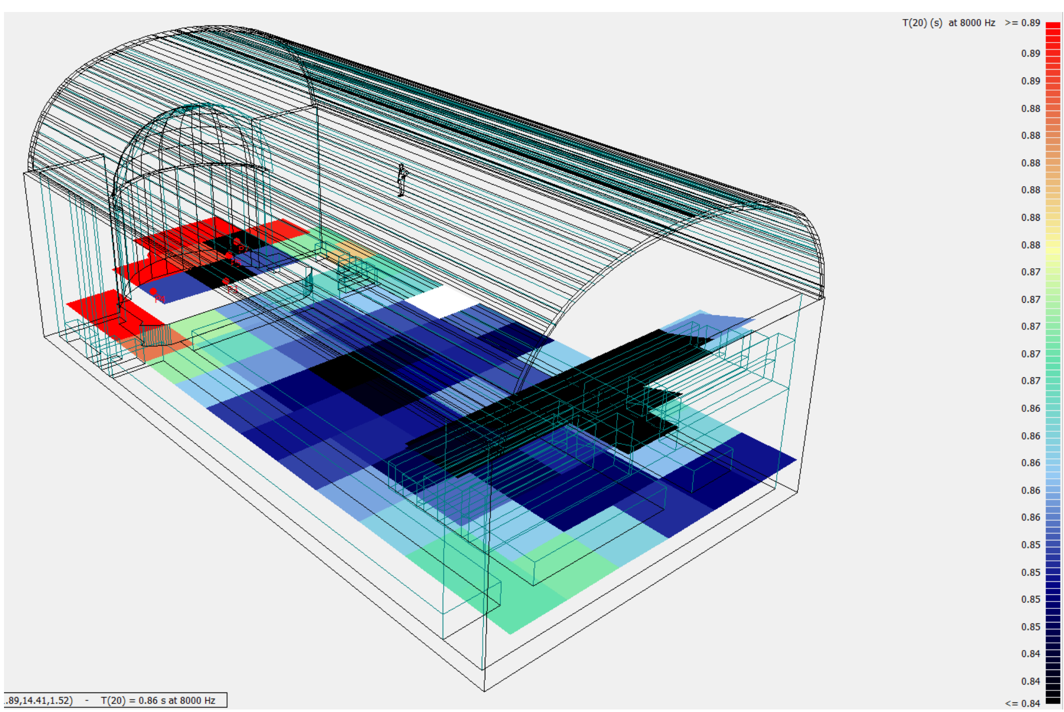


Figure 205 ODEON Wigmore Hall - Source Ensemble on stage RT – 8000Hz

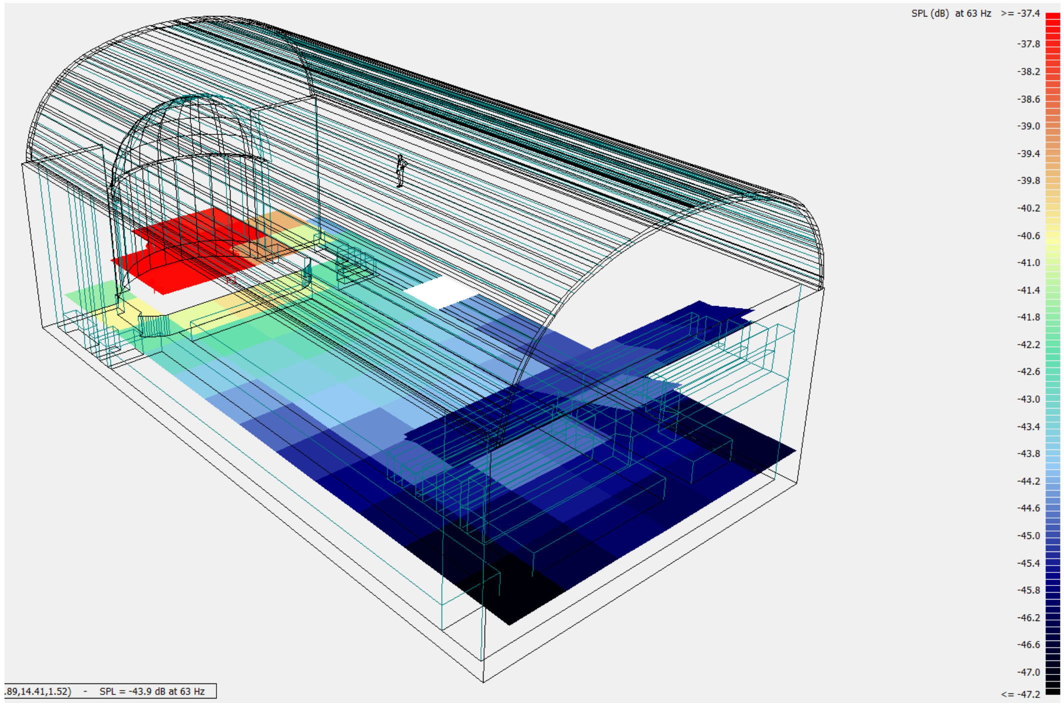


Figure 206 ODEON Wigmore Hall - Source Ensemble on stage SPL – 63Hz

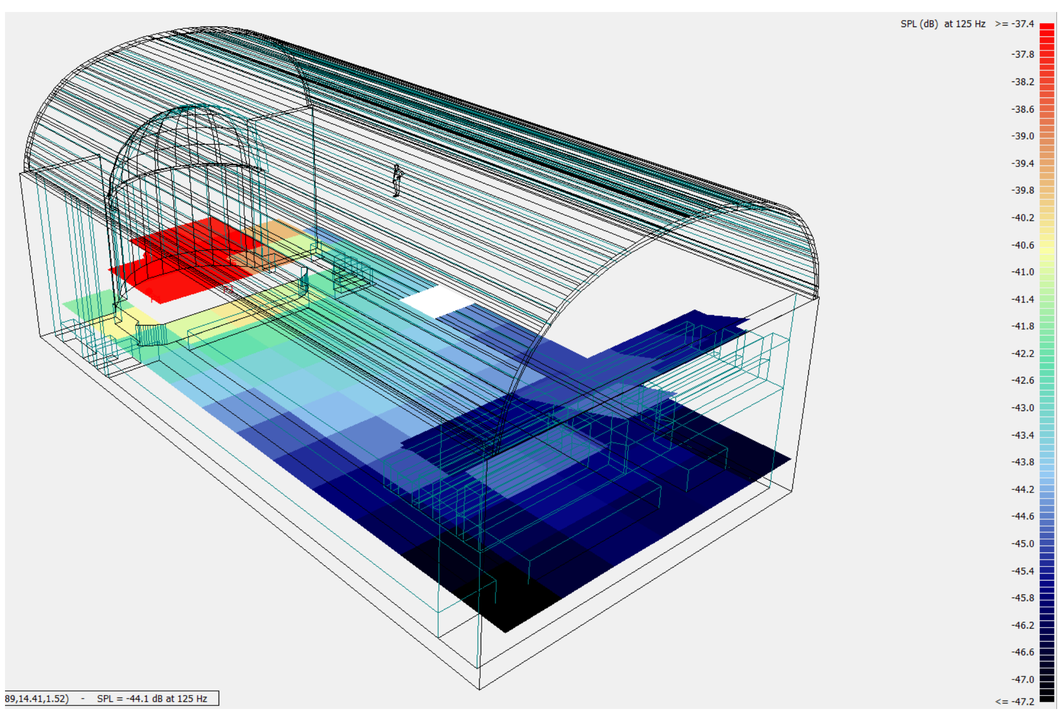


Figure 207 ODEON Wigmore Hall - Source Ensemble on stage SPL – 125Hz

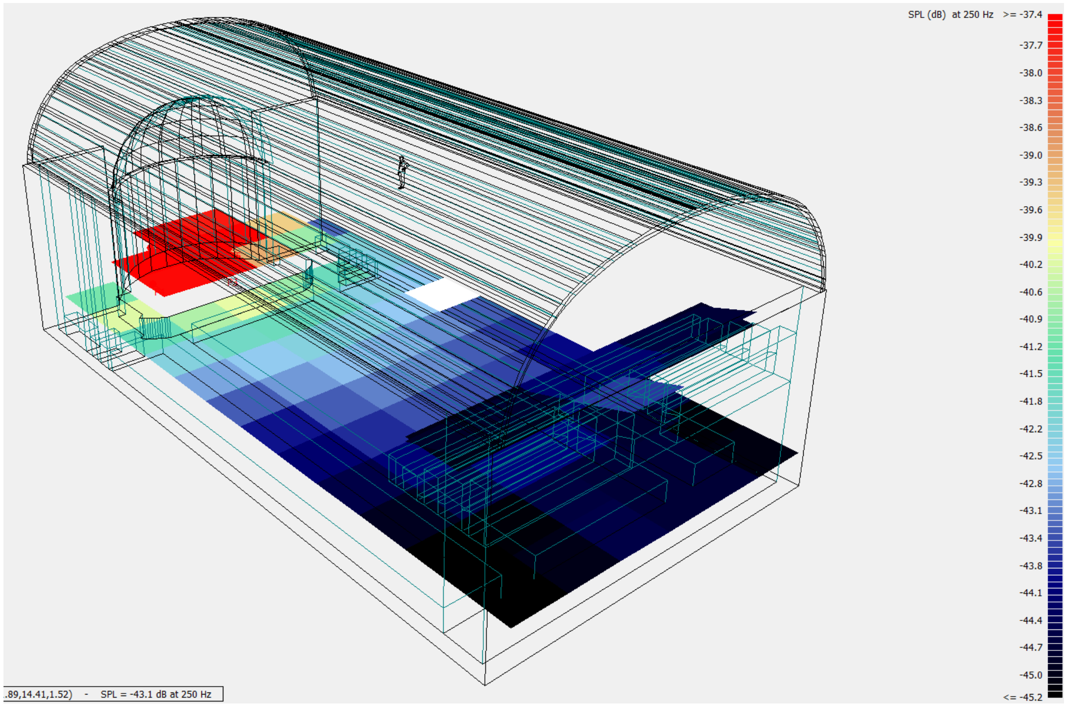


Figure 208 ODEON Wigmore Hall - Source Ensemble on stage SPL – 250Hz

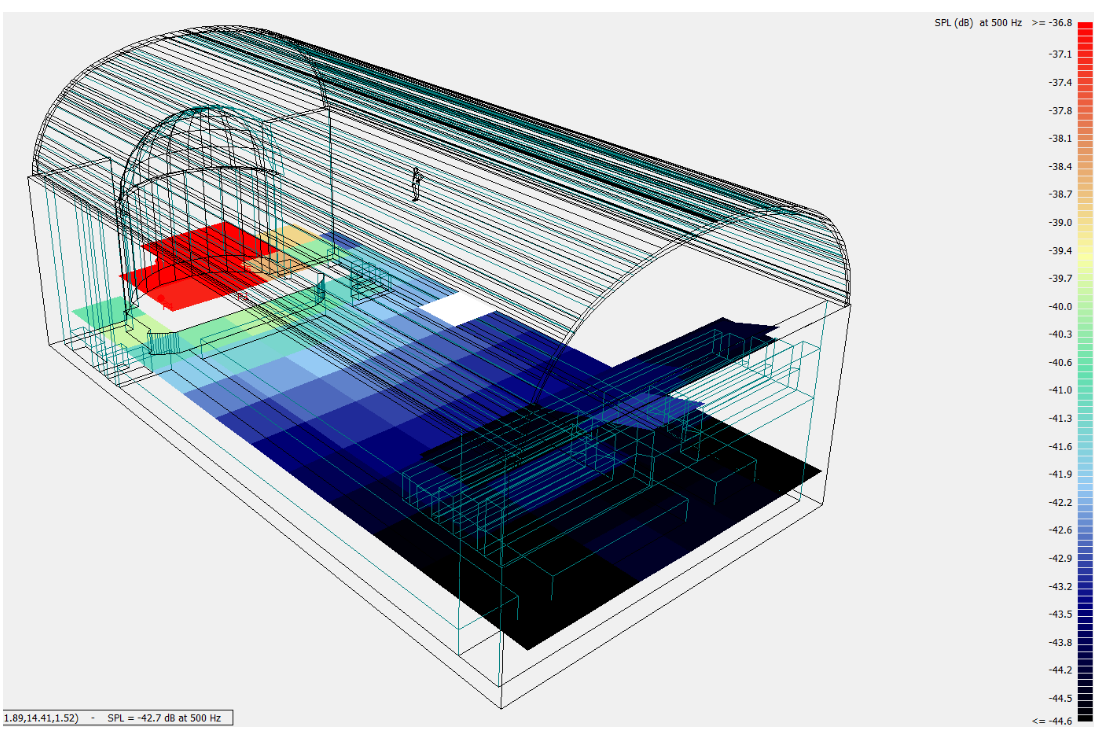


Figure 209 ODEON Wigmore Hall - Source Ensemble on stage SPL – 500Hz

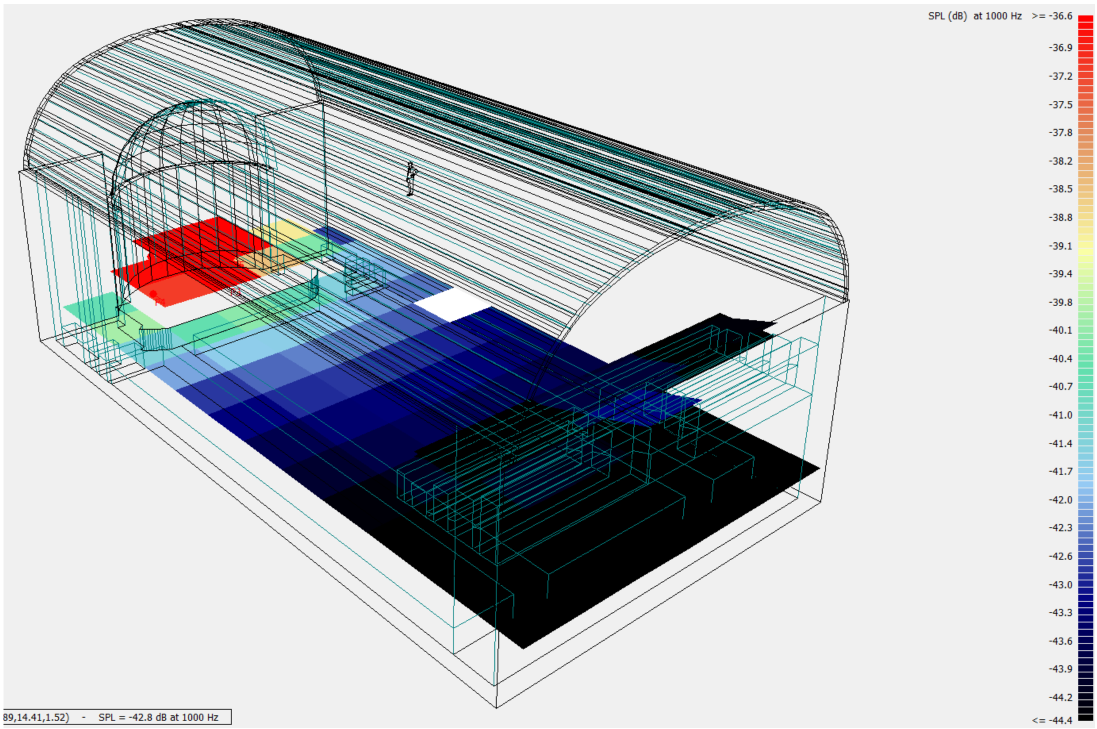


Figure 210 ODEON Wigmore Hall - Source Ensemble on stage SPL – 1000Hz

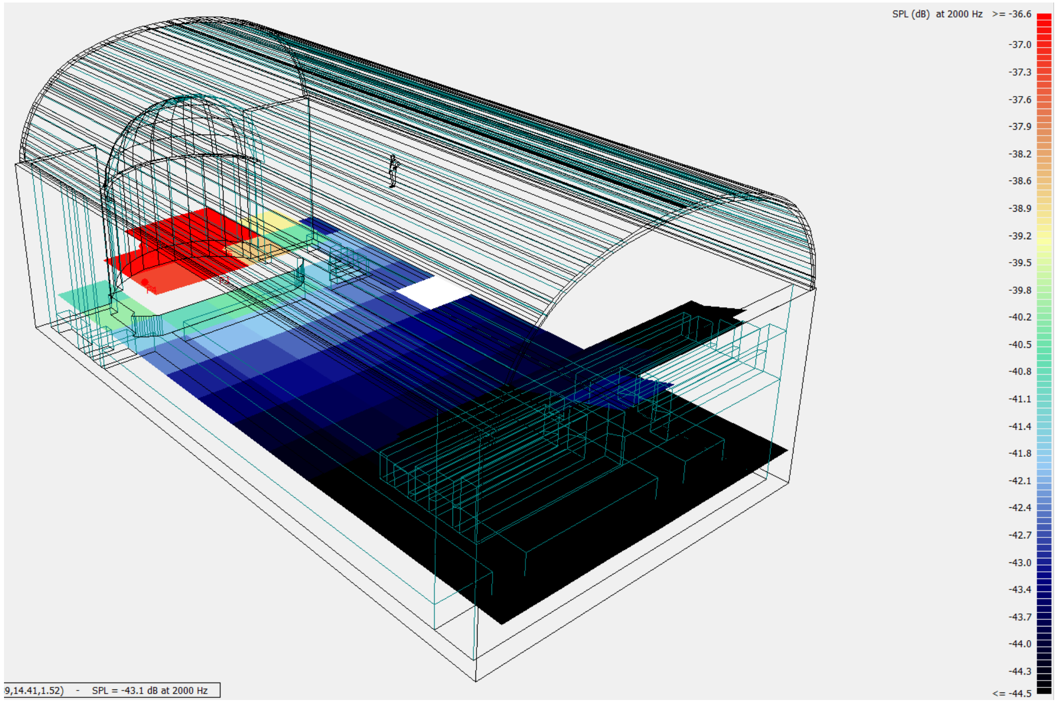


Figure 211 ODEON Wigmore Hall - Source Ensemble on stage SPL – 2000Hz

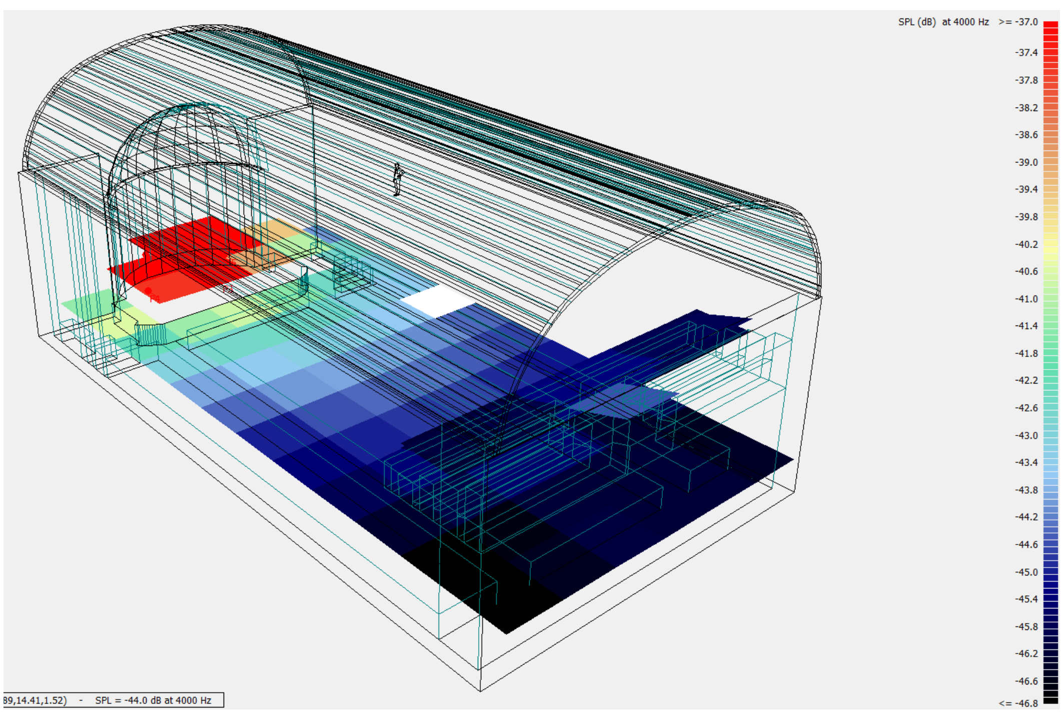


Figure 212 ODEON Wigmore Hall - Source Ensemble on stage SPL – 4000Hz

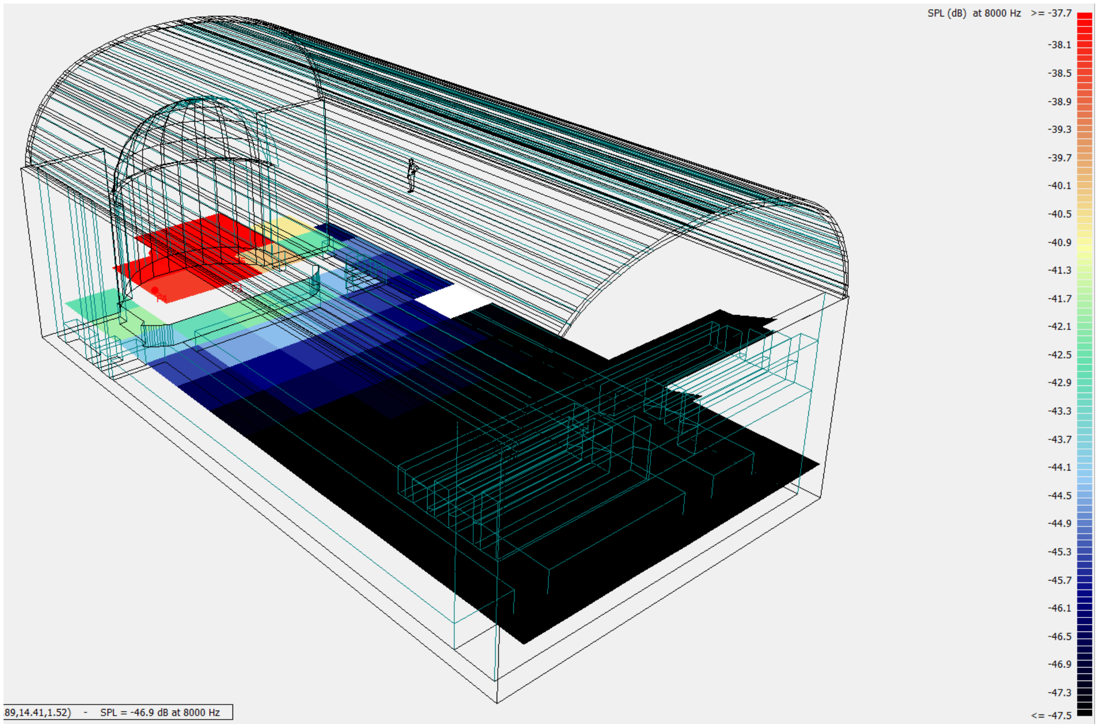


Figure 213 ODEON Wigmore Hall - Source Ensemble on stage SPL – 8000Hz

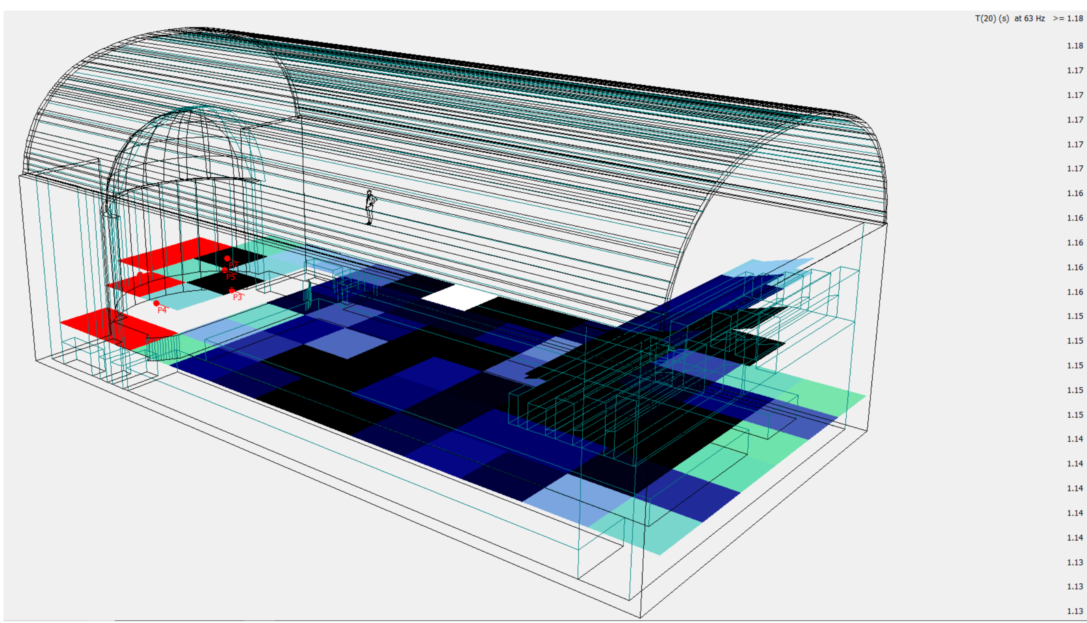


Figure 214 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT – 63Hz

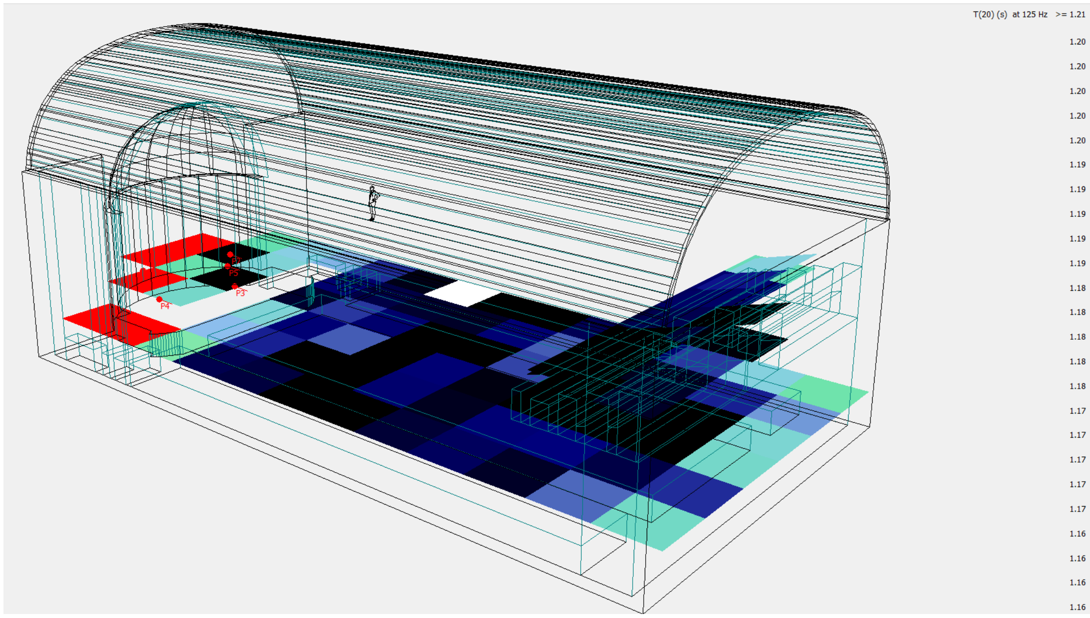


Figure 215 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT–

125Hz

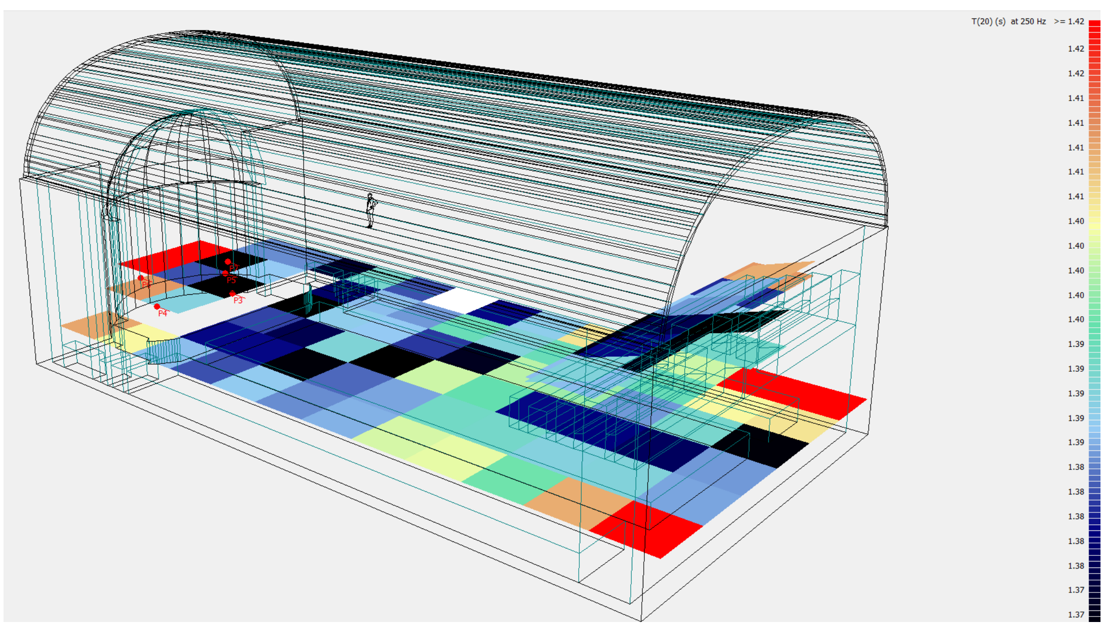


Figure 216 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT –

250Hz

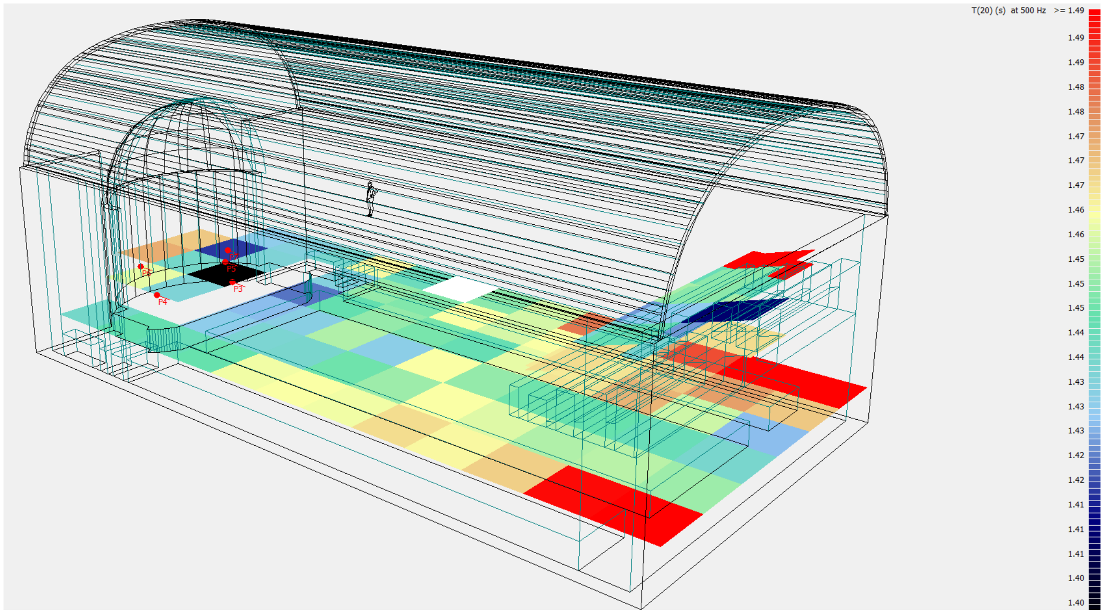


Figure 217 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT – 500Hz

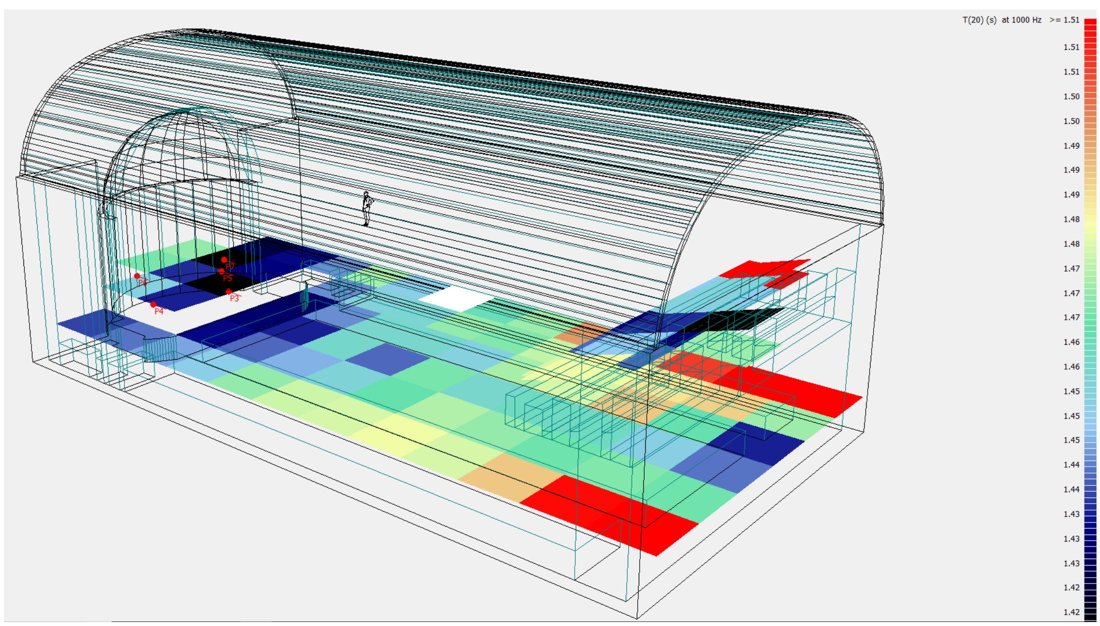


Figure 218 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT – 1000Hz

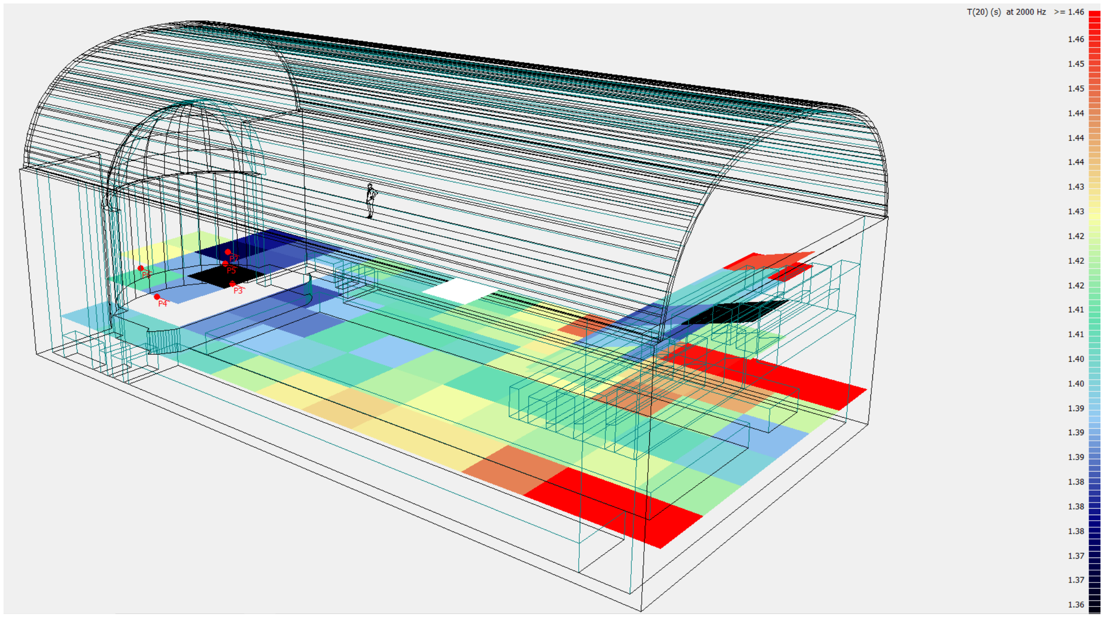


Figure 219 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT – 2000Hz

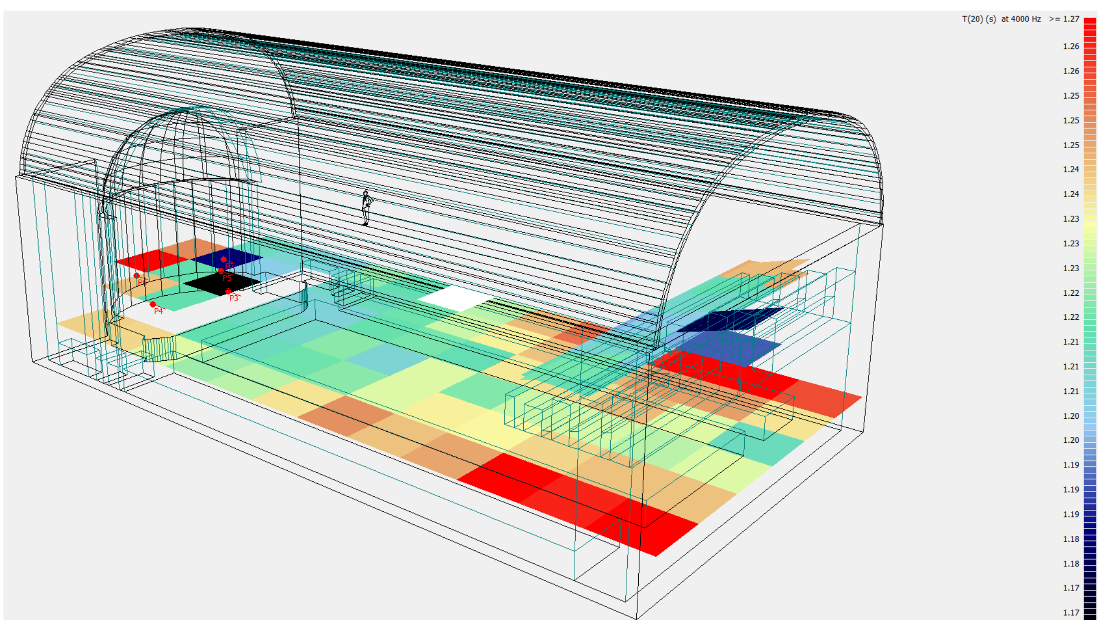


Figure 220 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT– 4000Hz

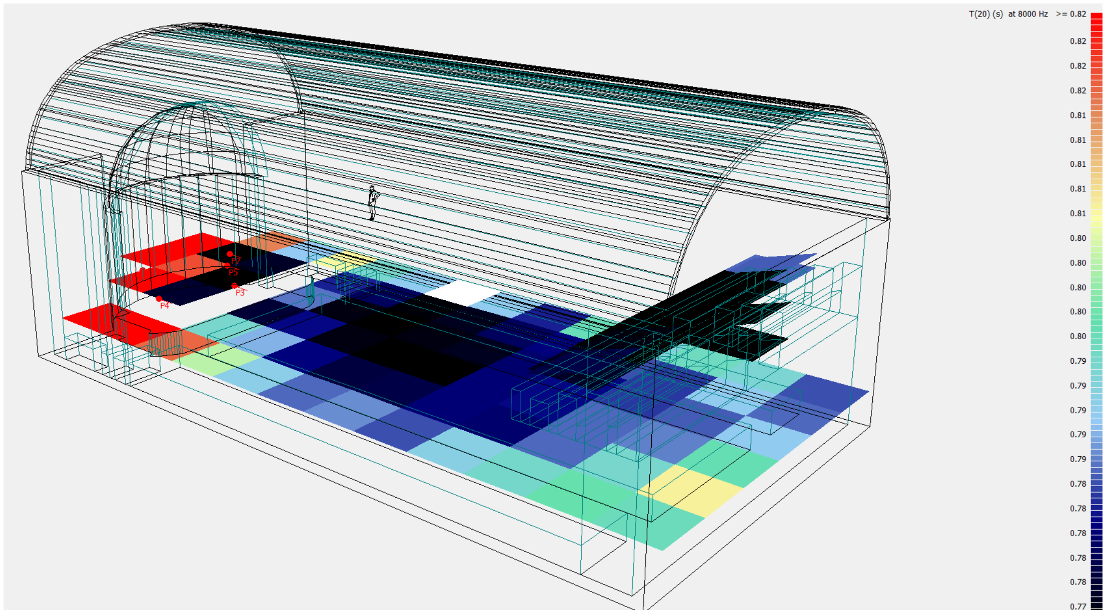


Figure 221 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating RT – 8000Hz

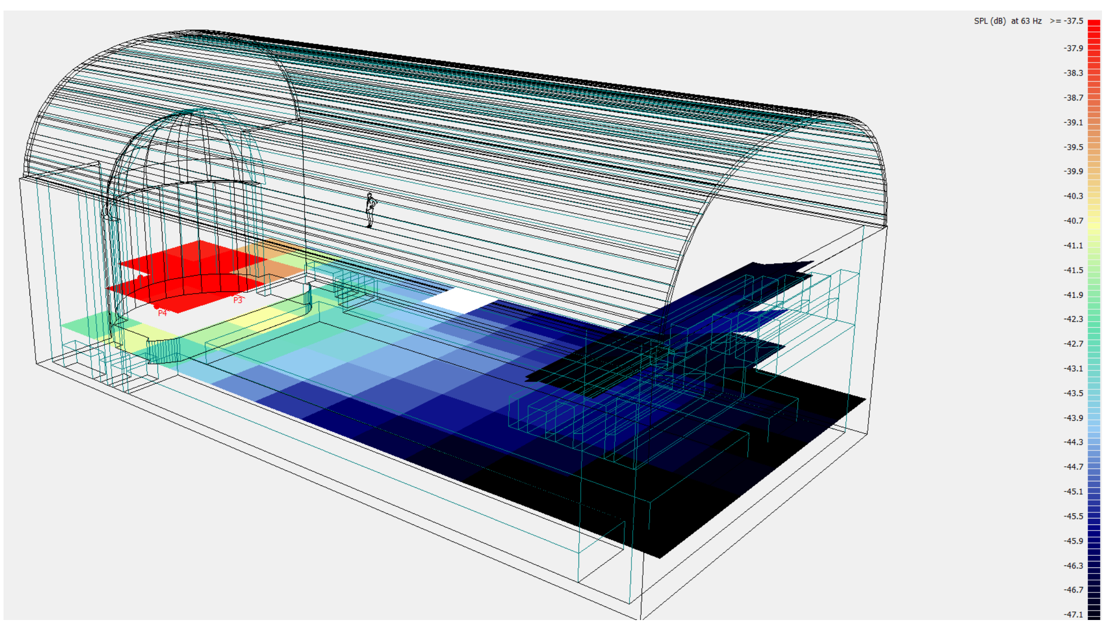


Figure 222 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL – 63Hz

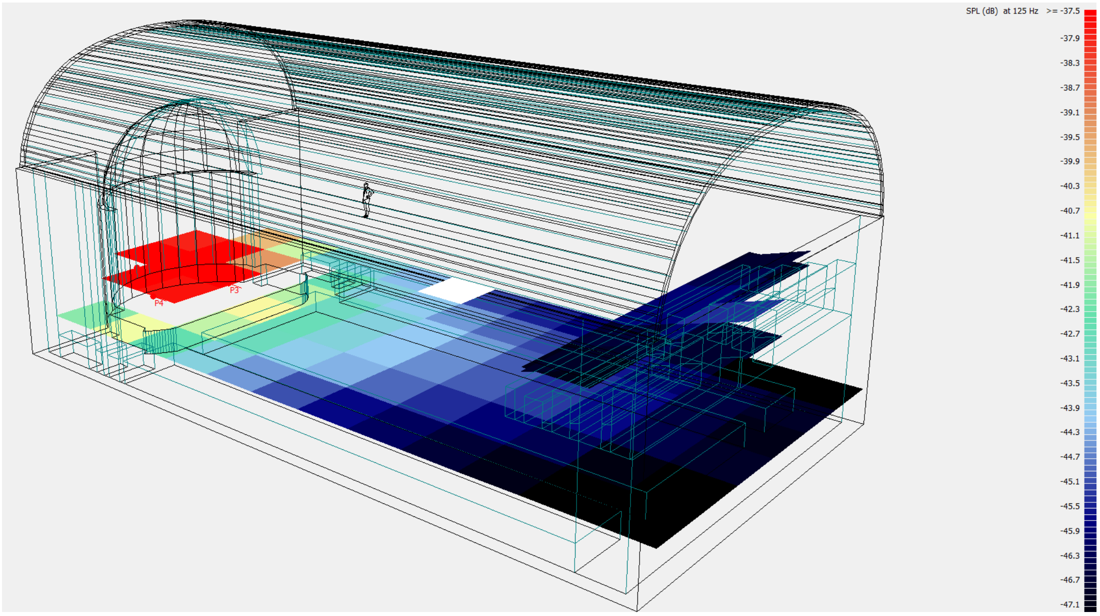


Figure 223 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL – 125Hz

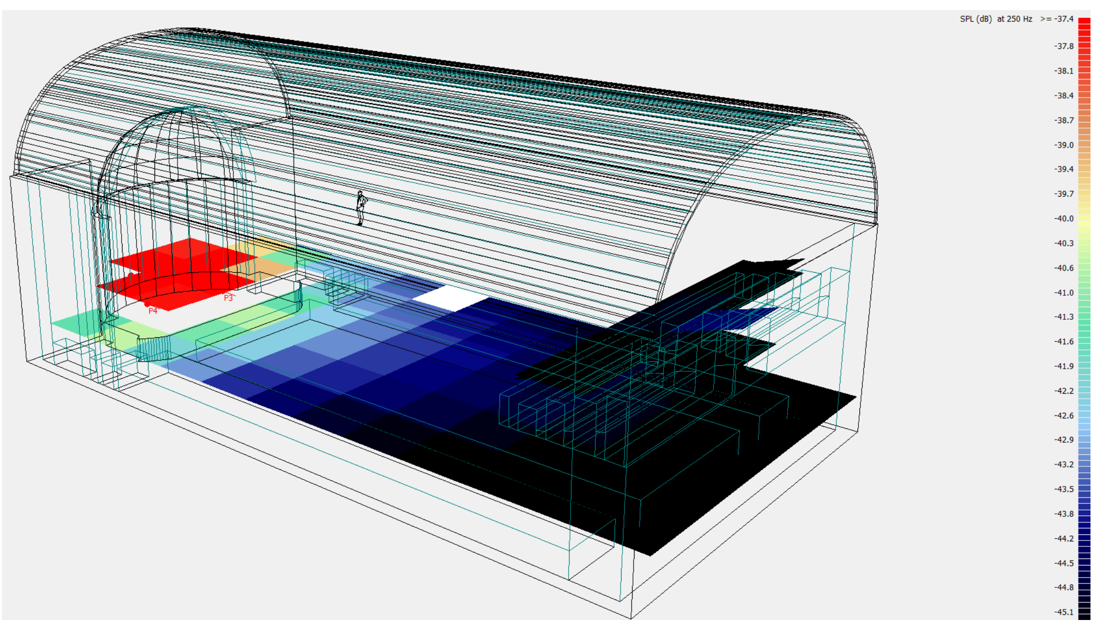


Figure 224 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL – 250Hz

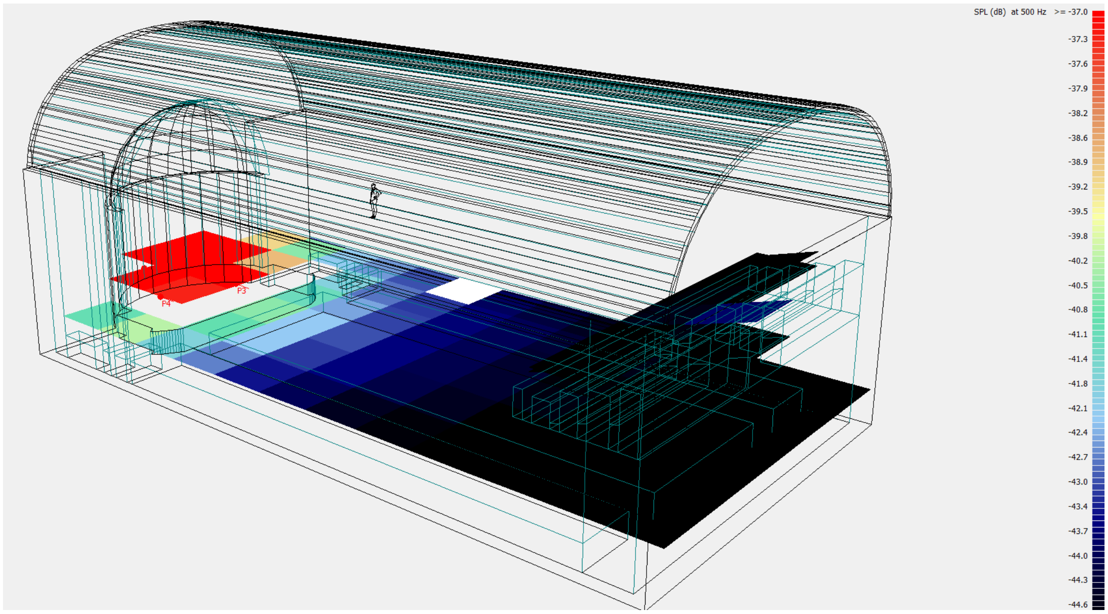


Figure 225 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL – 500Hz

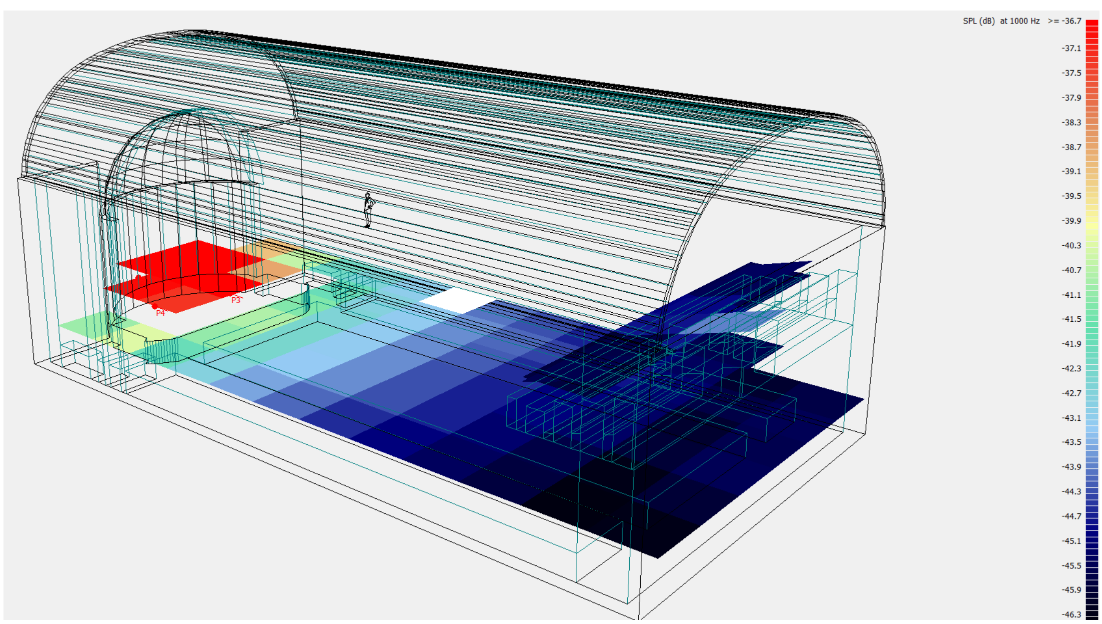


Figure 226 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL – 1000Hz

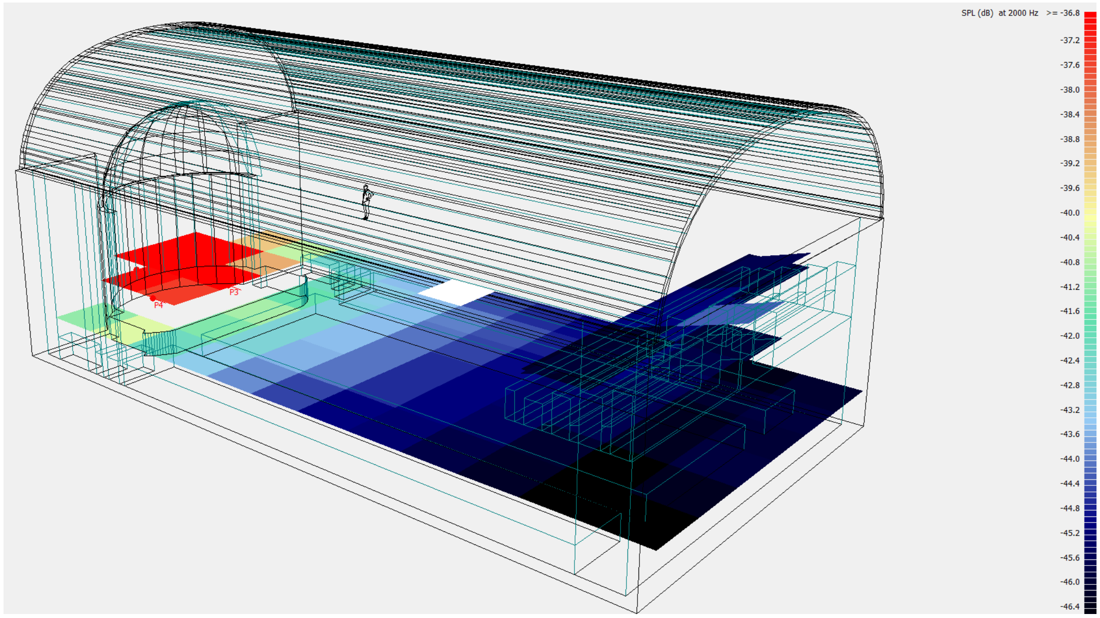


Figure 227 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL – 2000Hz

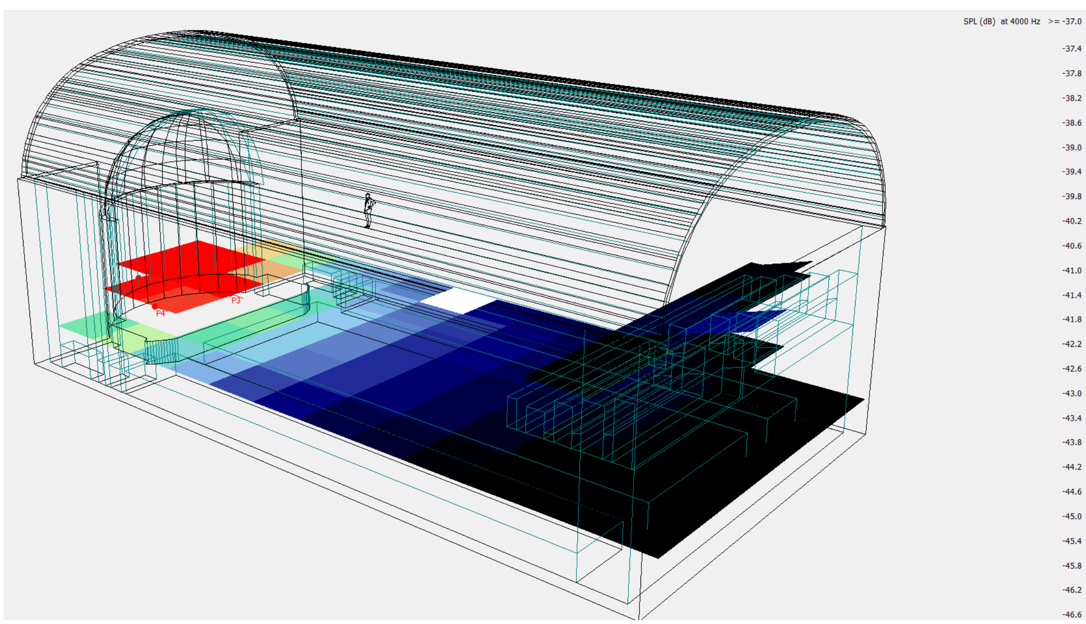


Figure 228 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL – 4000Hz

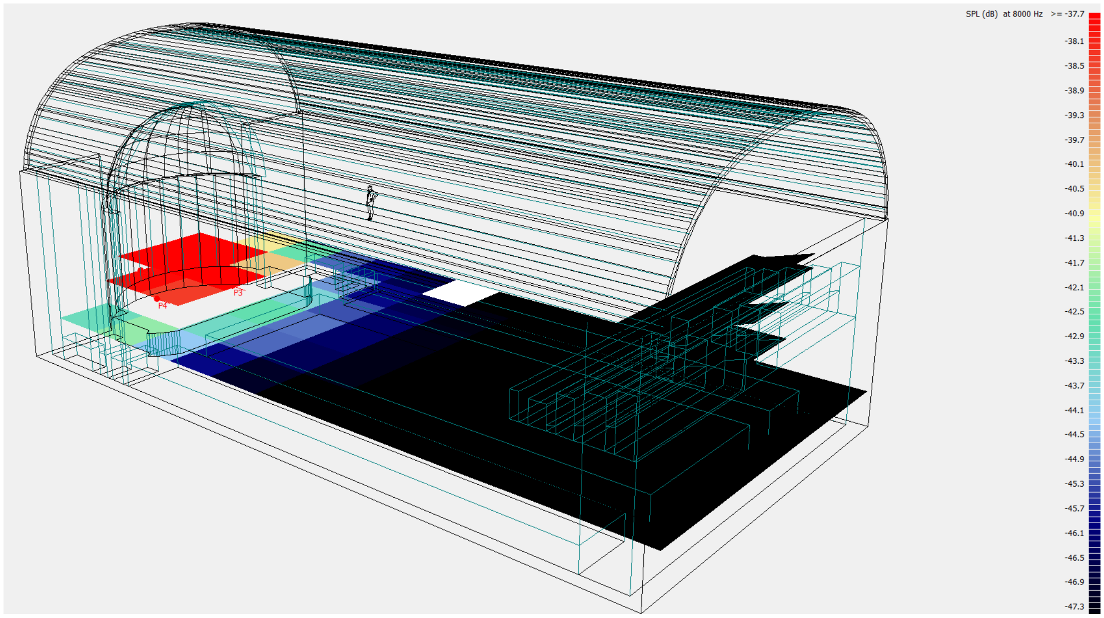


Figure 229 ODEON Wigmore Hall - Source Ensemble on stage - Occupied Seating SPL

– 8000Hz

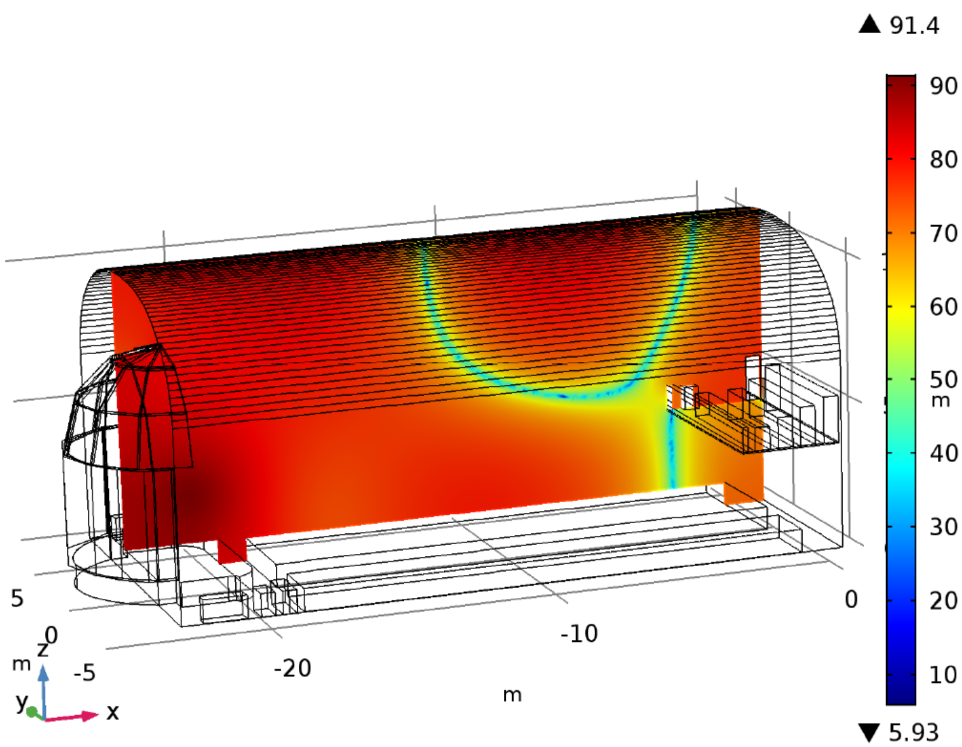


Figure 230: Wigmore Hall - One Source 25Hz

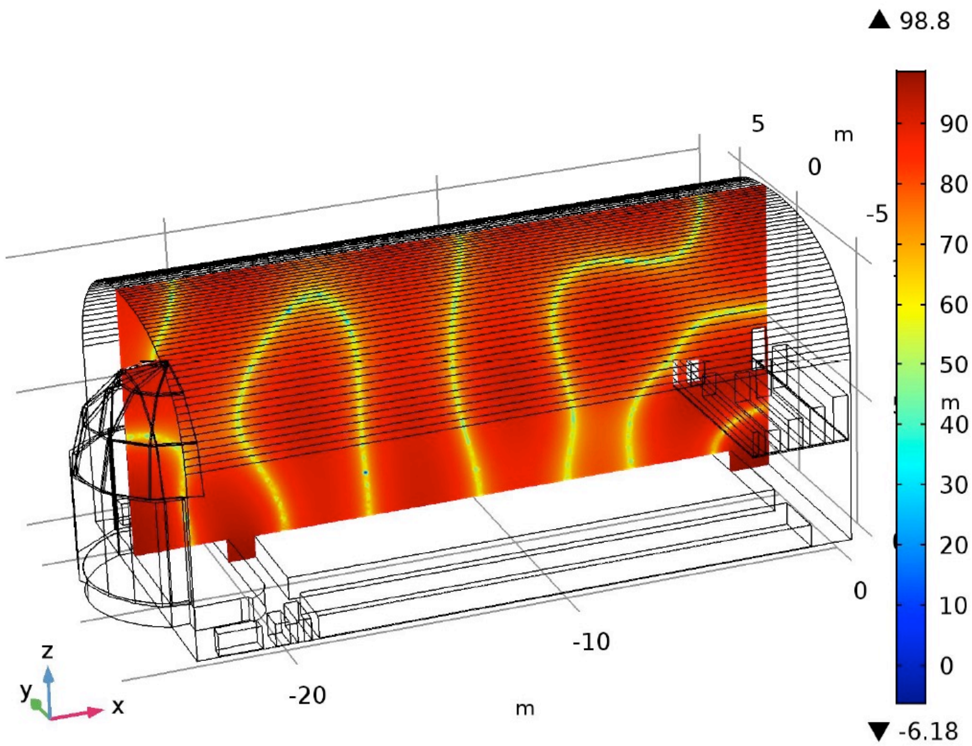


Figure 231: Wigmore Hall - One Source 50Hz

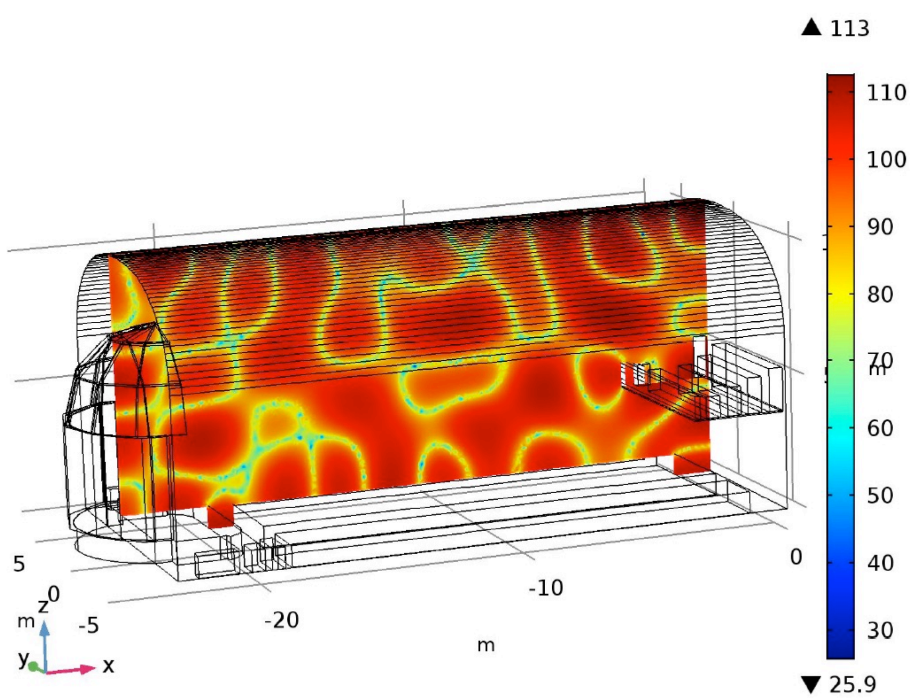


Figure 232: Wigmore Hall - One Source 100Hz

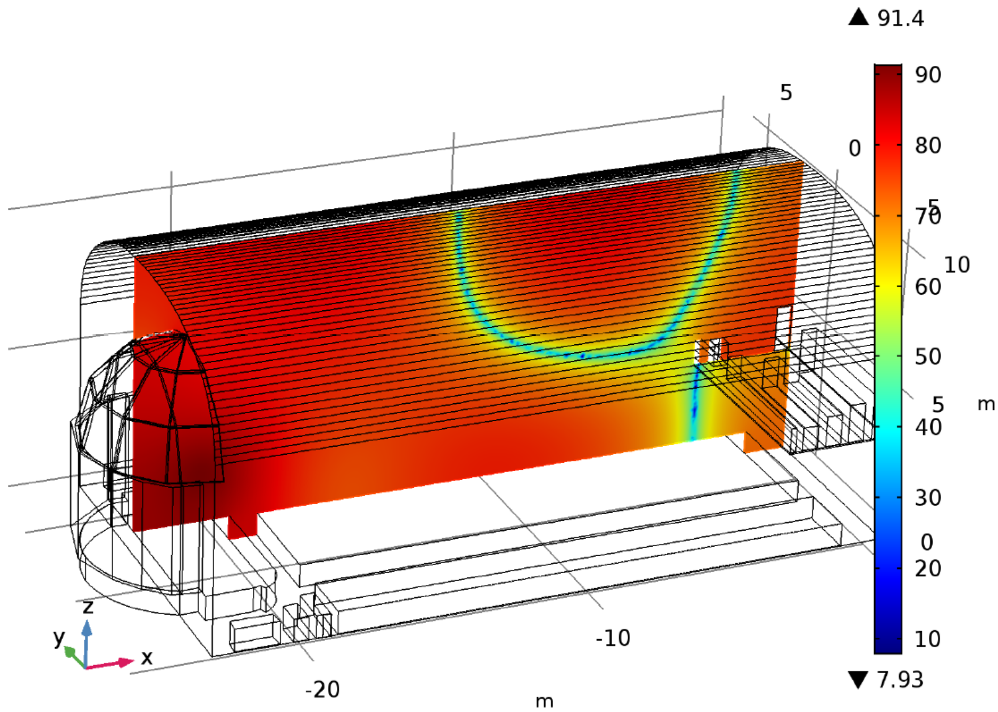


Figure 233: Wigmore Hall - One Source 25Hz

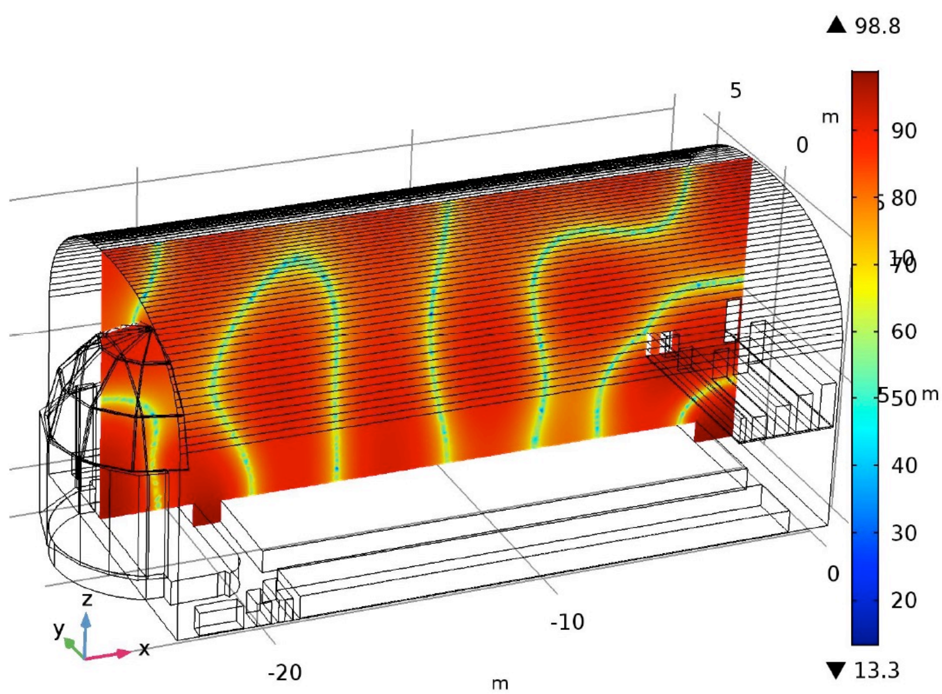


Figure 234: Wigmore Hall - One Source 50Hz

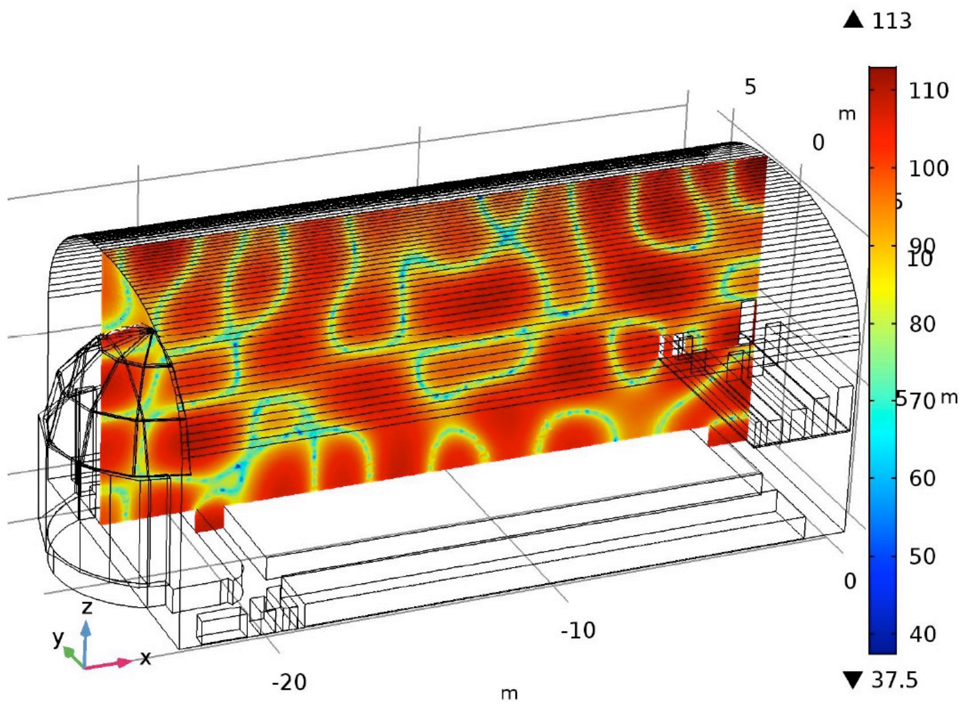


Figure 235: Wigmore Hall - One Source 100Hz

References

1. Vercammen, Martijn. *Sound Concentration Caused by Curved Surfaces.* Department of the built environment. Eindhoven : Eindhoven University of Technology. PhD Thesis.

2. Barron, Michael. *Auditorium Acoustics and Architectural Design.* Abingdon : Spon Press, 1993.

3. Princess of Wales Theatre. [Online] http://www.seetorontonow.com/listings/princess-of-wales-theatre/#sm.012jg9xt18phe5h11we2deupavkzi.

4. O'Keefe, John. *Learning Modern Acoustical Design from Traditional Choir Venues.* Toronto : akuTEK, 2013.

5. Wulfrank, Thomas and Orlowski, Raf. *Acoustic Analysis of Wigmore Hall, London, in the Context of the 2004 Refurbishment.* Cambridge : s.n., 2006. Institute of Acoustics, Copenhagen 2006. Vol. 28. Part2.

6. Wigmore Hall. [Online] https://www.timeout.com/london/music/venues/wigmore-hall.

7. Vercammen, M. Peutz. *The reflected sound field by curved surfaces.*: Acoustics 08 Paris, 2008. Acoustics 08 Paris.

8. Gade, A. C. *Objective measurements in Danish conert halls.* 1985. Institute of Acoustics. Vol. Part 1, pp. 9-16.

9. Barron, Michael. *Objective survey of UK concert halls.* 1985. Institute of Acoustics. pp. 1-8.

10. Barron, Michael. *Theory and Measurement of Early, Late and Total Sound Levels in Rooms.* 3087, 2015, The Journal of the Acoustical Society of America, Vol. 137.

11. History. *Wigmore Hall.* [Online] 2018. https://wigmore-hall.org.uk/about-us/history.

12. Odeon Room Acoustics Software, http://odeon.dk. [Online] https://odeon.dk/acoustics_simulation_software/specifications/.

13. Comsol Multiphysics Software, https://www.comsol.com.

14. Jensen, Mads Herring. Modeling Room Acoustics with COMSOL Multiphysics. *COMSOL Multiphysics.* [Online] 02 25, 2015. [Cited: 03 22, 2018.] https://www.comsol.com/blogs/modeling-room-acoustics-with-comsol-multiphysics/.

15. ROXUL. *Rockwool.* [Online] https://www.rockwool.com/.

16. Reynolds, Douglas D. *Engineering Principles of Acoustics - Noise Vibration Control.* [ed.] Robert Roen. Boston : Allyn and Bacon, Inc., 1981.

17. Kimura, Masateru, et al. *A new high-frequency impedance tube for measuring sound absorption coefficient and sound transmission loss.* Melbourne : Brüel & Kjær Sound & Vibration Measurement, 2014. Inter-Noise 2014.

18. Russel, Daniel A. Acoustics and Vibration Animations. *Acoustics and Vibration Animations.* [Online] PennState Acoustics, 2011. [Cited: March 22, 2018.] http://www.acs.psu.edu/drussell/demos.html.

19. Angus, J. A. S., Marvin, A. C. and Clegg, J. *The effect of acoustic diffusers on room mode decay.* New York : University of York, 1995. Audio Engineering Society 99th Convention. pp. 1-13.

20. Room Modes. [Online] [Cited: March 22, 2018.] http://artsites.ucsc.edu/ems/music/tech_background/TE-02/modes/Modes.html.

21. Sorensen, Mike. Room Modes. *AcousticFields.com.* [Online] July 15, 2012. [Cited: March 22, 2018.] https://www.acousticfields.com/room-modes/.

22. Vercammen, M.L.S. *Reflection of sound by concave surfaces.* Sydney : s.n., 2010. International Congress on Acoustics.

23. Vercammen, M.L.S. *Auditorium Acoustics and Architectural Design.* Wijchen : s.n., 2008. Acoustic '08 Paris.

24. Gade, Anders Christian. 9. Acoustics in Halls for Speech and Music. [book auth.] Thomas D. Rossing. *Springer Handbook of Acoustics.* New York : Springer Science+Business Media, 2007.

25. Associates, Gracey &. *Acoustic Glossary.* [Online] http://www.acoustic-glossary.co.uk/definitions-e.htm.

26. Bradley, J. S. *Review of objective room acoustics measures and future needs.* Melbourne : Institute for Research in Construction, National Research Council, 2010. Proceedings of the International Symposium on Room Acoustics, ISRA 2010.

27. ISO 3382-1 . *Acoustics - Measurements of room acoustic parameters - Part 1: Performance Spaces.* Geneva, Switzerland : s.n., 06 15, 2009.

28. Ahnert, Wolfganf and Schmidt, Wolfgang. Fundamentals to perform acoustical measurements; Appendix to EASERA. *Easera.* [Online] 2016. http://easera.afmg.eu/.

29. ISO 3382-2 . *Acoustics - Measurement of room acoustic parameters - Part 2: Reverberation time in ordinary rooms.* Geneva, Switzerland : s.n., 06 15, 2008.

30. Cavanaugh, William J. and Wilkes, Joseph A. *Architectural Acoustics:Principles and Practice.* New Work : John Wiley and Sons, Inc., 1999.

31. Cremer, L. and Müller , H. *Principles and Applications of Room Acoustics, Volume 1.* s.l. : Applied Science Publishers Ltd, 1982.

32. Rindel, J. H. *Attenuation of Sound Reflections from Curved Surfaces.* 1985. Proceedings of 24th Conference on Acoustics. pp. 194-197.

34. Looking down the nave, St. Pauls Cathedral. [Online] https://www.stpauls.co.uk/visit.

35. Zhengqing, Liu, Fard, Mohammad and Jazar, Reza. *Development of an Acoustic Material Database for Vehicle Interior Trim.* Melbourne : Researcg Gate. 18th Asia Pacific Automotive Engineering Conference.

36. Morgans, Rick C., et al. *Statistics and the Two Microphone Method for the Measurement of Sound Absorption Coefficient.* Adelaide : School of Mechanical Engineering. Acoustics 2004.

Equation

1. M. R, Schroeder, *The Schroeder frequency revisited.* Physics Today, Woodbury, MASS, American Institute of Physics, May 1996.