Case study: La Geode, Paris
Measurements and simulations of the focussing phenomenon in a discretized hemispherical building

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Introduction

The Geode is located in the XIX^{th} district of Paris, in the Parc de la Villette. It is a building unique of its kind, a fusion of art, architecture and sound. It is almost an entire sphere, equivalent of a twelve story building, composed of thousands of polished, mirror alike, stainless steel triangles. Inside, the main hall (used as a cinema), there was a giant hemispherical screen that resembled to a planetarium complimented by a distinctive sound system. It first opened doors in 1985 and acoustic consultant was a team from Peutz, alongside the architect - Adrien Fainsilber. The amplified sound system was custom designed by the speaker manufacturer CABASSE. Although it was a masterpiece at first, the modern flavour of the building evaporated, along with economic and governance changes, renovations are currently in progress. The aim of the project is to design a modernised interior, adapted to the contemporary IMAX cinema halls. The shape and purpose of this space make room acoustics one of the essential design-leading affiliates. A theoretical study was conducted, acoustic measurements were done in the existing hall and geometrical acoustics software (CATT Acoustics) was used for simulations and testing possible solutions. The similarities between the measurements and the simulations results are shown. Optimized geometrical model was used to propose a design solution.

Architecture and Geometry

The entire building consists of two volumes (1), the rectangular base, entrance and public area, and the sphere, where the main cinema hall is, enclosed by its complex facade. There are no typical walls and ceiling and the interior side of the facade is the shell shaping the main hall.

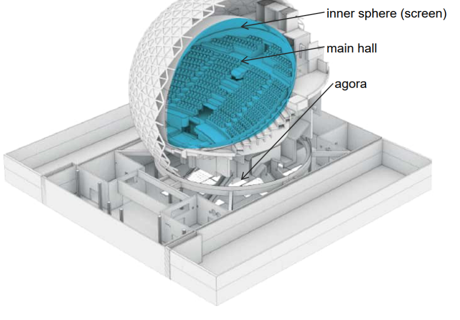


Figure 1: 3D of the building and the volume of the hall

The frame of the triangular geodesic structure is made of thin metal bars net, that is the main bearing construction for the enclosing sandwich panels, composed of folded metal sheet, hydro insulation and mineral wool. Their overall thickness is approximately $50cm$. The outer, visible layer has a diameter of $36m$ and 6433 equilateral triangles. The main hall, however, is a much smaller volume that it appears on the outside, of approximately $8000m^3$ in less than half of the upper hemisphere. The floor surface is approximately $400m^2$ and it fits 350 chairs. Although often referred as a spherical building, the Geode is in fact, a very well meshed sphere. All the elements, bars and nodes are planar and identical, but the assembly they form appears as curved.

Sound in the Geode [1]

In any space enclosed by curvature, the sound is converged and because of the massive concentration we hear a narrow amplification, a tone coloration or an echo, especially in large spaces, with listeners further from the source. These echoes are very persistent and often problematic in speech intelligibility, music appreciation, source localisation or feedback on microphones. To find out whether the phenomena is 'just existing' or problematic for the use of the hall, we need to position the listening area plane and determine its amplitude.

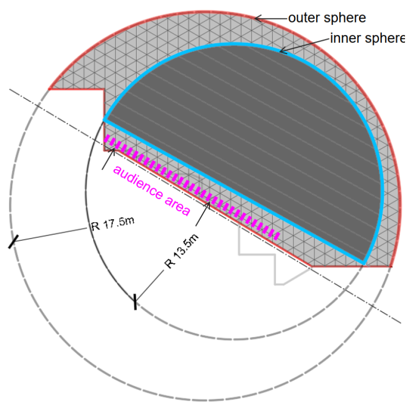


Figure 2: Vertical section of the volume trough the audience area

In fact, the listening area is exactly between the central planes of both spheres (2). Relative to the bigger sphere, it is inside, while in regards to the screen, the audience plane is outside. When the inner sphere (screen) is absorptive, the amplitude can be reduced.

Objectives

The constraints of the projects are separated into two main categories, first being the technical and legal limitations of a renovation project and second the future use as a certified IMAX cinema hall.

The core of the project is the heavy renovation of the projection room. The biggest particularity comes from the fact that it is impossible to fix anything on the external dome bearing construction, due to the ownership and concession contract. Accordingly, excluding the facade (the shell), the entire absorbing treatment, in addition to the seating and walls, must be positioned on the screen structure. This is a very limiting circumstance and a base line for a multi-speciality compromise.

The IMAX objectives concerning the room acoustics parameters are mainly the Reverberation time and the control of sound reflections.

The reverberation time (RT60) Reference at 500 Hz and above should be nominally 0.5 second for smaller theatres with fewer than 400 seats. A smooth rise below the 500 Hz value is acceptable as long as it is gradual without significant peaks or voids. The applicable values to the case are shown in Table 1.

Table 1: IMAX max reverberation time requirement

f (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k
$Rt(s)$	1	0.75	0.65	0.55	0.5	0.5	0.5	0.5	0.5	0.5

To obtain such low reverberation time, all wall and ceiling surfaces in the theatre require full coverage of absorption, including the face of the screen pit and any low walls or parapets facing the screen or audience. Any hard surfaced architectural or structural elements require absorptive or diffusive treatment. Since the audience is a component of the interior absorption and reflection control, it is necessary that the seats selected have similar acoustical characteristics when unoccupied. The floor is typically treated with carpet and pad for the lower pit area. Carpet without pad is acceptable for all other surfaces of the seating riser and steps.

To provide a proper listening environment, the interior of the theatre must be designed to eliminate and control discrete sound reflections within the theatre, which is just as important as achieving the desired reverberation time. Audible discrete reflections, flutter echo, image shifting and focusing must be avoided to produce the clearest possible image of the reproduced sound from the loudspeakers [2].

In order to meet the IMAX acoustic performance aim in the audience area, it is essential that the acoustic treatment to be implemented above the screen meets the two constraints at the same time: high absorption demand in all frequency bands and a minimum surface mass. By treating all recommended surfaces, we would comply to the requirements for the low reverberation time. As a result, the following study is stressing the essential issue - the focussing in the hemisphere.

Methods: Measurements

Two measurement campaigns were conducted in the existing volume. The first was mainly to measure Room Impulse Response using MLSSA (Maximum-Length Sequence System Analyzer), with MLS (maximum length sequence signal). MLSSA is an audio and acoustics measurement system based on maximum-length sequences. It is a single channel analyzer that employs a test signal (MLS, logarithmic or linear sweep) as the preferred alternative to the conventional white noise stimulus, because it can be precomputed and does not need to be measured simultaneously with the system response. A peculiarity prior to the measurements themselves was the determination of the positions for the equipment. An internal company protocol was followed, therefore all the standard distances in an axis were included, moreover a few additional receiver points were included to observe the extreme amplitude of the focussing phenomena. The source positions are illustrated in blue and the microphone positions are shown in red (see Figure 3).

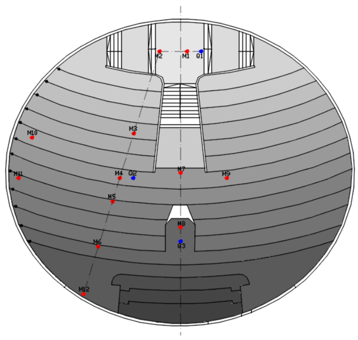


Figure 3: measurement positions (source-blue; receiver-red)

In the second campaign, STI (Speech Transmission Index), Spatial Decay, Clarity, Definition and Centre of gravity time were measured, obtained and analyzed, respectively, however the results are not a part of this study.

Extracting the Reverberation time as genuine values was hard, due to the many reflections arriving, therefore, we stressed on the research and result on the Energy Time Curve plots.

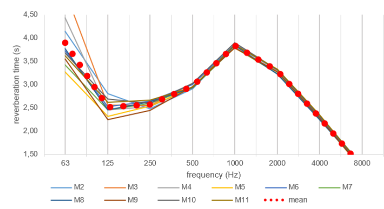


Figure 4: Measured Rt(s) in the empty Geode mean par receiver Rt(s)=3,4s

On the Figure 4 it is evident that for all the receivers the peak is at 1kHz. Due to the fact that the focussing is frequency dependent, multiple hypothesis of why this might be the case arose, some of which are the radius of the sphere ($\approx 17m$), the size of the stairs or the size of the triangles themselves ($1.05m$).

Methods: Simulations

The simulations were performed using CATT Acoustics. The models were mainly created in Google SketchUp, with exception to the precise triangle sphere models generated in 3ds Max.

Model validation

The model calibration is done by comparing the measurement results with different model complexities. Due to the difficulties encountered in the process of comparing the reverberation time, in addition to its irrelevance regarding the main focussing issue, it was decided to look in the arrival times at the reflections in the ecograms. Since the sources used in both measurements and simulations had different amplitudes, while comparing, amplitudes are neglected. Hence, the arrival time overlap of the reflections on the time axis is the one relevant parameter we observe. Four geometry complexities were created (Table 2). Starting from a simple model, with approximation in geometry and poor material precision, the file has evolved into a highly detailed geometry (Figure 5), including the entire bearing construction.

Table 2: model evolution

No.	planes:	material coeff.:
model I :	2532	no specification
model II :	2532	aproxximated values
model III :	7278	high precision
model IV :	2019	medium precision

The fourth and final model is a compromise, keeping the triangular facade but missing its bearing construction. This geometry simplification was made to reduce the long calculation time, without decreasing the accuracy. Simulations were launched for each of the models, some of which were repeated multiple times to remove minor errors. All simulations were with three sources and twelve receivers, placed at the exact positions as the measurement equipment was installed.

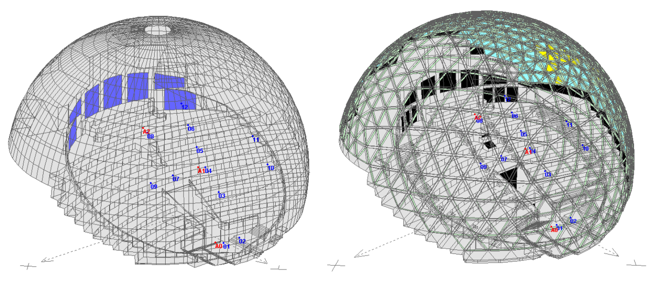
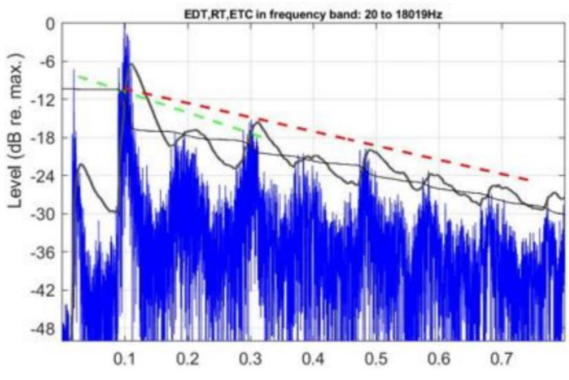


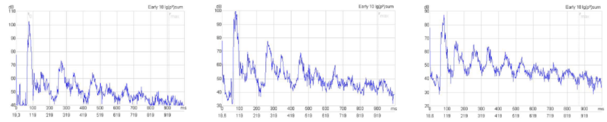
Figure 5: model I (left) and model III (right)

Ecograms of measurement and simulations were compared (Figure 6) from the various complexities models, parallel to their evolution. High correlation is visible in the echograms compared and the model was successfully validated.

It was concluded that the precision of the geometry does not modify dramatically the proximity of the result with the measured one, contrary to the absorption coefficients of the various materials. In Table 3 the fine-tuned values of the last validated model are shown.



(a) *measurement*



(b) *model I* **(c)** *model II* **(d)** *model III*

Figure 6: Comparison of energy - time plots between measurements and three complexity models for SxR at position Q3xM7

Table 3: absorption coefficients
used for the existing materials in the CATT simulation

surface \freq (Hz)	**125**	**250**	**500**	**1000**	**2000**	**4000**
metal triangles	0,15	0,12	0,11	0,1	0,07	0,07
mineral wool triangles	0,25	0,65	0,8	0,85	0,85	0,75
concrete	0,05	0,05	0,05	0,05	0,05	0,05

Screen modelling

The screen is a hemisphere with a diameter of $27m$, inclined at an angle of 29 degrees, positioned eccentrically (2) in the projection hall (integrated in the model, coloured in magenta on the Figure 7).

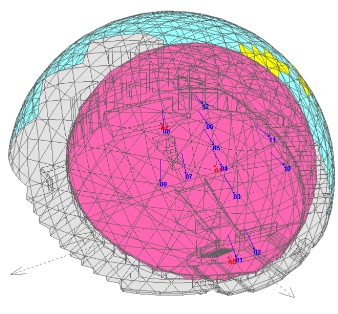


Figure 7: model IV - geometry for screen simulation

Design recommendations

The design instructions are to conform the initial objectives set, by both the project owner and IMAX. All available surfaces were treated with high performance absorptive materials to guarantee the lowest possible Reverberation time. Meanwhile, a concept for screen absorption is developed.

All accessible interior surfaces are treated with soft absorbing finishes. The floor is entirely covered with high thickness carpet, the sitting is with heavy upholstery cinema chairs and the walls and siding concrete are covered with 130mm and 100mm mineral wool layers, respectively, veiled with acoustically transparent fabric. In spite of it all, the highly relevant screen performance yet varies. The proposed solution (Figure 8), tested on the simulation, includes all surfaces treated as described, stressing on the trial absorption parameters for the screen. The proposed solution includes all surfaces

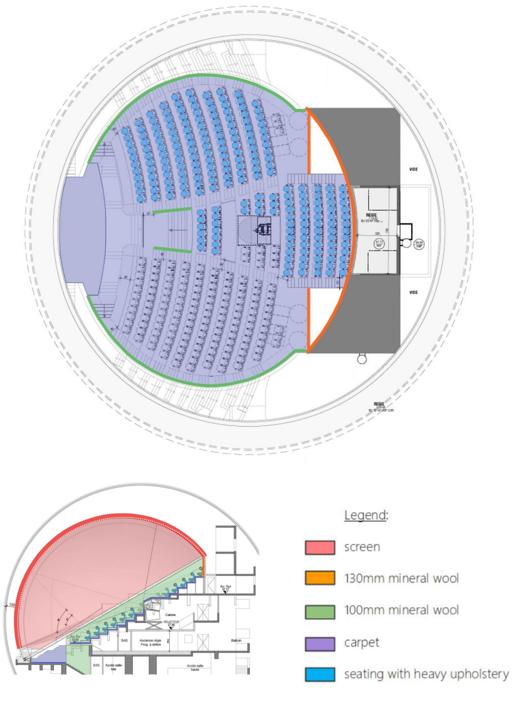


Figure 8: proposed solution

treated as described, stressing on the trial absorption parameters for the screen. The values for the absorption coefficients used in the simulation are shown in Table 4.

Table 4: absorption coefficients used for the design project

surface \freq (Hz)	**125**	**250**	**500**	**1000**	**2000**	**4000**
metal triangles	0,15	0,12	0,11	0,10	0,07	0,07
mineral wool triangles	0,25	0,65	0,80	0,85	0,85	0,75
concrete	0,05	0,05	0,05	0,05	0,05	0,05
seating (heavy upholstery)	0,30	0,45	0,55	0,60	0,65	0,75
carpet	0,10	0,10	0,12	0,20	0,27	0,35
100 mm mineral wool	0,75	0,85	0,90	0,95	0,95	0,95
130 mm mineral wool layers	0,85	0,90	0,95	0,98	0,98	0,98
screen	0,90	0,90	0,95	0,99	0,99	0,99

Screen - specifics and simulation

The surface of the dome is approximately $1170m^2$ and it is made of an aluminum structure forming I-beams braced by crosses and maintained between them by horizontal tubular rails. The projection screen is made of perforated aluminum sheet with perforation rate of approximately 20%. On top of it lays the absorption layers.

The exact composition of the layers of materials laying on top of it is not yet chosen, but considering into account all the restrictions (mass per unit area - max $10kg/m^2$; thickness - max $300mm$; colour density - intense black), we were able to propose several options with similar acoustic performance and insert the data into CATT Acoustics [3].

All these propositions are based mainly on mineral wool (glass or rock), acoustic fleece and aluminum foil placed directly on the micro-perforated screen. For the simulation, CATT Acoustic can take into account the transparency of a material, as a function of its absorption and its sound reduction index (R) [3]. The used coefficients for two cases during the study are shown in Table 5.

Table 5: complex structure absorption coefficient

proposed solution \freq (Hz)		**125**	**250**	**500**	**1000**	**2000**	**4000**
case 1	absorption (Î±)	0,75	0,85	0,95	0,95	0,95	0,95
	transparency (Ï„)	0,99	0,32	0,32	0,10	0,02	0,00
case 2	absorption (Î±)	0,90	0,90	0,95	0,95	0,95	0,95
	transparency (Ï„)	0,79	0,63	0,32	0,02	0,00	0,00

Comparison between design solution and objectives

Lastly, the fourth model was used for prediction of the reverberation time. The simulated reverberation time, mean par receiver, is shown in Figure 9.

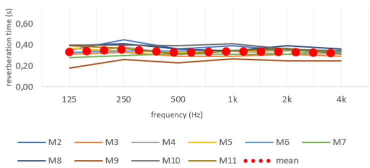


Figure 9: Simulated Rt(s) in the empty Geode mean par receiver Rt(s)=0,33s

Is is evident that the Rt mean is below the aimed value (mean $0.5s$), and there is no low value limit [2]. A plot comparing the RIR before and after is not shown, due to the fact that there was almost nothing after the direct sound.

Conclusion and discussion

We conclude that the GA software (CATT Acoustics) can be used for the purpose of detecting the focussing phenomena. If we look in further, in frequency or amplitude, this might not apply. A future prospect could focus on the frequency domain and establish the link between the peak in reverberation time at $1kHz$ relative to the size of the hemisphere ($r \approx 17m$) or the rhythm of the stairs. Also, it would be interesting to repeat the RIR measurements after the opening of the IMAX cinema and compare with our prediction.

References

[1] Vercammen, M.: Sound concentration caused by curved surfaces. Proceedings of Meetings on Acoustics (2013), 10.1121/1.4800250

[2] IMAX Corporation : ANC - Requirements for IMAX Theatres (2017), Mississauga, Ontario

[3] CATT-A v9.1e:1 - User Manual (2019)