ACOUSTIC STUDY OF MADRID AUDITORIO NACIONAL DE MÚSICA

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1 INTRODUCTION

This paper analyzes the acoustic of Auditorio Nacional de Música, built by the architect José María García de Paredes in 1988 and placed in the city of Madrid (Spain). It shows the relationship of geometry with the parameters that characterize the sound of the enclosure, which have been analyzed by simulation and measurements. It also describes the influence of the acoustic consultant Lothar Cremer, which marks the evolution in the design of the auditorium and has a large impact on the acoustic result. In the election of Auditorio Nacional de Música influenced several reasons:

- The architect designed this room for achieving optimum acoustics.
- In the context of the Spanish musical rooms, Auditorio Nacional de Música has an emblematic position because it is the starting point about the modern conception of these spaces and is, perhaps, the first concert room in Spain.
- Complementing the studies prior to its construction through the acoustic simulation and measurements.

2 AUDITORIO NACIONAL DE MÚSICA

2.1 The architect

José María García de Paredes was born in Seville (Spain) in 1924 and died in Madrid (Spain) in 1990. Architect for the Architecture School of Madrid (1950). Within his production, auditoriums constitute a proper board of a singular importance; along with Auditorio Nacional de Música, he designed and built more than a dozen of large auditoriums, highlighting Auditorio Manuel de Falla (Granada, 1978) and Palau de la Música (Valencia, 1987).

2.2 The construction

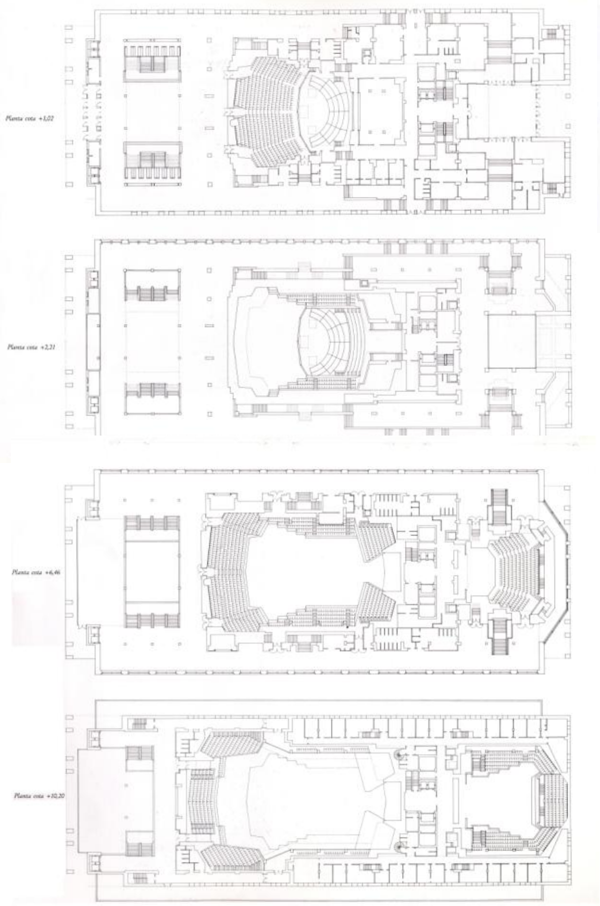
Figure 1.- Northern façade of Auditorio Nacional

In 1982 the Ministry of Education, Culture and Sport commissioned García de Paredes the project to build Auditorio Nacional. The site chosen was a rectangular solar of 120 x 50m in wide situated in Príncipe de Vergara street. The construction began in 1984 and was inaugurated in 1988. In the interior Auditorio Nacional hosts a wide range of installations, highlighting the symphony hall (2324 seats), which will be studied below, and the chamber music hall (692 seats); these rooms are located in the northern and southern areas of the building. Currently, the building acts as headquarters of the National Orchestra and Choir.

3 ACOUSTIC STUDY OF THE AUDITORIUM

3.1 Overview of the room: sizing and capacity

The symphony hall of Auditorio Nacional has a capacity of 2324 seats. Its volume is about 22,000m^3. The room is symmetrical with respect to its longitudinal axis. Its geometry can be entered into a rectangle about 62 x 36m in width, but with dimensions that grow organically up. The plans of Figure 2 show the growth of the room.



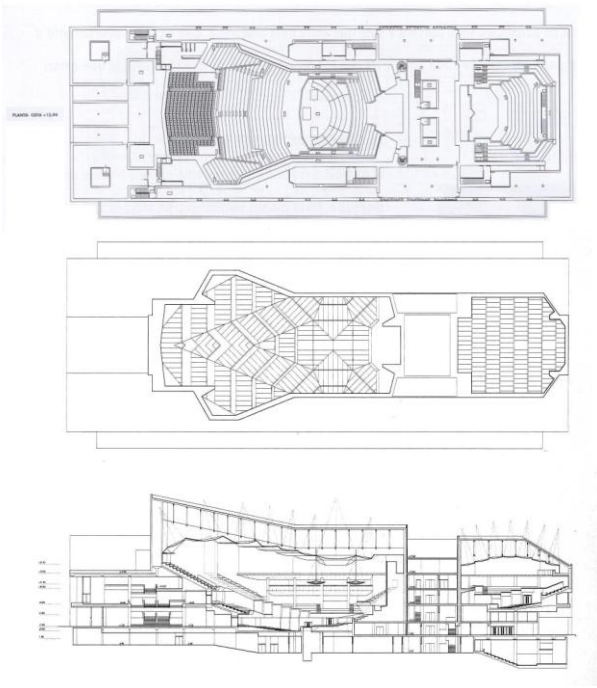


Figure 2.- Plans of Auditorio Nacional.
Left: levels 1.02, 2.21, 6.46 and 10.20.
Right: level 13.94, ceiling and longitudinal section.

The spatial organization responds to a careful distribution of the public in the different audience areas. Figure 3 shows the interior of the room:

Figure 3.- Interior of the Symphony Hall

3.2 The advice in the design stage: Lothar Cremer

Auditorio Nacional was in the planning stage with the acoustic advice of Lothar Cremer and Thomas Fütterer, the engineer Cremer´s collaborator. According to the documentation we have[1], from Cremer´s study were sent four reports between 1982 and 1988, prepared by Fütterer. These reports are actually unpublished material, and collects working procedures, proposals for changes to be made by the architect as well as calculations of acoustic parameters. The working procedure is summarized in these points:

- Study of the acoustic behavior of the room with an optical model.
- Graphic study of the early reflections, especially those from the ceiling.
- Prior calculation of the reverberation time.

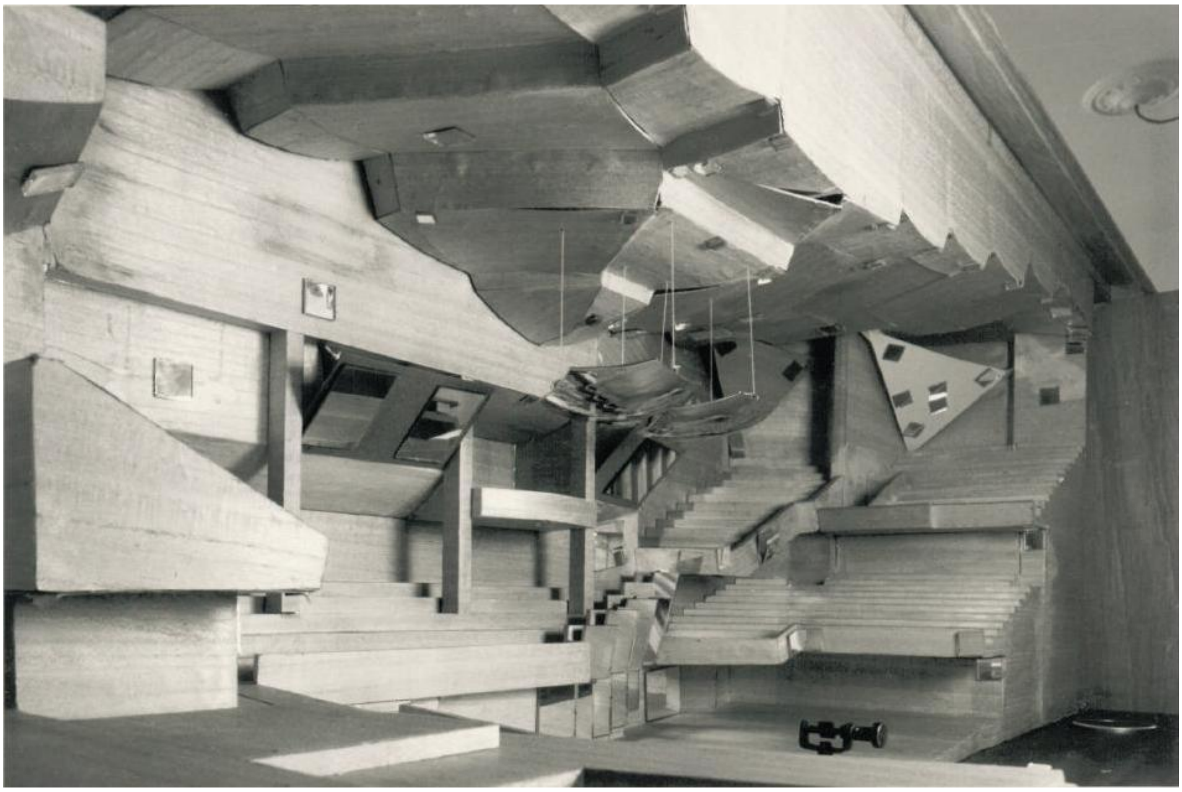


Figure 4.- Model of the room: view from the rear part behind the stage to the right side of the hall

In Cremer´s study they used to work with 1:50 scale models, in which an optical test was performed. This test uses the attribute of the sound at high frequencies that it will be reflected at surfaces in the same way as light does in the mirrors. This kind of test was very useful for getting information about the distribution of the sound reflections from all the inside surfaces and finding easily reflections with too much time delay (echo). Fütterer explains the study process: “To have a very strong, easy visible and as well small light ray here it was used a small LASER equipment. This equipment was put outside the model and the light ray coming from there was sent to a small mirror (the sound source) positioned on the stage, which can be turned into all directions. With that turnable mirror the light ray was shifted to all the interesting inside surfaces. From there it was reflected by small fixed mirrors to any other part of the hall. Those reflection-points give the information to which places the sound is reflected from a certain surface. So the sound reflections become visible and controllable. In case of, it can be shown at once how to change the inclination of a certain surface, to get the necessary reflections at the intended places and to measure the time delays”.

The test had been started in October 1983. At that time there had been a meeting in Berlin with García de Paredes, Cremer and Fütterer to show the architect the first results of the test and to discuss the necessary changes. The suggested changes were:

- Position of the reflectors over the stage for sound reinforcement in that area and avoiding echoes from the ceiling.
- Prevent parallel walls in the stage for no flutter echoes
- Inclination of the balustrades of the amphitheatres, the side galleries and the balconies behind the orchestra to give reflections to the audience of the stalls, as made by Cremer in Berlin Philarmonie 25 years before.
- Curvature of the ceiling panels of the side galleries and the balconies behind the orchestra to give, in combination with the walls, reflections to the public of those areas.
- Placement of triangular panels in the side balconies which flank the second amphitheatre to give reflections to the audience of those areas.
- Placement of diffusing material on the rear walls of the stalls, the first amphitheatre and the choir stalls for avoiding echoes on far away seating areas.

3.3 Modelling and materials

For the simulation an acoustic model based on a drawing of the hall in three dimensions, taken from the architect's plans and visits to the auditorium[2], has been performed. The geometry is characterized using the AutoCAD software and then we have operated with the CATT Acoustic program. We have obtained 1518 3D faces and 0% of lost rays.

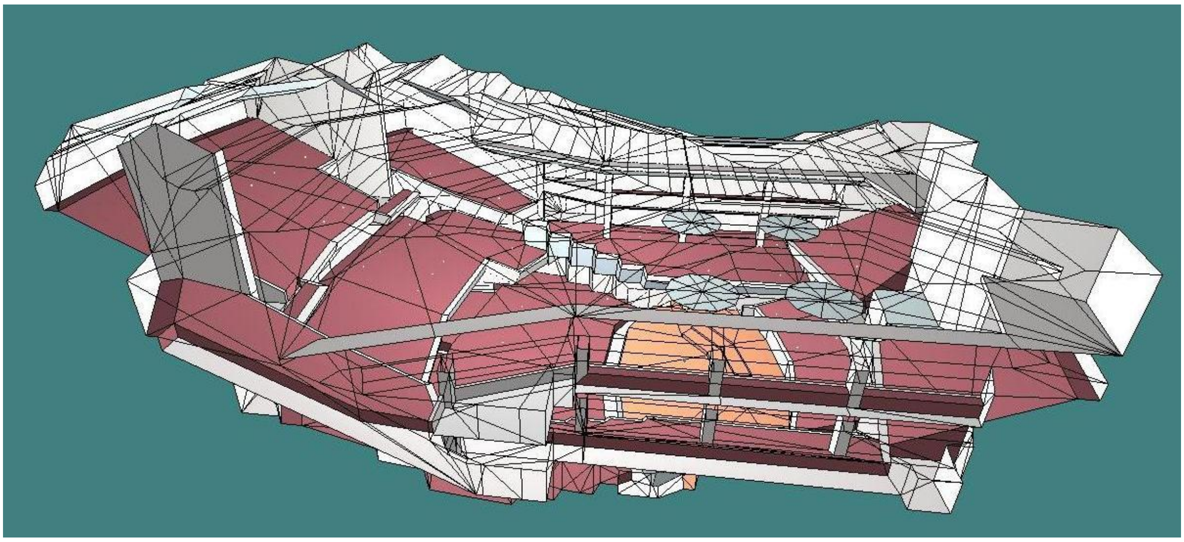


Figure 5.- Modelling of the room where the complex ceiling has been sectioned

The software marks the achievement of certain adjustments for the simulation process:

- The **curved lines** of the ceiling section and the circular plan of the lamps were replaced by straight lines, because the program does not allow curved lines.
- The audience has been modelled by **boxes** of height 0.8m. We have also included as audience boxes some stairs that separate a public area from a wall or two public areas. The audience area considered in the simulation occupies 1552m^2.

The choice of materials obeyed to obtain a balance between reflective, diffusing and absorbing surfaces to get an appropriate reverberation time. Although we have no written constancy of what was the searched reverberation time, taking into account that in Manuel de Falla Auditorium was 1.85 sec in the symphony hall of Auditorio Nacional we can think about 2 sec for the midrange. The information about the used materials has been obtained by visiting the room. Due to the complexity of its geometry, its large volume and the experience provided by a high number of simulations in this room, we have decided to give to the reflective materials a default diffusion of 18% for all the frequency bands, as recommended by the bibliography[3]. Table 1 shows the coating surfaces with its absorption at the octave bands of 125Hz, 250Hz, 500Hz, 1kHz, 2kHz and 4kHz[3 4 5]:

MATERIALS	ABSORTIÓN	DIFFUSIÓN
Glued wood, for the stage floor (without musicians), corridors and balustrade armrests	4 4 7 6 6 7	18 18 18 18 18 18
Diffusing glued wood, for all the stairs	4 4 7 6 6 7	50 50 50 50 50 50
Wood with air space, for the ceiling panels	19 14 9 6 6 5	18 18 18 18 18 18
Wood with diffusion, for the organ and lamps	19 14 9 6 6 5	30 40 50 60 70 70
Solid brick plastered, for the columns, walls and balustrades of the balconies	2 2 3 4 5 5	18 18 18 18 18 18
Plaster with air space, for the balustrades of the side galleries	20 15 10 8 4 2	18 18 18 18 18 18
Linoleum, for the floor of the second floor side gallery	2 3 3 3 3 3	18 18 18 18 18 18
Occupied chairs (unoccupied)	34 67 84 86 86 74 (19 42 59 67 67 55)	30 40 50 60 70 70
Stage with musicians	10 21 41 65 75 71	30 40 50 60 70 70
Iron, for the doors of the stage	2 3 3 4 2 3	18 18 18 18 18 18
Plywood on metal support, for the public access doors	2 3 3 4 2 3	18 18 18 18 18 18

Table 1 - Absorption of surfaces in the octave bands

3.4 Acoustic simulation

We consider an omnidirectional source A0 centered on the width of the stage, to 5m from the edge and 1.5 m height, which emits a sound pressure level of 90dB at 1m distance in all the octave bands (125Hz, 250Hz, 500Hz, 1kHz, 2kHz and 4kHz). There have also been placed 52 receivers in one side of the plan of symmetry xz, distributed in the stalls, choir stalls, first amphitheatre, side galleries, balcony behind the stage, second amphitheatre and side balcony, as seen in Figure 6.

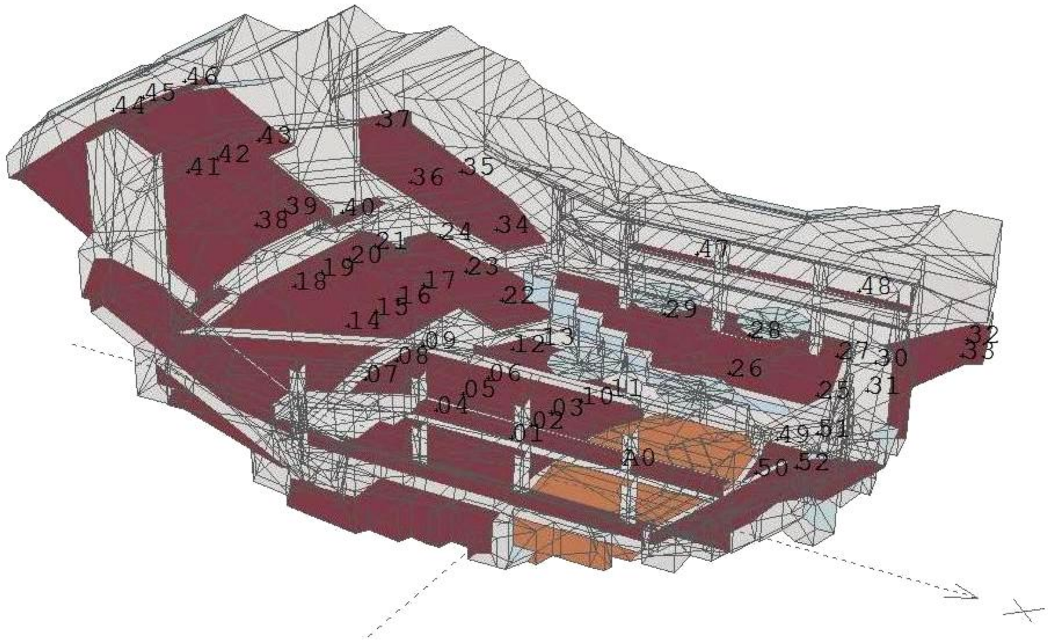


Figure 6.- Position of the source and receivers in the audience area

Data provided by the simulation are classified in two sections:

- Geometrical analysis: sound ray trajectories source-receptor.
- Results of acoustic parameters: SPL, G, RT, BR, Br, C_{80} and LF. Though we have also simulated other parameters, here we analyse the mentioned parameters, taking into account the musical use of this hall. They are calculated in the occupied room, except indication.

3.4.1 Geometrical analysis: results per receiver

We have analyzed the trajectories of the issuing rays from the source to the receptors, considering the reflections of order less or equal to three (echogram). It has been studied for each receiver the continuity of the reflections, where they come from, how they are spread over each time interval (0-20ms, 20-50ms, 50-80ms and 80-150ms) and the sequence of intensities, for ensuring the absence of echoes. We have examined how to change the echogram between receiver and receiver along the axial directions (x, y) of the hall. The conclusions are:

- The number of reflections in different parts of the room is uneven. The most benefited zone is the stalls. The second amphitheater receives a significant number of reflections, which contribute to increase the loudness of these locations, the farthest from the stage. In the rest of the audience, the number of reflections is generally low or uneven.
- As regards to the origin of the reflections, it is detected a significant participation of the walls and balustrades in the reflections received in the stalls. In the rest of areas these surfaces are less involved, taking more ownership the ceiling of the room, which takes part with great effectiveness in the reflections on the choir stalls and the central area of the first amphitheatre, as well as in the second floor; in all other areas their effectiveness decreases. The ceiling curved panels of the side galleries and the rear balconies participate, alone or in cooperation with the walls, in the reflections on the localities inside them, fulfilling their role in these areas.
- The lamps have a rather discreet participation in the reflections of the surrounding areas: first rows of the stalls, choir stalls and side galleries. It is estimated that the lamps would not be enough to cover all the zenithal reflections on the stage, so there would be a big part that would come directly from the overall ceiling of the room. Taking into account the height of the ceiling, we can expect differences exceeding 27m between the direct and reflected sound on the stage.
- An echo is detected in the receiver 38 of the second amphitheatre for capturing a reflection of order 2 from the rear wall and ceiling of the balcony behind the stage, which is reinforced by three reflections of order 3 from the side walls (or column) and the ceiling (Figure 7).

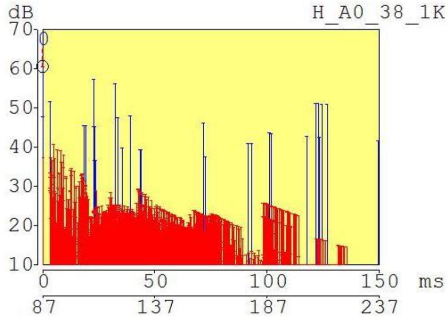


Figure 7.- Echogram of the receiver 38

3.4.2 Results of acoustic parameters

- *Sound pressure level SPL and Loudness G*

Figure 8 represents the sound pressure level SPL and the loudness G in the band of 1kHz. Though the average value exceeds 70dB in all frequencies, the SPL values are different depending on the area of the auditorium we try. So, the SPL values in some seats located in the second amphitheatre and the side balconies of the second amphitheatre or under a balcony (receiver 24 of the first amphitheatre) are lower at some frequencies, reaching 66dB.

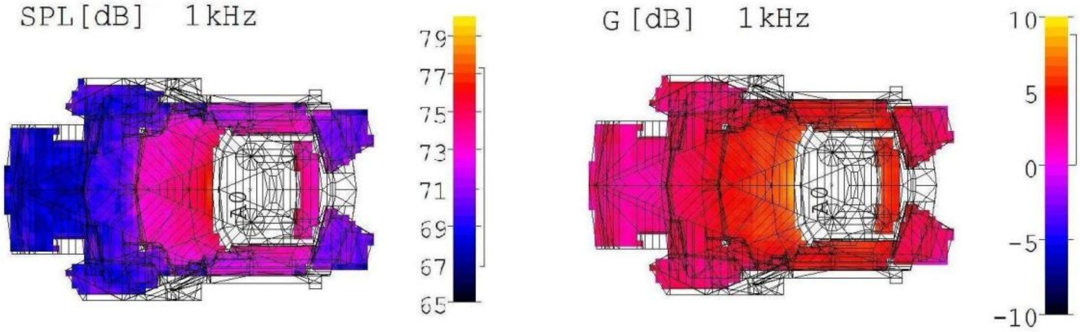
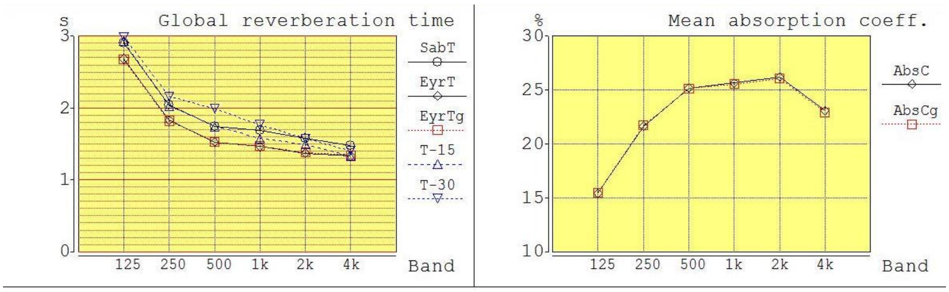


Figure 8.- Values of sound pressure level and loudness in the band of 1kHz

The average value of the loudness G for the receivers in the midrange is **G_{mid} = 3.9dB** for the empty room, standing almost at the lowest than recommended by the bibliography[6]. Taking into account the size of the room it can be considered a good result.

- *Reverberation time RT*

Figure 9 shows table and graphs of the different values of the reverberation time, some of them obtained through its corresponding formula (Sabine and Eyring), other calculated from the geometry of the room with their coating surfaces, as T-15 and T-30:



	125	250	500	1k	2k	4k	
EyrT	2,68	1,83	1,52	1,46	1,37	1,33	s
EyrTg	2,68	1,82	1,53	1,47	1,38	1,34	s
SabT	2,90	2,05	1,75	1,69	1,58	1,48	s
T-15	2,93	2,03	1,74	1,57	1,49	1,33	s
T-30	2,99	2,16	1,99	1,77	1,57	1,40	s
AbsC	15,42	21,66	25,17	25,66	26,21	23,08	%
AbsCg	15,45	21,72	25,14	25,55	26,05	22,93	%
MFP	11,24	11,24	11,24	11,22	11,23	11,24	m
Diffs	22,00	25,02	27,98	31,01	33,96	33,93	%

Trunc	3500,0	ms
Rays	61634	(used/oct)
	21	(lost/oct)
	0	(absorbed/oct)
Angle	0,82	degrees

Figure 9.- Table y graphs of the values of reverberation time

We can see a good correspondence between the calculated values of the reverberation time for all the frequencies. It means that in the step from a frequency band to the next, the values fluctuate with similar trend, which is achieved by applying the mentioned diffusion coefficients by default. As the software manual considers the values from the descriptor T-30 as the best estimate of the reverberation time, we take this reference, obtaining **RT_{mid} = 1.88 sec**. This value would be in tune with the claims of the architect and the acoustic consultant, enabling the optimal use of the hall for symphonic music. It is also noted the high value of the reverberation time obtained in the band of 125Hz, a result that is justified by the low absorption of the chairs at that frequency. The Bass Ratio BR and the Brightness Br take values **BR ≈ 1.37**, **Br ≈ 0.79**, so the room gives a high response in bass and somewhat low in treble.

A study of the reverberation time in the empty room has been also made, considering the absorption of the seats without audience and the stage without musicians. Using T-30, the value in the mids is RT_{mid} = 2.29 sec, suitable for a rehearsal of the orchestra.

- *Clarity C_{80}*

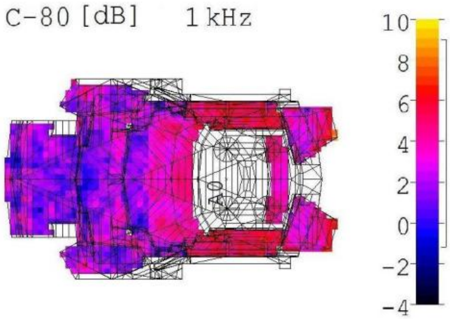


Figure 10.- C_{80} in the band of 1kHz

Figure 10 shows the values of the clarity C_{80} in the frequency band of 1kHz.

The average for the 52 receivers in the three frequency bands of 500Hz, 1kHz and 2kHz, is **$C_{80}(3)$ = 4.3dB**, higher than recommended by the bibliography[6] for a hall which is used for music. It is related to the lack of reflections after 80ms detected by the echograms in several receivers.

- *Lateral energy Fraction LF*

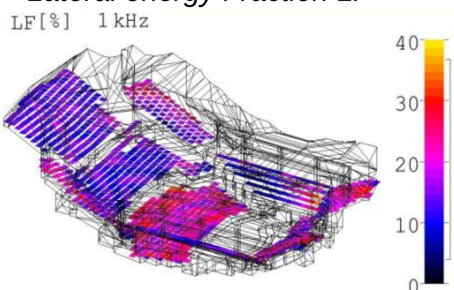


Figure 11.- LF in the band of 1kHz

Figure 11 shows the values of the lateral energy fraction LF in the frequency band of 1kHz. We can notice the irregularity of the obtained values, which are related to the lateral energy fraction received by the receptors, sometimes very different even if they are contiguous, as verified by the echograms. The average percentage value in the bands 125Hz, 250Hz, 500Hz and 1kHz for the receivers is **LF(4) = 19.1** in the empty room, which would be above the recommended limit.

3.5 Sound measurements

During the days 13th and 14th September 2010 measurements in Auditorio Nacional were carried out on our own. The measurements were performed under the empty room and the stage without musicians, but it was with chairs, music stands and some percussion instruments. The situation corresponds to the empty room simulation, although in the simulation was considered the empty stage. So, we would be able to expect in the measurement a more diffusing stage, both in its back wall and floor. Our goal has focused on approximating the conditions of the measurement to the simulation methodology. In this way, the receptors were placed at a height of 1.2 m exactly in the 52 receiving positions. The source was omnidirectional and placed at 5m from the edge of the stage centered on the same. The measured parameters were: SPL, RT (T-20 and T-30), EDT, C_{80}, D_{50}, t_s, G and RASTI. We achieved a satisfactory agreement between the simulated and measured values.

4 CONCLUSIONS

1.- The contact of the architect with the acoustic consultant Lothar Cremer is fundamental to understand the final outcome of the auditorium. This is particularly evident in the treatment of geometrical acoustics from working with an optical model, in the provision of public terraces and in the slope of the balustrades of the amphitheatres, side galleries and rear balconies.

2.- The analysis of the echograms shows that the number of reflections in the different parts of the room is uneven, being the stalls the most benefited area because of the reflections from the walls and the balustrades. The ceiling takes part overall in the reflections on the choir stalls and the central area of the first amphitheatre, although their effectiveness is uneven throughout the room. The ceiling panels of the side galleries and rear balcony fulfill their mission there, while the lamps are involved, but quietly, in the reflections on areas close to the stage. An echo is detected in the receiver 38 of the second amphitheatre.

3.- It has been simulated with the CATT Acoustic software. The parameter results are:

ACOUSTIC PARAMETER	SIMULATION VALUE
Sound pressure level SPL	**> 69dB, except in mentioned areas**
Loudness G_{mid}	**3.9 dB (**empty room**)**
Reverberation time RT_{mid}	**1.88 sec**
Bass Ratio BR	**1.37**
Brightness Br	**0.79**
Clarity C_{80}(3)	**4.3dB**
Lateral energy Fraction LF (4)	**19.1 (**empty room**)**

6 .- It has achieved a satisfactory agreement between the simulated and measured values in the empty room, which reinforces the reliability of the simulations.

5 REFERENCES

1. Lothar Cremer´s reports have been submitted by Ignacio García Pedrosa, García de Paredes´ associate architect at the Auditorio Nacional. We thank the study Paredes-Pedrosa the provision of this material.
2. We want to thank José Manuel López López, Director of Auditorio Nacional, and Jesús Clavero Rodríguez, Technical Director of Auditorio Nacional, for facilitating the visits aimed at the visual prospecting and the performance of acoustic measurements.
3. CATT-Acoustic v8.0 *User´s Manual*, SPECTRA D´Sign Kopiering AB, Gothenburg, 2002.
4. Beranek, L. Concert & Opera Halls. How they sound, A.S.A., New York, 1996.
5. Measurements of different chairs absorption by García BBM acoustics consulting firm. Unpublished material. We thank Vicente Mestre (García BBM) the provision of this material.
6. Carrión Isbert, A. Diseño acústico de espacios arquitectónicos. Edicions de la Universitat Politècnica de Catalunya, Barcelona (España), 1998.