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BARCELONA SYMPHONY HALL: L'AUDITORI

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ABSTRACT: This paper describes the design of the new Concert Hall of Barcelona, called "L'Auditori". The architect for the hall was the famous R. Moneo, with Estudi H. Arau advising on the acoustics. The acoustics of the concert hall have been very well received to widespread national and international critical acclaim. Richard Fairman wrote in the Financial Times, May 2 1999: "Hopefully, the sound from there will be as regal as it is from the other seats. The acoustic at the concert I attended - a programme featuring two Beethoven piano concertos played by Christian Zacharias and Bach's Fourth Brandenburg Concerto was full and majestic. There is a generous resonance around the orchestral sound, which makes a change in a modern hall. The 'Orquestra Sinfònica i Nacional de Catalunya' and its music director, Lawrence Foster, have acquired an ideal home to play the Bruckner symphonies ... "

1. INTRODUCTION: A NEW MODERN CLASSICAL HALL

The Concert Hall of the Barcelona Auditorium was opened on 22nd March 1999 to widespread critical acclaim. This hall was designed with the aim of emulating the acoustics of the three most famous concert halls in the world: the Amsterdam Concertgebouw, Boston Symphony Hall and the Vienna Grosser Musikvereinssaal. It aimed to be a modern version of a classical hall. The hall nominally seats 2326 (maximum 2335) and is the home of Barcelona City & Catalonian National Orchestra.

The hall is rectangular with a length that is double its width. It has a width of nearly 31.1m between sidewalls; the height of hall ceiling above the stage is 19.3m. There are large areas for the performers: the orchestral platform is $210m^2$ and the choir occupies $60m^2$. The stalls are divided into three sections: the main stalls with 594 seats in front of the orchestral platform and the side stalls in two terraces to the sides of the stage at two different heights containing 146 and 304 seats each. The main stalls are lightly raked. Beyond the main stalls are two elevated terraces, steeply raked and called Amphitheatre (Tier) 1 and Amphitheatre (Tier) 2. On both sides of these terraces are sixteen boxes that seat 10 to 18 each. The first Amphitheatre contains 188 seats, the second 603 and the boxes 196. Finally, there are 8 boxes placed in each side wall, distributed in two levels over the side stalls. They seat a maximum of 19 each.

The ceiling is divided into two areas. The first one, over the stage, is inclined starting at a height of 11.1m above the stage and ending at 15.2m; it is divided into saw-tooth segments of approximately 2m. The main ceiling of the hall is horizontal but subdivided by means of 14 transverse beams, defining 15 spaces in the ceiling of 3.15m wide. The transverse beams have a rhomboidal section with a 40cm depth, and widths of 30 cm at the bottom and 40 cm at the top.

All the transversal beams are recollected by two longitudinal beams, in both sides of the ceiling, therefore these beams do not touch to sidewalls. The transverse beams do not in fact extend to the sidewalls but are joined to longitudinal beams that run the full length of the hall and are located just inside from the cornice.

Longitudinal beams run between the transverse beams; they have a depth of 30 cm and have a rhomboidal section with widths of 10 cm at the bottom and 20 cm at the top. The number of longitudinal beams varies along the length of the hall with fewer beams close to the stage. The number of longitudinal beams is as follows, starting from the stage end: 4, 5, 6, 8, 10, 13, 16, 21, 26, 34, 42, 55, 68, 89. Here the second, fourth, sixth numbers etc. follow a Fibonacci sequence: 5, 8, 13, 21, 34, 55, 89. We regard that the beams sequence of odd position is obtained from the last Fibonacci sequence adding, to each number respectively, (with negative number), this other Fibonacci sequence: -1, -2, - 3, -5, -8, -13, -21. This play with Fibonnaci sequences offers a very good combination of grid beams.

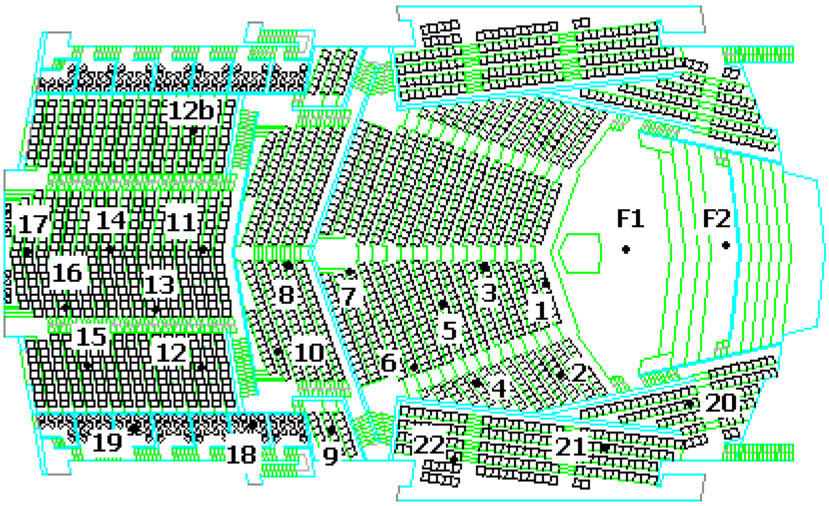

Figure 1: Barcelona Auditorium Concert Hall in plan. The numbers indicate the measurement points. F1 and F2 are source positions.

To exception of the space 15 in where are repeated the beams distribution of the space 14 reduced to 35 beams adding two triangular flat planes placed in both sides.

This arrangement of beams thus defines a beautiful coffered ceiling, with big coffers near the stage and small coffers at the rear of the hall. The grid of beams, which define the coffers, harmonise specular reflection with diffraction produced by the spacing between the beams and their depth. The acoustical principle behind this ceiling is to provide diffraction, progressively from low to high frequencies. At high frequencies the ceiling section close to the stage provides specular reflections, whereas remote from the stage it diffracts.

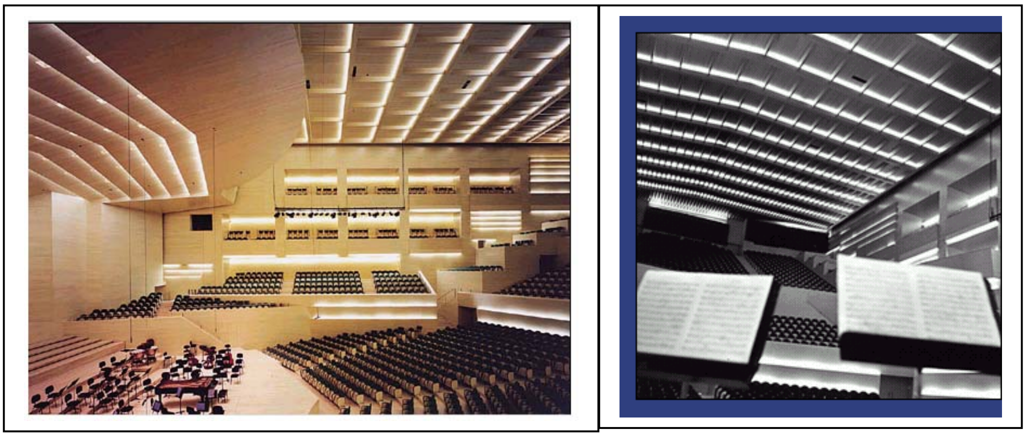

Figure 2: Barcelona Auditorium ceiling

The sidewalls combine vertical and inclined surfaces to provide good reflections to the audience area but at the same time, taking care to avoid echoes and long-path reflections. The walls surrounding the stage project lateral sound reflections to the main floor. The impulse response is rich everywhere, even in the first rows of the hall!

The hall provides the intimacy and early lateral reflections typical for a rectangular hall; reflections are supplemented by those from the walls of the lateral terraces and boxes.

The general subjective impression is in agreement with expectations from objective measurements. The sound is impressive, clear and uniform throughout the hall; it is rich in bass and good for high strings.

One major feature of the design is the absence of any balcony overhangs, which are found in all classical halls.

In our case we have balconies integrated in the sidewalls. This was chosen in order to obtain an even absorption distribution in the hall, resulting in an improved Sabine space, and moreover getting an optimum diffraction from the sidewalls without losing specular reflections required to obtain a good lateral energy. The sidewalls alternate flat zones with inclined zones, the alternations becoming more frequent towards the rear of the hall.

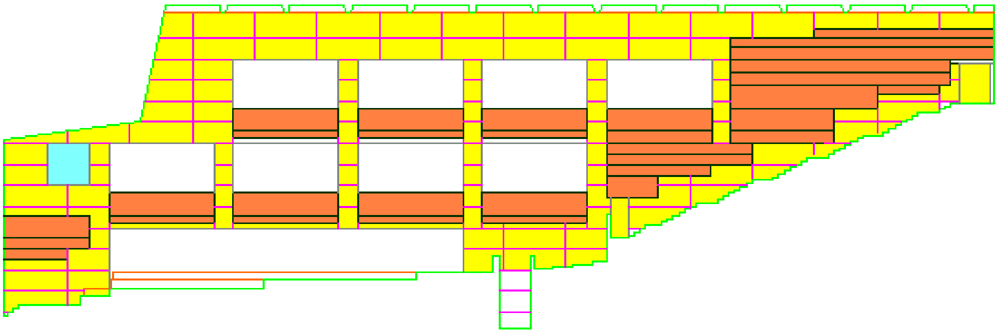

Figure 3: Sidewall elevation. Inclined walls are brown, vertical planes yellow, balconies white and windows blue.

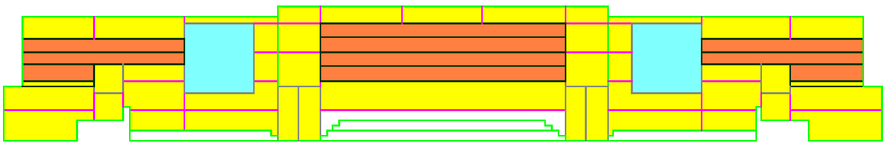

Figure 4: Rear wall elevation. Inclined walls are brown, vertical planes yellow and windows blue.

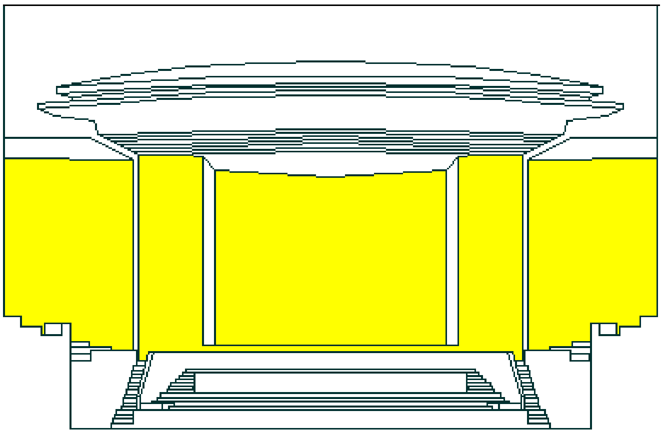

Figure 5: Transverse section through the stage.

Contrary to the Vienna Musikvereinssaal, there is not much difference in the sound during rehearsal conditions and the sound with audience. The upholstered seats have been carefully designed to minimise that.

The Concert Hall has been designed for symphonic music. It can also be used as a conference room or for amplified music. When configured for symphonic music there are no additional sound absorbing materials. The hall is finished in plywood throughout; there is only the absorption due to the seats, musicians and audience. For this use, the reverberation time at mid-frequencies fully occupied and with musicians on stage is 2 sec, ideal for symphonic music.

For conference-use, several velvet curtains cover the sidewalls (second and third floor of balconies) and the rear walls and also the wall behind the stage. In this configuration, the reverberation time at mid -frequencies fully occupied is 1.3 sec, good for reinforced music and conferences. In this situation a sound system is used to improve intelligibility and coverage.

The background noise inside the hall is very low. With the air conditioning system on, it satisfies the NC15 criterion. The building is mounted on springs that insulate it from underground and main line train vibrations.

Architectural and structural details

Uses: symphonic music, recitals and conferences. *Ceiling:* 20-mm to 35-mm plywood with airspace behind. *Side, front and rear walls:* 25-mm plywood fixed to wall with a hard and elastic filling up material. *Floor:* Maple parquet fixed over rigid floor. *Carpet:* none. *Stage floor:* 45-mm maple over plywood over deep airspace. *Stage height:* 0.85 m. *Added absorptive material:* (Only in reinforced music and conferences) Velvet curtains covering the side and the rear walls and also the back stage wall. *Seating:* Special designed, rigid seat back, front of seat back upholstered; top of the seat-bottom upholstered; underseat, wood linear perforated Helmholtz resonator.

Acoustical and technical details *

Symphonic Music

V = 24298 m^3	S_A = 1621 m^2	S_c = 60 m^2
S_o = 210 m^2	S_T = 1891 m^2	N = 2326
H = 15.75 m	W = 31.1 m	L = 40.3 m
D = 41.2 m	SD = 15.26 m	SW = 15.3 m
SH = 13.15 m	V/S_T =12.85 m	V/S_A = 14.99 m
V/N = 10.45 m^3	S_A/N = 0.697 m^2	H/W = 0.5
L/W = 1.29		

T_{MID} = 2.06 s (occ.) | EDT_{MID} = 2.4 s (unocc.) | EDT_{MID} *unoc./*T_{MID} occ.= 1.17
$C_{80\ MID}$ = -0.5 dB (occ.) | BR(occ.) = 1.18 | LEF (unocc) > 0.20
ITDG = 19.5 ms | G_{MID} (unocc) = 3.5 dB | ST1 = -14.2 dB

Conferences and Electroacoustical Music
T_{MID} = 1.3 s (occ.) | *RASTI* > 0.6 (occ.)

* *The terminology is explained in Appendix 1 of Beranek[1].*

2. MODEL TESTS

In the first phase of the acoustical design (1989 - 90), M. Barron tested a 1:50 scale [2] of the original hall design. At the time, the hall had a larger audience capacity and more volume than finally built and the stage ceiling was different. These model tests were valuable for the analysis of anomalous reflections (echoes) and other aspects learnt from energy measurements. A low EDT was observed, which resulted in the ceiling being raised. However during a nine-year delay, many changes were made to the auditorium design. From 1990 an in-house computer simulation program was developed, which was used to study anomalous reflections. This analysis led to prescriptions for inclining relevant surfaces to remove long delay reflections and provide useful reflections for the audience. The program has subsequently been developed to calculate objective quantities.

3. ACOUSTICAL PERFORMANCE OF HALL

Objective values measured in the hall using an MLS testing system are presented below. The prescriptions in ISO 3382 [3] were followed. Comparisons are made with the best halls considered in references [1,6].

Measurement positions are given in Figure 1 and Table 1.

Table 1: Measurement positions

Measurement point	Zone	Source-receiver distance for F1 (m)
1	Stalls	6.57
2	Stalls	10.64
3	Stalls	10.50
4	Stalls	14.09
5	Stalls	14.50
6	Stalls	17.53
7	Stalls	20.49
8	First Tier	24.69
9	Lateral second Tier	25.81
10	First Tier	27.02
11	Second Tier	31.37
12	Second Tier	32.58
13	Second Tier	33.28
14	Second Tier	38.97
15	Second Tier	40.42
16	Second Tier	42.00
17	Second Tier	44.07
18	Lateral 2 Tier	30.44
19	Lateral 2 Tier	39.09
20	Lateral Stage	13.27
21	Lateral 1 Tier	15.32

22	Lateral 1 Tier	19.61
23	Place 6–8 3erd Balcony	-
24	Place 6–8 2ond Balcony	-
25	Place 14–16 2ondBalcony	-

- ## NC NOISE CRITERIA

The average values of the Noise level produced by air conditioning are:

Table 2: Noise level produced by the air conditioning

Noise of air conditioning	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**A**
100% (on)	43,1	34,4	28,4	21,4	16,1	13,2	12,3	25
NC – 15	47	36	29	22	17	14	12	25,8

- ## ITDG INITIAL TIME DELAY GAP

The average value obtained from impulse responses were:

Auditorium	ITDG (ms)
Barcelona	19.5
Boston	15
Vienna	12
Amsterdam	21

- ## RT REVERBERATION TIME

Reverberation time[1] values measured, for unoccupied and occupied seats are given below.

	125	250	500	1000	2000	4000	T_{low}	T_{mid}	T_{high}
RT Barcelona (unoc.)	**2,75**	**2,64**	**2,35**	**2,41**	**2,55**	**2,40**	**2.65**	**2.38**	**2.47**
RT Boston (unoc.)	2.13	2.29	2.40	2.63	2.66	2.38	2.21	2.51	2.52
RT Vienna (unoc.)	2.97	3.03	3.06	3.05	2.67	2.10	3.00	2.86	2.38
RT Amsterdam (unoc)	2.68	2.51	2.55	2.62	2.39	1.96	2.59	2.58	2.19
RT Barcelona (occ.)	**2.45**	**2.30**	**2.09**	**2.03**	**2.02**	**2.00**	**2.37**	**2.06**	**2.01**
RT Boston (occ.)	1.95	1.85	1.85	1.85	1.65	1.30	1.90	1.85	1.47
RT Vienna (occ.)	2.25	2.18	2.04	1.96	1.80	1.62	2.21	2.00	1.71
RT Amsterdam (occ.)	2.20	2.15	2.05	1.95	1.80	1.55	2.17	2.00	1.67

Table 3: Reverberation Time for unoccupied and occupied seats

In "L'Auditori" the occupied RT values have been obtained from the expression given by [4], using the experimental test values obtained in a reverberant room of "Laboratori General d'Asssaigs i Investigacions". The incremental absorption values $\Delta\alpha$ between occupied and unoccupied seats were:

	125	**250**	**500**	**1000**	**2000**	**4000**
Incremental absorption $\Delta\alpha$	0.130	0.136	0.129	0.187	0.244	0.201

Table 4: Incremental absorption values $\Delta\alpha$ between unoccupied and occupied seats in Barcelona hall

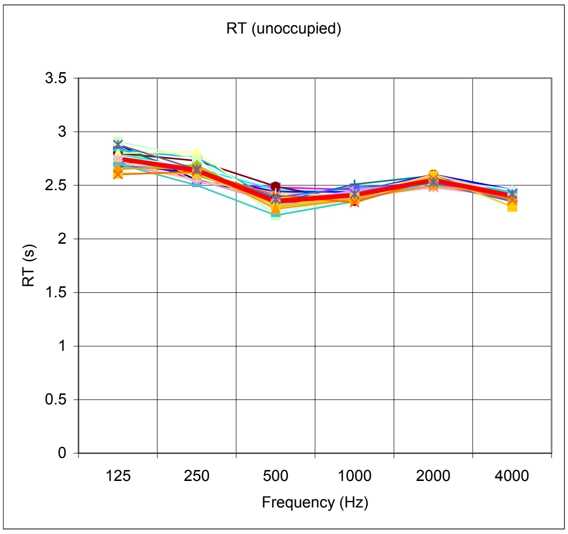

Figure 6: Measured reverberation times in the unoccupied Barcelona hall

From Figure 6, we see that the RT is very similar for all analysed points, and therefore we can say that it is independent of the source - receptor position.

We also find good agreement between the measured T_{mid} and the prediction by the theory of Arau [4, 5], as shown in Figure 7.

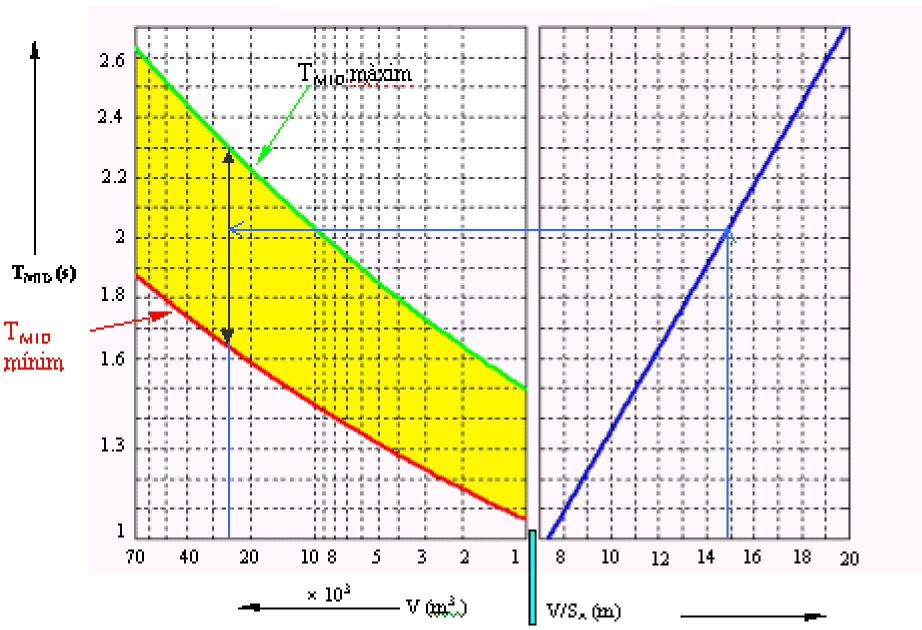

Figure 7: T_{MID} predicted by Arau [4,5]. **T_{MID} predicted = 2.04 s (occ.)**

- **BASS RATIO AND BRILLIANCE INDEX**

Averaged (occupied)	Bass Ratio(T_{low}/ T_{mid})	Brilliance(T_{high}/ T_{mid})
Barcelona	**1.18**	**0.97**
Boston	1.03	0.79
Vienna	1.11	0.85
Amsterdam	1.08	0.83

Table 5: Bass Ratio and Brilliance for occupied conditions

The values measured in Barcelona are noticeably better than those exhibited by the classical halls.

In the following we will use the expressions proposed by Bradley[6], to obtain the energy magnitudes for the occupied condition.

- **EDT EARLY DECAY TIME**

The average values of Early Decay Times EDT obtained for unoccupied hall are:

	125	250	500	1000	2000	4000	EDT_{mid}
EDT Barcelona (unoc.)	**2,30**	**2,25**	**2,33**	**2,40**	**2,51**	**2,30**	**2.38**
EDT Boston (unoc.)[1]	2.04	2.14	2.24	2.50	2.62	2.23	2.37
EDT Vienna (unoc.)[1]	2.96	3.04	3.05	3.01	2.71	2.09	3.03
EDT Amsterdam (unoc)[1]	2.61	2.50	2.59	2.66	2.42	2.00	2.625
EDT Barcelona (occ.)	**2.05**	**1.96**	**2.07**	**2.02**	**2.104**	**1.92**	**2.04**
EDT Boston (occ.)	1.87	1.83	1.73	1.76	1.63	1.22	1.75
EDT Vienna (occ.)	2.25	2.19	2.04	1.93	1.82	1.61	1.99
EDT Amsterdam (occ.)	2.20	2.15	2.05	1.95	1.80	1.55	2.00

Table 6: EDT values for unoccupied and occupied conditions

The EDT values in the Barcelona hall are close to the RT, which suggests good diffusion in the hall, and we see that for most positions the EDT is independent of source-receiver positions.

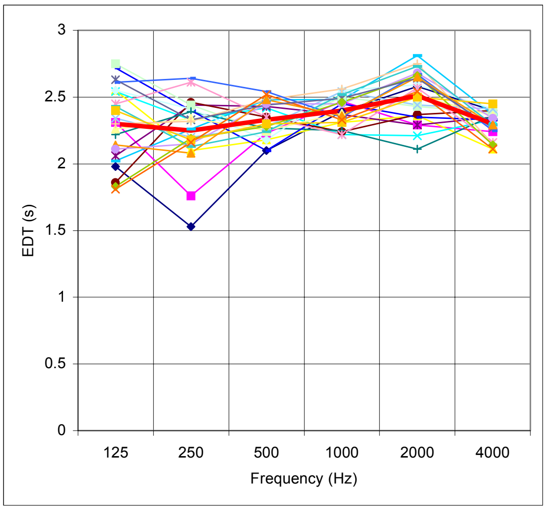

Figure 8: Measured EDT in the unoccupied hall Barcelona

- **CLARITY INDEX C_{80}**

The values measured were:

	125	250	500	1000	2000	4000	C_{80mid}
C_{80} Barcelona (unoc.)	**-3.04**	**-1.51**	**-0.24**	**-0,25**	**-0.7**	**-0.45**	**-0.47**
C_{80} Boston (unoc.)[1]	-2.42	-2.63	-2.76	-2.52	-2.97	-2.31	-2.63
C_{80} Vienna (unoc.)[1]	-5.28	-5.47	-4.72	-3.95	-3.32	-1.57	-4.33
C_{80} Amsterdam (unoc)[1]	-5.40	-4.67	-4.19	-3.07	-2.65	-1.47	-3.63
C_{80} Barcelona (occ.)	**-2.39**	**-0.73**	**0.42**	**0.72**	**0.30**	**0.58**	**0.57**
C_{80} Boston (occ.)	-1.92	-1.43	-1.29	-0.53	-0.27	1.1	-0.91
C_{80} Vienna (occ.)	-3.71	-3.61	-2.43	-1.45	-1.09	-0.1	-1.94
C_{80} Amsterdam (occ.)	-4.29	-3.8	-2.96	-1.4	-1.05	-0.4	-2.18

Table 7: Measured and calculated[6] C_{80}

Measured C_{80} values at mid-frequencies.are in the middle of the criteria for a full audience: -2 < C80 <2 dB, and are higher than the mean values of the other classical halls.

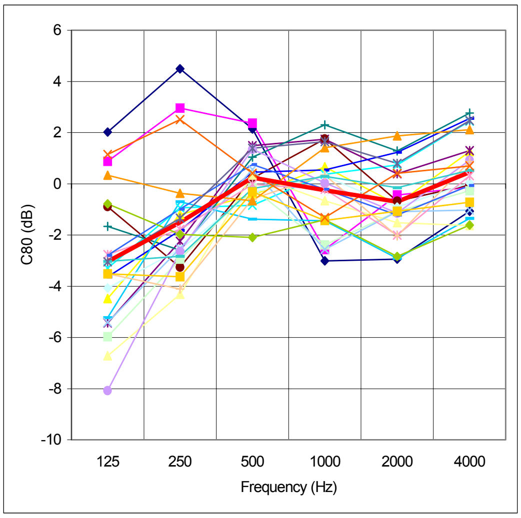

Figure 9: Measured C_{80} (unocc.) Barcelona

The behaviour of measured C_{80} at mid-frequencies in the unoccupied hall is compared with expectations from the Barron-Lee Revised Theory [7], using T_{mid} of the unoccupied hall in Figure 10.

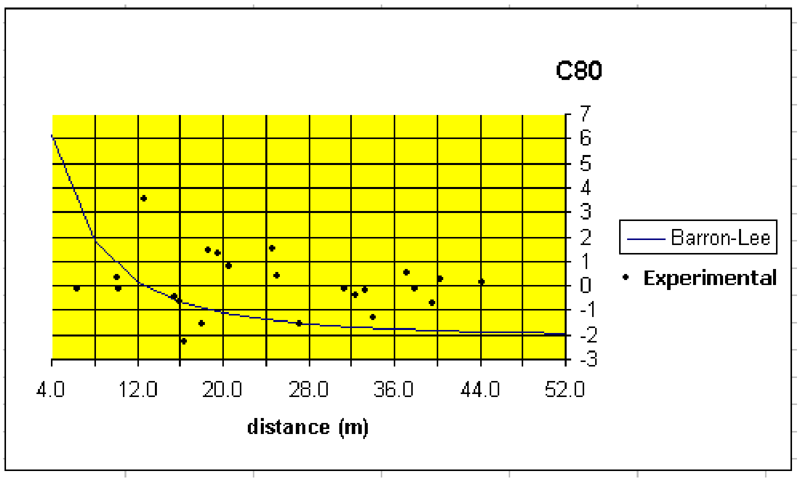

Figure 10: Measured C_{80} (unocc.) versus Barron-Lee theory

One observes that on average the C_{80} values conform to revised theory for distances up to 20m, while at larger distances most measured values are higher than theory. This may be due to enhanced early reflections.

- ## G TOTAL SOUND LEVEL OR STRENGTH FACTOR

	125	250	500	1000	2000	4000	G_{low}	G_{mid}
G Barcelona (unoc)	**4.29**	**4.12**	**3.52**	**3.61**	**3.92**	**3.62**	**4.20**	**3.56**
G Boston (unoc) [1(Bradley)]	1.43	2.61	3.70	4.27	3.70	2.34	2.02	3.98
G Vienna (unoc) [1(Bradley)]	6.10	6.04	5.97	6.57	6.04	4.51	6.07	6.27
G Amsterdam (unoc) [1(Bradley)]	5.46	4.99	5.37	5.71	5.23	4.20	5.22	5.54
G Barcelona (occ.)	**3.47**	**3.16**	**2.67**	**2.37**	**2.68**	**2.39**	**3.32**	**2.52**
G Boston (occ.)	0.82	1.13	1.89	1.83	0.38	-1.86	0.98	1.86
G Vienna (occ.)	4.17	3.75	3.15	3.5	3.3	2.71	3.98	3.33
G Amsterdam (occ.)	4.09	3.91	3.85	3.66	3.26	2.57	4.0	3.76

Table 8: Measured[1] mean and calculated [6] G values

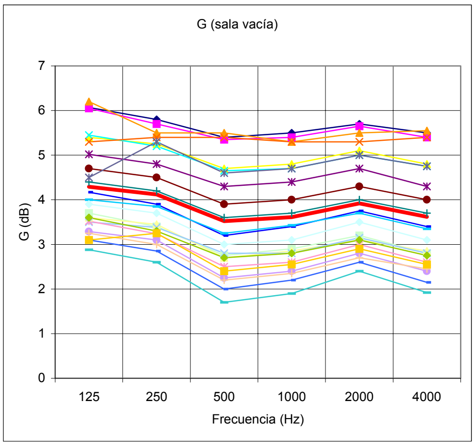

Figure 11: Measured G (unocc.) Barcelona hall

These values are good and satisfy the prescriptions of the acoustic criteria. Furthermore L'Auditori has a larger volume than classical halls yet the total sound level is very similar.

Comparing mid-frequency G values determined at each point measured to Revised Theory of Barron using the mean value of T_{mid} (unoccupied), we see in Figure 12 that there is excellent agreement between measured and predicted values.

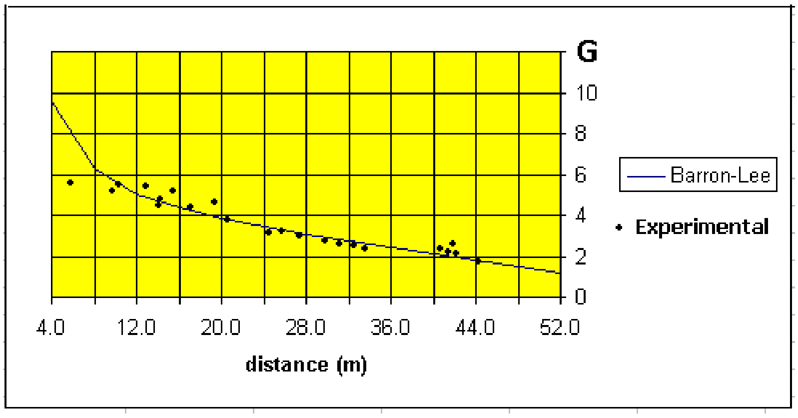

Figure 12: Measured G (unocc.) versus Barron-Lee Theory

- ## LATERAL ENERGY LE(%)

The value for the Barcelona hall is based on computer simulation (*).

Auditorium	LE (%)
Barcelona (*)	> 20
Boston	20
Vienna	17
Amsterdam	18

Table 9. Mean lateral energy fractions

- ## ST1 SUPPORT FACTOR

Auditorium	ST1 (dB)
Barcelona	-14.2
Boston	-13.7
Vienna	-13.9
Amsterdam	-17.8

Table 10: Measured Support ST1.

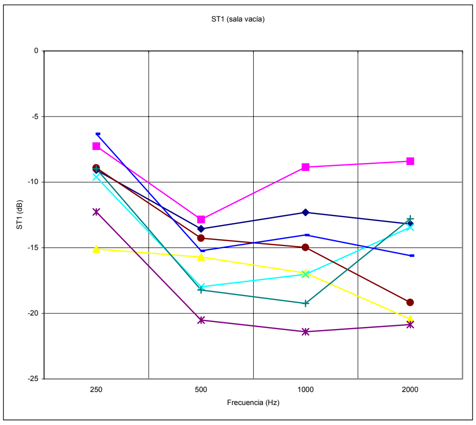

Figure 13: Measured ST1 (unocc.)

4. CONCLUSIONS

The measured results in "L'Auditori" of Barcelona are very encouraging and bear good comparison with those measured in three famous classical halls.

The general subjective impression is in agreement with expectations from objective measurements. The sound is impressive, clear and uniform throughout the hall; it is rich in bass and good for high strings. The local and international music critics have said: "This hall has a perfect acoustic". Jessy Norman said: "This hall has a wonderful acoustic". Lorin Mazel said that L'Auditori is the best; so have many other people and artists who have experienced the hall during the three years since the hall's inauguration, covering many newspaper pages and reviews.

5. REFERENCES

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6. ACKNOWLEDGMENT

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