Atotonilco Capilla Sound System
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Introduction

The Capilla was built about 130 years ago (ca 1890) as a Chapel to teach catechism to the local students. A few decades later, it was abandoned and fell into disrepair. The current priest, Padre Dante, is restoring the chapel to be used as a conference center where church educational and similar programs can be brought to the community.

The building itself is located adjacent to the church proper and is constructed of brick and cement. It is considered a historical site and thus protected by law against modifications. For example, the flat ceiling is painted with an intricate design that is in poor condition. It cannot be repaired; it must be restored.

The interior space measures 21 meters long and 5.2 meters wide. There is a raised area in the front that is 4.9 meters in depth and a rear vestibule that is 2 meters deep and covered by a balcony that is not easily accessible. The ceiling is flat plastered concrete and supported by 5 arches and the exterior walls. It is 6 meters high above an unfinished brick floor. There are two wooden side doors and a large wooden exterior door at the rear. There are also 5 windows set high on the side walls.

The exterior of the chapel is shown in Figure 1 (left) and the interior is shown in the same figure looking towards the front (center) and looking towards the rear (right). Since the chapel will no longer be used for church services, the building itself will be referred to as a center and the raised front area will be referred to as a stage.

Figure 1 Exterior (left), Interior Front (center) and Interior Rear (right)

The original plan was to provide a seating area with folding chairs about 2 meters in front of the stage to about 1 meter in front of the vestibule. This corresponds to a seating area of about 50 square meters (less the width of the center or side aisles). This plan changed during the course of the acoustic system design as discussed below.

Design Approach

The acoustic modeling program Ease5 was used to simulate the acoustic properties of the building and various possible speaker systems and wall treatments. The overall challenge was that the interior is basically an echo chamber since all surfaces were highly reflective and the interior shape itself is basically a long narrow tunnel. Since it is not actually a functioning Catholic church, the side walls between the supporting arches are flat spaces where acoustic absorption material might be located. The Ease simulations show that this is necessary to achieve good acoustic performance with any of the speaker systems, especially if the audience area is less than fully occupied.

The venue will be used almost entirely for speech, not music, so the frequency range of interest is about 500 Hz to 4 kHz. This means that speaker arrays lacking low frequency bass response can be considered.

The following criteria were used to evaluate the different speaker systems:

> Loudness over the listening area should be adequate for speech. The recommended sound pressure level for lecture halls is 68 to 75 dBA with peaks in the 85 to 95 dBA range.
>
> Clarity should be at least fair with the audience area 1/3 full and good with a full audience seated. (The presence of an audience adds significantly to the acoustic absorption). The technical definition of clarity for speech is called C35, and it the ratio of the sound energy received within the first 35 msec to the sound energy received after this time. C35 depends on the frequency, so the range 500 Hz to 4 KHz was used, unweighted. The commonly accepted criteria is - for good clarity C35 should be greater than 3 dB and for fair clarity, C35 should be between -3 and +3 dB. Below -3 dB, clarity is poor as the delayed reverberant sounds from one word or syllable interfere with the following syllable. In the tables below the average value of C35 (C35 Avg) is marked as green (good), yellow (fair) and red (poor).
>
> Sound level should be uniform over the listening area. Various measures can be used for this. L35, the sound energy received over the first 35 msec, which is also used in the calculation of C35, was selected. The absolute value of L35 is similar to the sound pressure level (SPL) but the important factor is its variation over the listening area. In the tables below, the standard deviation of L35 (L35 SD) is marked a green (good) when it is less than 2, yellow (fair) when it is between 2 and 3, and red (poor) when it is greater than 3.

The EASE model for the interior of the building is shown in Figure 2 for a typical sound system. The arch supports were simplified to be columns supporting straight concrete beams under the ceiling. The original listening area shown is 49 square meters (about 80 people maximum), and performance was evaluated with one of three “materials” – brick (no audience), 0.72 persons per square meter (1/3 full) and 2.0 persons per square meter (100% occupied). The six rectangles on the side walls represent areas that are either plastered brick (the same as the surrounding walls) or acoustic panels made of 1-1/2 inch thick absorbent fabric wrapped material. In total that amounts to 18 square meters of acoustic paneling which can be placed anywhere above the audience listening head height of 1.2 meters. The grey colored area above the floor is the listening area at the seated head height.

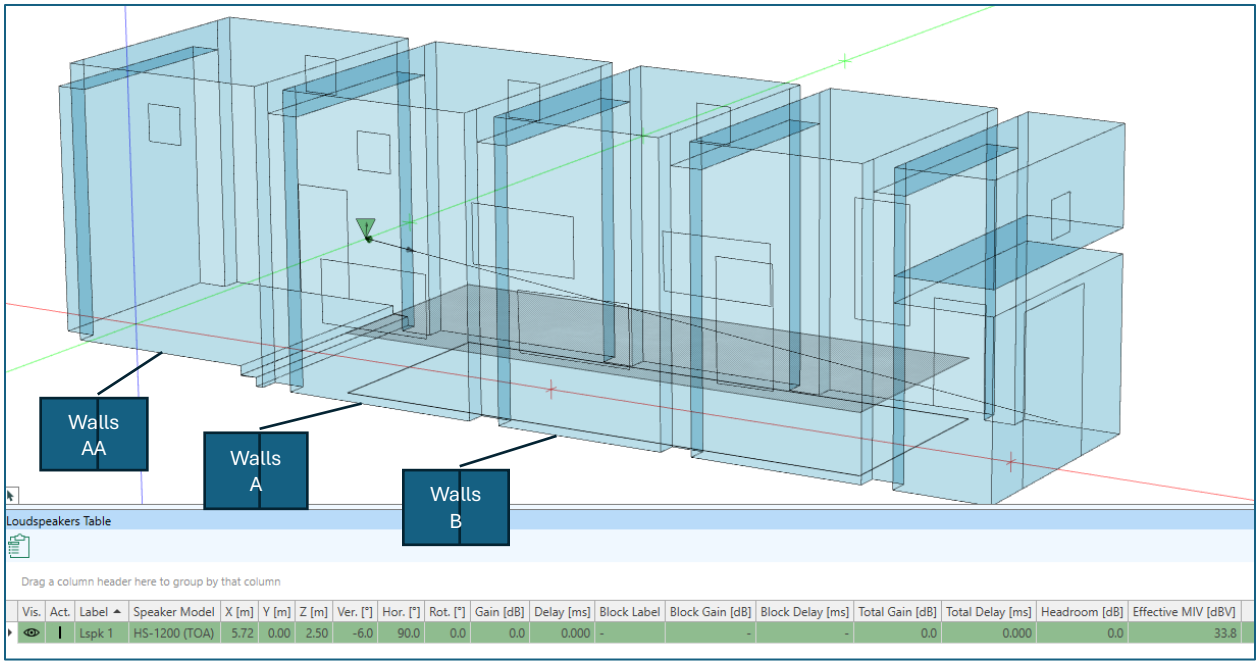

Figure 2 Ease Model Showing Interior Walls, Listening Area and Acoustic Panels with Single HS-1200 Loudspeaker

In the following section, various speaker systems were evaluated with and without the wall panels and with no audience, 1/3 full and fully occupied audience i.e., 6 conditions.

Because of the challenging acoustic surroundings, professionally rated speakers were used to provide directional sound distribution. These are expensive when purchased new, but reasonably priced when found used on eBay, so the availability of used ones played a part in the selection process.

Loudspeaker Selection

Single Overhead Speaker Array HX-5 or HX-7

These speakers are normally mounted above and in front of the audience and the splay angle between the speakers adjusted to provide the desired front to rear coverage. The dispersion side to side is about 100 degrees (+/- 50 degrees). This system is very common in modern churches in the US but not so much in Mexico. See Table 1.

Table 1 HX-5/HX-7 Speaker Properties

	Weight	16 kg
	Dispersion	100 x 60,45,30 or 15 deg
	Cost New	$1083/$2161
	Cost Used (eBay)	$250/NA

The HX-7 is a higher performance version of the HS-5 and costs about twice as much.

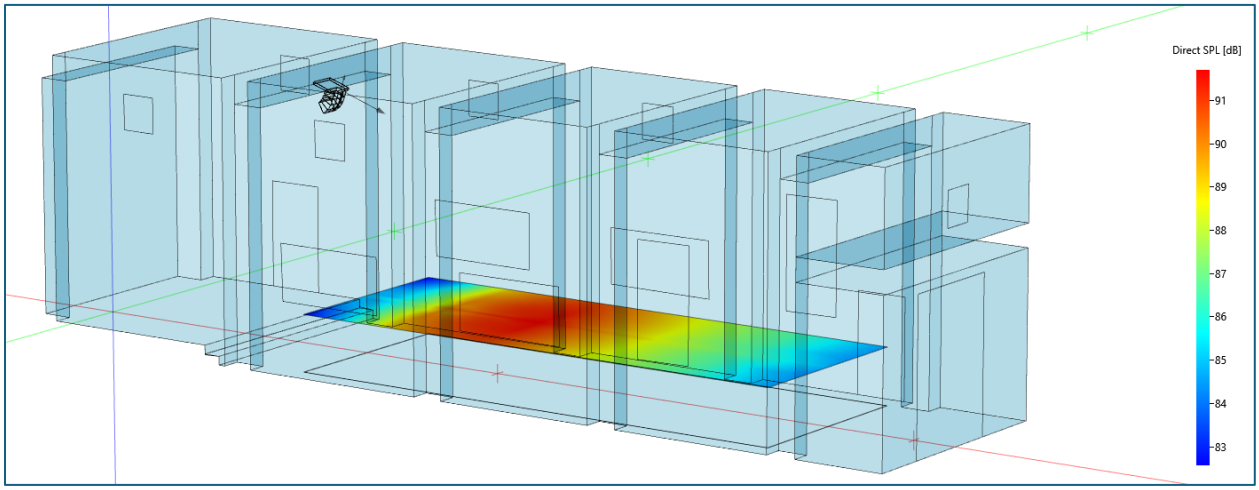

Figure 3 Geometry and SPL of Single HX-5 Speaker

The HX-5 speaker shown in Figure 3 places the speaker in front of and just below the top of the arch nearest the stage. Splay is adjusted to provide the most uniform coverage of the audience area. Overall volume (direct SPL) is more than adequate. Table 2 shows the clarity and uniformity obtained with up to 3 reflections considered.

Table 2 Average Clarity and Loudness Variation with Single HX-5 or HX-7 Speaker

Loudspeakers	Audience	No Side Wall Panels		6 Side Wall Panels	
		C35 Avg	L35 SD	C35 Avg	L35 SD
(1) HX-5 Top Front	Empty	-8.17	2.23	-5.49	2.24
	1/3 full	-4.04	2.17	-2.16	2.14
	Full	-2.00	2.50	-0.73	2.42
(1) HX-7 Top Front	Empty	-7.22	2.64	-4.09	2.55
	1/3 full	-2.81	2.44	-1.26	2.46
	Full	-0.03	2.96	-0.44	2.51

The clarity of the HX-5 is fair with the side panels and at least 1/3 of the audience present. The HX-7 is about 1 dB better, but still does not provide good clarity with a full audience. This speaker system would be a good solution for a room that was wider and had less reflection, but does not provide the desired clarity for this application.

HS-1200 at Front Center(1), Front Sides(2), Front and Rear Sides(4), or Front, Center and Rear Sides(6)

These are the same loudspeakers used at San Juan de Dios church in San Miguel de Allende. They consist of a line array having a narrow (40 degree) vertical dispersion in the voice frequency range concentric with a large diameter speaker that provides good bass response (not required in this application). See Table 3.

Table 3 HS-1200 Speaker Properties

Weight	10 kg
Dispersion	90 x 40 deg
Cost New	$540
Cost Used (eBay)	$130

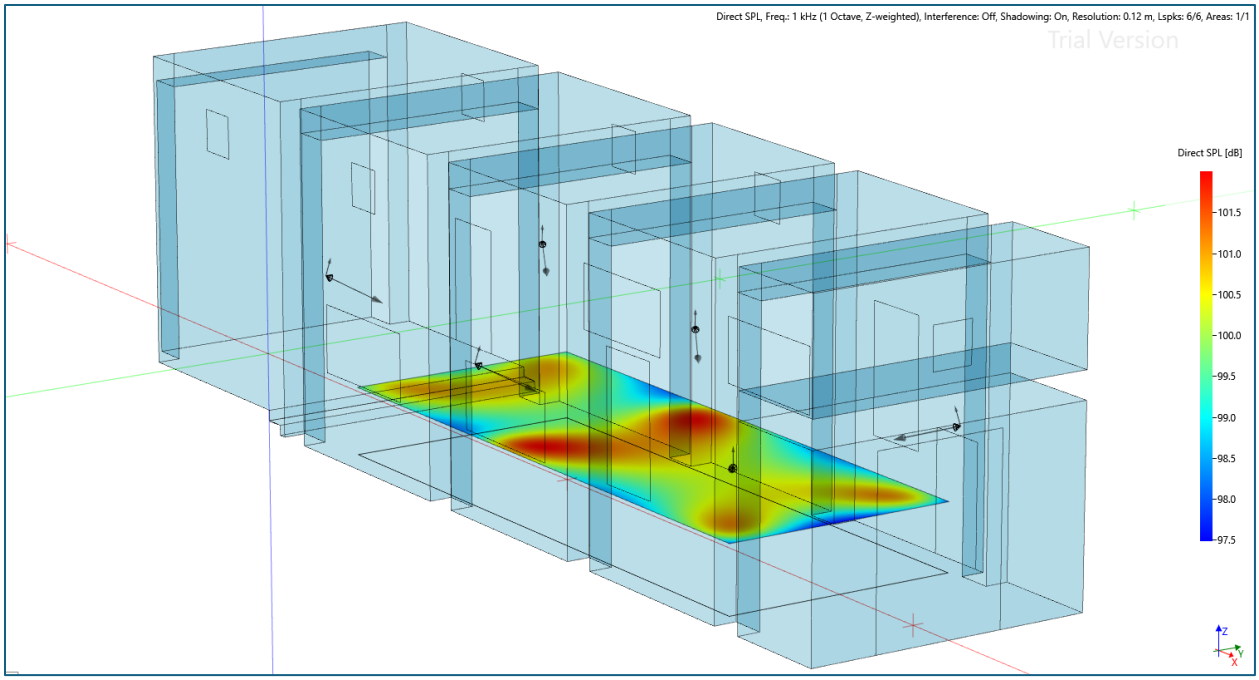

Figure 4 Geometry and SPL for 6 HS1200 Speakers

Figure 4 shows one of the five arrangements evaluated using these loudspeakers. Note that the rear pair of speakers is mounted behind the audience rather than in front of the back third of the audience. Both orientations were simulated in Ease for this speaker and several others, and this configuration was found to provide a better uniformity for both clarity (C35) and early sound energy (L35).

Table 4 Average Clarity and Loudness Variation with 1, 2, 4 and 6 HS-1200 Speakers

Loudspeakers	Audience	No Side Wall Panels		6 Side Wall Panels	
		C35 Avg	L35 SD	C35 Avg	L35 SD
(1) HS1200 Front Center	Empty	-8.89	2.53	-5.19	2.67
	1/3 full	-4.20	2.76	-2.22	2.86
	Full	-1.93	2.97	-0.33	2.99
(2) HS1200 Front	Empty	-8.83	2.62	-5.27	2.56
	1/3 full	-4.26	2.91	-2.29	2.88
	Full	-1.90	3.02	-0.54	3.17
(2) HS-1200 Front	Empty	-7.83	0.95	-4.10	0.91
	1/3 full	-3.47	1.04	-1.38	1.04
(2) HS-1200 Rear Reversed	Full	-1.21	1.17	0.40	1.17
(2) HS-1200 Front	Empty	-5.39	1.56	-2.83	1.51
(2) HS-1200 Center	1/3 full	-1.12	1.43	0.40	1.38
(2) HS-1200 Rear Reversed	Full	0.00	1.35	1.34	1.36
(2) HS-1200 Front	Empty	-8.11	1.06	-4.74	1.04
(2) HS-1200 Center	1/3 full	-3.76	0.92	-1.90	0.94
(2) HS-1200 Rear Normal	Full	-1.51	0.89	-0.15	0.94

Table 4 shows that the best configuration for this speaker is the 3 pairs noted with the arrow. This is better than the single HX-5 or HX-7, but still only fair with a full audience.

Column Line Array Speakers LBC-3200 & LBC-3201 at Front and Rear(4) and at Front, Center and Rear(6)

Table 5 LBC-3200/LBC-3201 Speaker Properties

	Weight	3/6 kg
	Dispersion	70 x 18 deg
	Cost New	$440/$620
	Cost Used (eBay)	$150(?)

These line array speakers listed in Table 5 are designed to provide very low vertical dispersion and are typically aimed straight across the audience head heights. The LBC-3201 is a taller and higher performance version of the LBC-3200. They are made by Bosch and sold online in the UK but may be obsolete or at least not easily available in the US. Only one is listed on eBay, and it is not clear whether it is an LBC-3200 or LBC-3201.

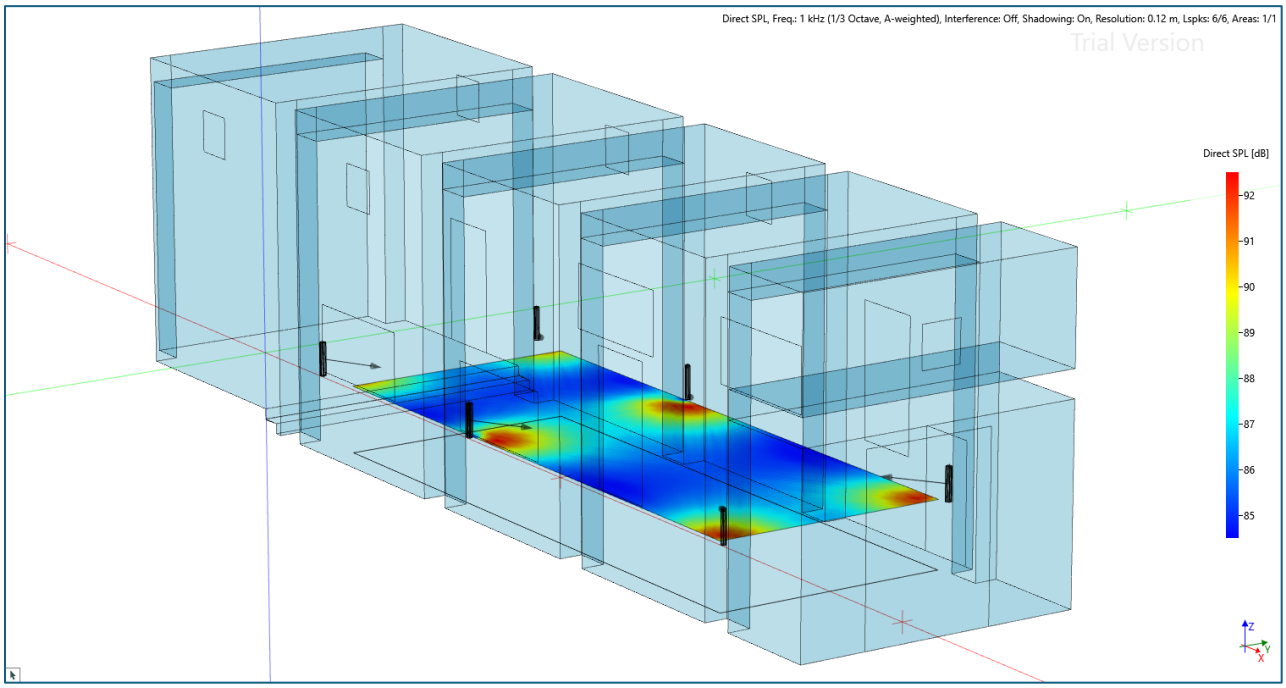

Figure 5 Geometry and SPL for 6 LBC-3200 Speakers

Arrays of four and six of these speakers were evaluated. Figure 6 shows the latter case.

Table 6 Average Clarity and Loudness Variation with 4 and 6 LBC-3200 Speakers

Loudspeakers	Audience	No Side Wall Panels		6 Side Wall Panels	
		C35 Avg	L35 SD	C35 Avg	L35 SD
(2) LBC-3201 Front	Empty	-6.70	1.43	-3.17	1.54
	1/3 full	-2.05	1.57	0.07	1.70
(2) LBC-3200 Rear Reversed	Full	0.23	1.68	1.93	1.77
(2) LBC-3200 Front	Empty	-5.48	0.98	1.98	0.99
(2) LBC-3200 Center	1/3 full	-1.02	1.06	1.13	1.05
(2) LBC-3200 Rear Reversed	Full	1.07	1.08	2.84	1.10

The best configuration listed in Table 6 is (6) LBC-3200's. With the panels and a full audience the clarity almost reaches the 3.0 value required for a score of good.

Column Line Array Speakers SR-H2L, SR-H3L, SR-H2S & SR-H3S at Front and Rear(4) and at Front, Center and Rear(6)

The SR-H3 is a longer version of the SR-H2 speaker and the L designates a straight version while the S indicates it is slightly curved at its base. This curvature provides some advantage for an application with ascending seating, but it is not important in this application. See Table 7.

Table 7 SR-Hxx Speaker Properties

	Weight	4.2/7.9 kg
	Dispersion	90 x 20 deg
	Cost New	$689/$1071
	Cost Used (eBay)	2@$400 SR3S 2@$500 SR2S

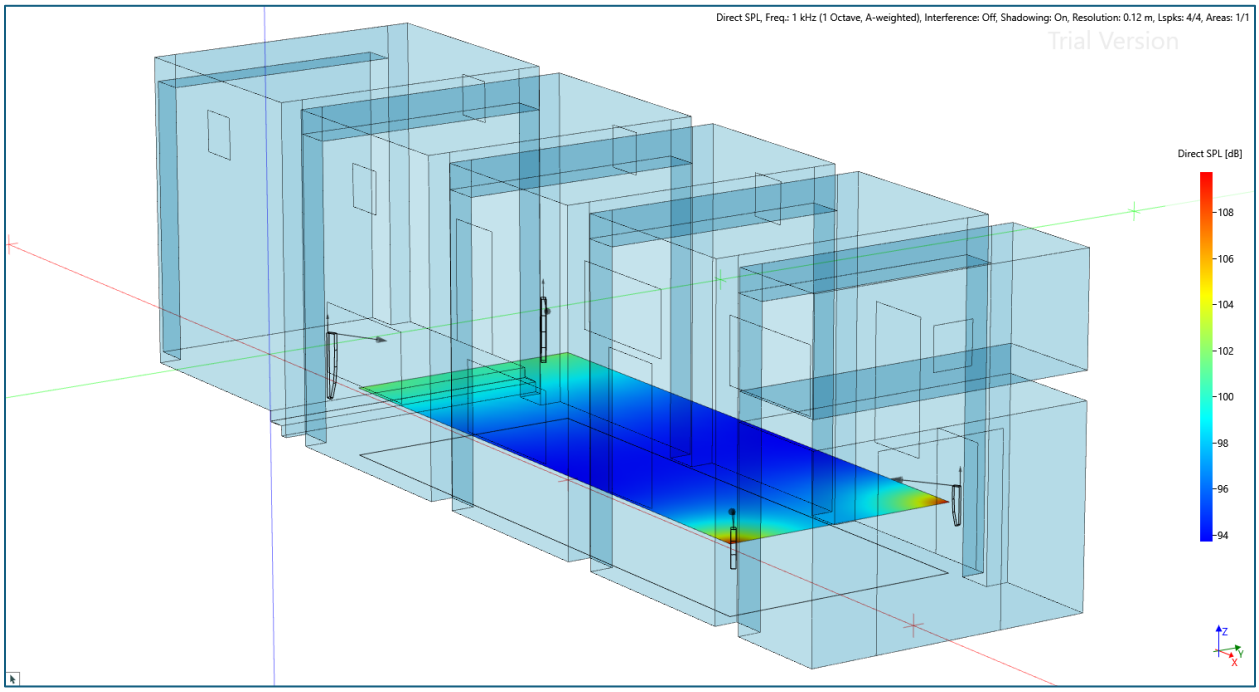

Figure 6 Geometry and SPL for 2 SR-H3L and 2 SR-H2L Speakers

Combinations of four and six of these speakers were simulated. Figure 6 illustrates the chosen design.

Table 8 Average Clarity and Loudness Variation with 4 and 6 SR-Hxx Speakers

Loudspeakers	Audience	No Side Wall Panels		6 Side Wall Panels	
		C35 Avg	L35 SD	C35 Avg	L35 SD
(2) SR-H2L Front	Empty	-3.62	2.93	0.17	2.94
	1/3 full	1.03	3.08	3.39	3.05
(2) SR-H2L Rear Reversed	Full	3.34	3.16	5.17	3.19
(2) SR-H2L Front	Empty	-2.91	2.68	0.74	2.68
(2) SR-H2L Center	1/3 full	1.74	2.76	3.94	2.75
(2) SR-H2L Rear Reversed	Full	4.00	2.83	5.72	2.82
(2) SR-H3S Front	Empty	-3.89	2.35	-0.46	2.41
	1/3 full	0.77	2.49	2.71	2.55
(2) SR-H2S Rear Reversed	Full	2.96	2.54	4.49	2.58

All three of the configurations listed in Table 8 meet (or almost meet) the design objectives. If the speakers were bought new, the first configuration (4) SR-H2L would be the most cost effective. A small improvement is obtained with the second one, (6) SR-H2L. But for purchase on eBay, the third option of (2) SR-H3S in the front and (2) SR-H2S in the rear is best as these speakers are available at a very good price.

Loud Speaker Selection

Based on the above results, it was concluded that we need at least 18 square meters of acoustic panels.

The best solution is 4 or 6 SR-H2L speakers but the most cost effective are 2 SR-H3S in front and 2 SR-H2S in rear because they are available used on eBay. These speakers were purchased.

Interior Changes and Acoustic Treatment

After reviewing the above results and ordering the speakers, some design changes were made to the structural layout of the hall:

A 6 ft tall glass partition was added just forward of the side door which blocks off the vestibule.

A floor to ceiling drywall screen was placed in front of the front wall.

For both esthetic and acoustic reasons, the side walls A and B will be curtained to a height of 3 meters. That is an area of about 46 square meters.

The effect of these changes was to prevent the use of the 2 SR-H2S speakers at the rear arch supporting the balcony. The model was changed to move these speakers forward to the next arch. The listening area was also reduced so that the rear row was 1 meter forward of this arch. This reduces the audience area to 27 square meters (about 45 seats maximum).

These changes resulted in the new model called 2A shown in Figure 7 below.

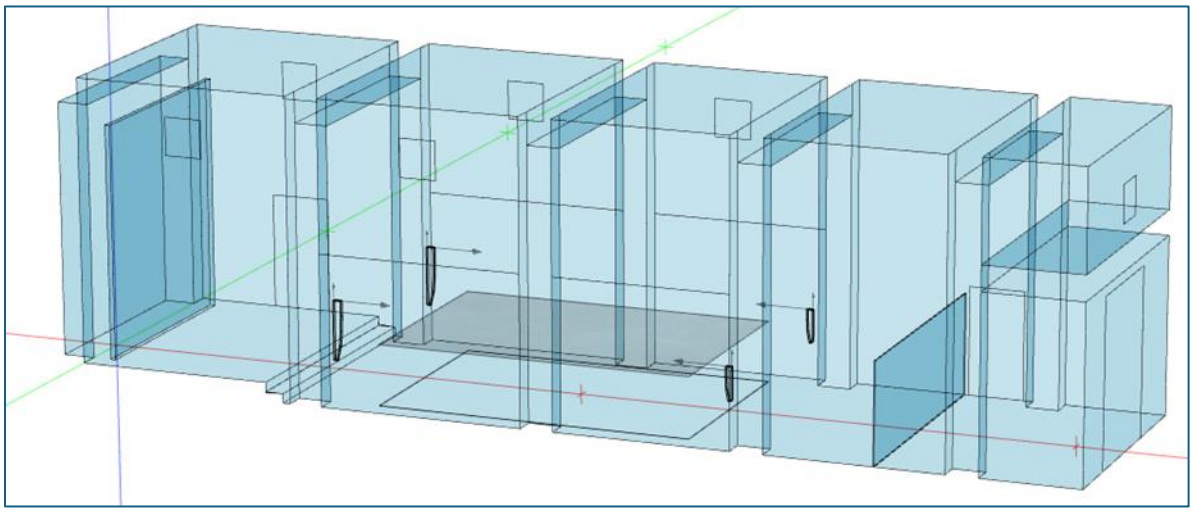

Figure 7 Model 2A Model with Curtains on Walls A and B, Glass Rear Partition and Front Screen

Curtains on Sidewalls A and B

The performance with and without curtains is given in Table 9.

Table 9 Average Clarity and Loudness Variation for Option 2A Model with and Without Curtains on Walls A&B

Curtain Area	Audience	C35 Avg	L35 SD
0	Empty	-1.67	0.88
	1/3 full	1.10	0.92
	Full	2.46	0.97
46	Empty	0.85	1.05
	1/3 full	2.57	1.03
	Full	3.54	1.12

The last case above (Full audience with curtains on Walls A and B was repeated with different speaker combinations. Note that the average clarity listed in Table 10 is nearly the same without the rear speakers. This suggests that two speakers might be adequate.

Table 10 Average Clarity and Loudness Variation with Different Speaker Combinations

Speakers		C35 Avg	L35 SD
Front	Back		
SR-H3S	SR-H2S	3.54	1.03
SR-H3S	none	3.58	1.69
none	SR-H2S	3.56	3.60
SR-H2S	none	3.61	3.41

Larger Audience Area and Curtains on Sidewalls AA, A and B

With the rear speakers eliminated, the audience area can then be extended rearward to 1 meter in front of the glass divider, increasing its area to about 40 square meters (about 70 person maximum). To improve the clarity further, curtains were added to the side stage areas AA. Model 5A is shown in Figure 8.

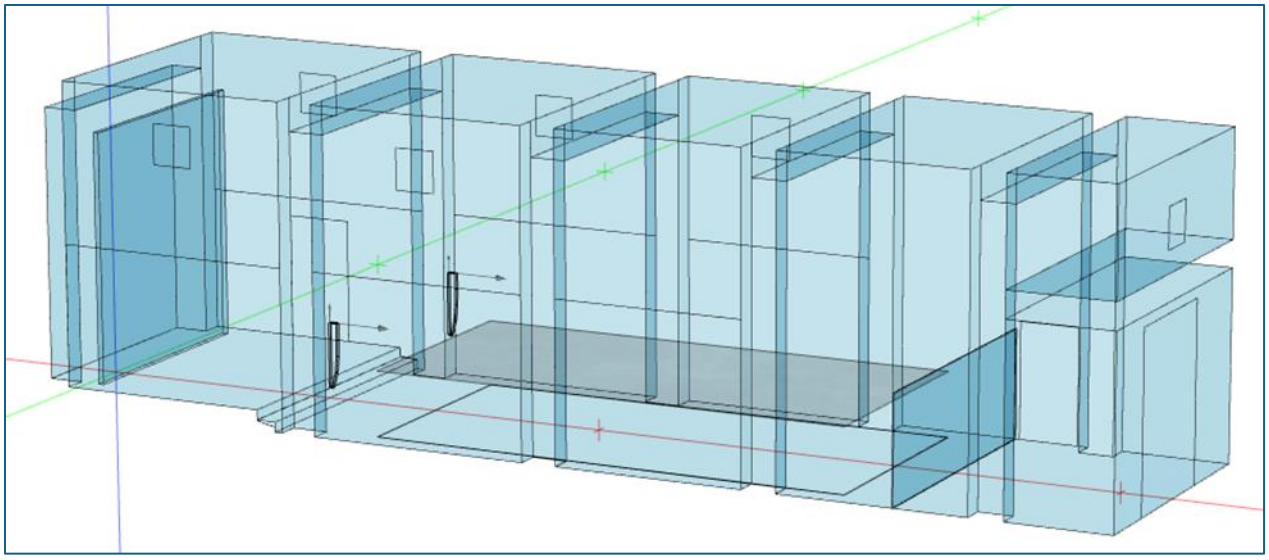

Figure 8 Model 5A with Curtains on Sidewalls AA, A and B, Larger Listening Area and SR-H3S Speakers at Front

Performance is now good even with the smaller (1/3) audience. See Table 11

Table 11 Average Clarity and Loudness Variation with Curtains on Walls AA, A and B, SR-H3S Speakers at Front

Audience	C35 Avg	L35 SD
none	1.24	2.02
third	3.58	2.12
full	5.00	2.39

If the front speakers are changed to the smaller SR-H2S devices, the results are essentially the same clarity but with more loudness variation. See Table 12.

Table 12 Average Clarity and Loudness Variation with Curtains on Walls AA, A and B, SR-H2S Speakers at Front

Audience	C35 Avg	L35 SD
none	1.11	3.50
third	3.21	3.69
full	4.46	3.88

Display Panels on Walls A and B

The above results were presented at a meeting on March 3, 2026 and it was decided to continue with the two SR-H3S speakers at the front, but to use display panels on walls A and B. The latter decision was based on the higher cost of the curtains and the desire to provide painting display panels on the side walls. These panels would be constructed using 100 mm thick fiberglass insulation on 1x4 or 2x4 wood frames that were 4 ft wide and 8 ft tall. Three of these frames fit into walls A and two frames into walls B this providing a total of 320 square ft or 29 square meters of acoustic absorption. Model 6A is shown in Figure 9.

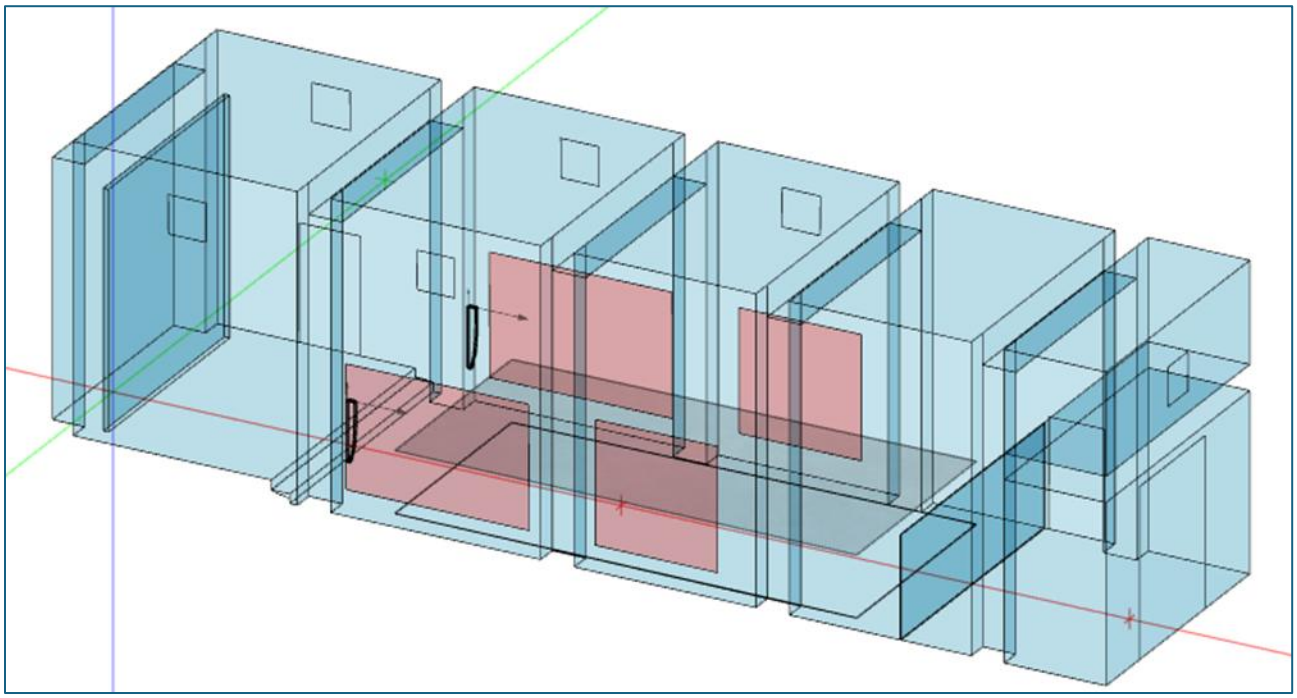

Figure 9 Model 6A with 29 sq m of Acoustic Panels at A and B, 2 SR-H3S Speakers at Front

Table 13 shows the results with and without the insulation for different audiences.

Table 13 Average Clarity and Loudness Variation with Display Panels on Walls A and B, SR-H3S Speakers at Front

Insulation	Audience	C35 Avg	L35 SD
none	none	-2.92	2.27
	third	0.91	2.40
	full	2.88	2.61
29 sq m	none	-0.91	2.03
	third	1.60	2.33
	full	3.14	2.30

These results meet the objectives for both clarity and loudness variation (with the panels) and are surprisingly fair without the panels. The no-audience cases are important because they will be used for testing. Ease5 provides a mapping function for these cases.

Clarity and Loudness maps are shown in Figure 10 and Figure 11 for no display panels.

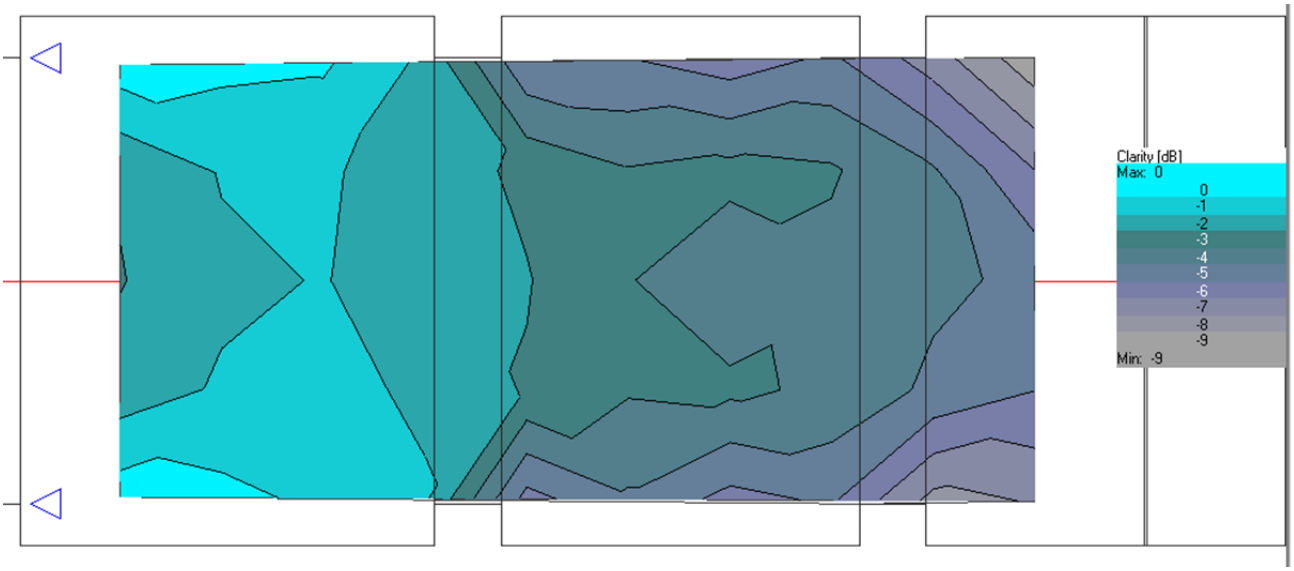

Figure 10 Clarity Mapping with No Display Panels, No Audience, SR-H3S Speakers at Front

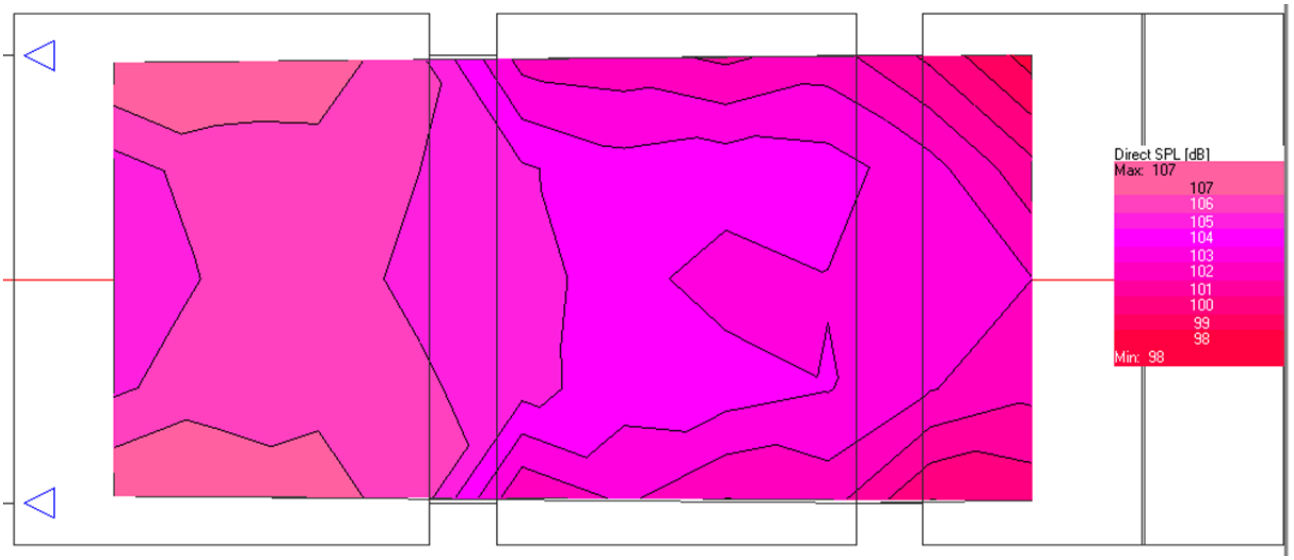

Figure 11 Loudness Mapping with No Display Panels, No Audience, SR-H3S Speakers at Front

With the display panels present, the clarity and loudness maps are shown in Figure 12 and Figure 13.

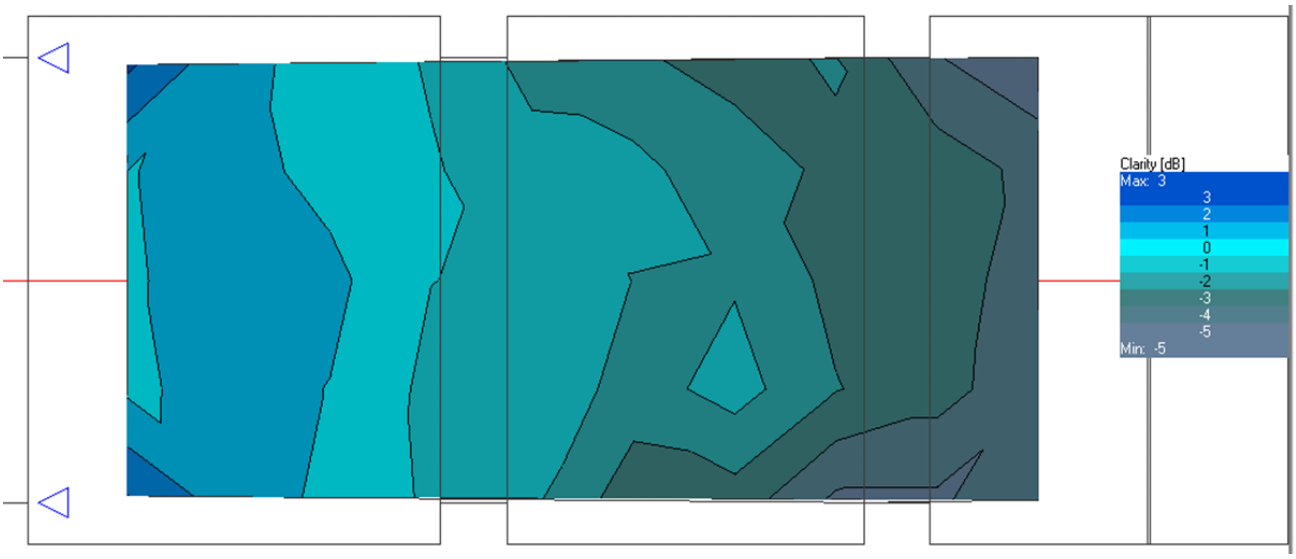

Figure 12 Clarity Mapping with 29 sq m Display Panels, No Audience, SR-H3S Speakers at Front

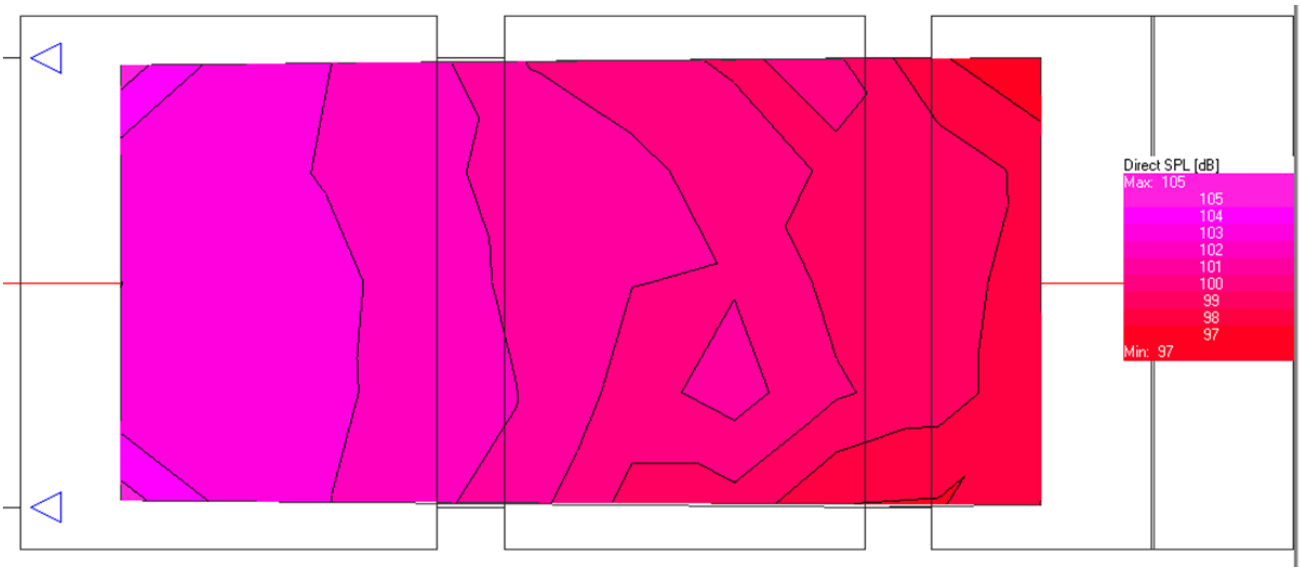

Figure 13 Loudness Mapping with 29 sq m Display Panels, No Audience, SR-H3S Speakers at Front

Sound System Implementation and Testing

Amplifier and Wiring

When the SR-H3S speakers were ordered, they were advertised as including the transformers that let them operate in a 70 V system. There are many advantages to a running multiple speakers at this voltage rather than as 4 or 8 ohm low voltage. However, when the speakers arrived, they were missing the transformers (TOA model MT-SO301) which cost about $120 each. They are occasionally available on eBay for about $100 each. Since the final design only required 2 speakers, they can be connected in parallel and run from an amplifier having a 4 ohm output.

An amplifier OSD Audio Model PAM245 was available, left over from the San Juan de Dios project. This amplifier provides six inputs and five high impedance zoned outputs. It also provides an 8 ohm and a 4 ohm output. It is a bit of overkill for this project, but since it was available, it was used with the 4 ohm output.

There is some consideration of adding the two SR-H2S speakers to the foyer as an overflow crowd addition. The best way to do this is to add the transformers to all four speakers and rewire them into 2 switchable zones. But they can also be wired in parallel then series connected to the front speakers to produce an 8 ohm load which can then be driven by the single 8 ohm amplifier output. It would be difficult to switch them on or off with this arrangement, however.

Acoustic Panel Construction

Some effort was spent researching locally available panel materials to construct 10 acoustic panels, each providing 4x8 ft of area with fiberglass absorption material.

Home Depot (Mexico) carries fiberglass insulation including a single package that contains 20 precut pieces each measuring 2-1/2 inch thick by 24 inch wide by 96 inch long. This is their stock number 850615 “Aislacustic R-8” and is stocked at their store in Humilpan Queretaro.
Both Home Depot and Trima Maderaria in San Miguel carry thin (3.0 or 4.7mm) plywood sheets 4 by 8 ft in size. Trima was a bit more expensive but delivers to Atotonilco at a very low cost, so the lumber was all purchased there.

The frame to hold the fiberglass consists of “1 by 3” pine lumber which actually measures about ¾ by 2-1/2 inch. A total of (4) 8 ft lengths are required for each panel. These were provided by Trima.

Finally, the covering selected was burlap (*yute*) and the only source found for the required size was Home Depot US. Two sizes are listed. Both are rolls 63 inches wide by 100 ft long. One is 6.3 oz weight and the other 7.7 oz weight. Either would work but only the heavier weight was available at the time of ordering.

The pine frame was constructed first from the 1x3’s using 2-1/2 inch long wood screws. Then the plywood back was attached using ¾ inch wood screws. The fiberglass was inserted in the two cavities and the burlap wrapped around the panel and fastened using 3/8 inch staples.

See Figure 14 and Figure 15 photos.

Figure 14 Panel Wood Frame (left) and Fiber Glass Insert (right)

Figure 15 Panel Burlap Attachment

System Testing

The speakers were connected in parallel and wired to the amplifier's 4 ohm output. Smart8 was used to record the impulse response along the centerline between the speakers at distances of 2,4,6,8, and 10 meters from the plane of the speakers. The room was otherwise empty, but as noted below, there was some noise disturbance from workers behind the glass divider during one of the measurements.

The panels were placed in their approximately locations along the walls, but not permanently attached. Tests were first run with the panel front facing the wall, then they were turned around to see the effect of the absorption. See Figure 16.

Both clarity (C35) and early arriving sound energy (LD35) variation were calculated from the Smart8 impulse response (Schroeder integral). The results are shown in Figure 17. The data point for 8 meters without panels was omitted from these graphs because there was a background noise that interfered with the measurements during this test which was not detected at the time. (During analysis, the "tail" of the Schoeder integral was found to be about 4 dB higher than the other cases

due to the background noise). The panels are working as they provided an improvement in clarity of up to 3 dB. The loudness variation was not affected by the panels.

Figure 16 Panels Facing Outward During Clarity Testing

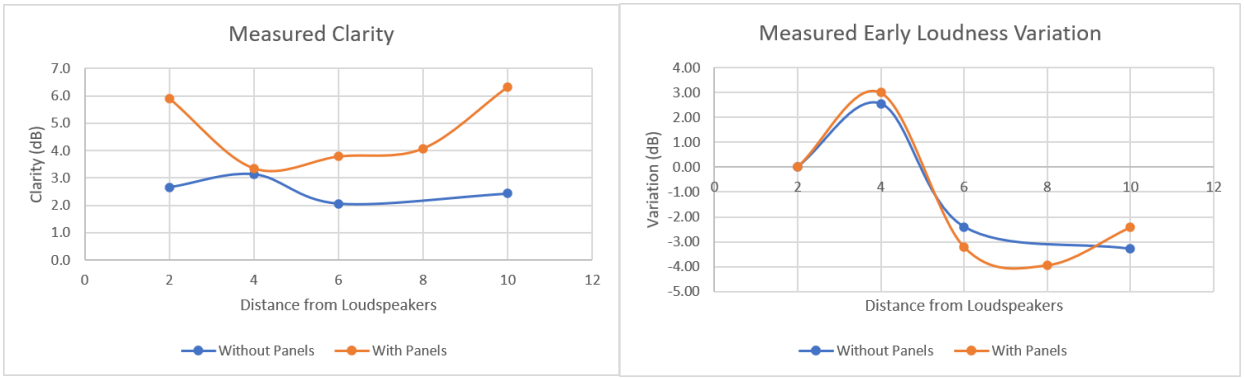

Figure 17 Measured Clarity and Loudness Variation with and without Acoustic Panels

Even more encouraging is that the clarity is greater than 3 dB (good) all along the centerline. The variation in loudness is about 6 dB peak to peak or about 2 dB standard deviation (fair). These measurements are, of course, with no audience present, which is the worse case.

Summary Conclusions

Like most historical churches, the Atotonilco Capilla is built as a long narrow structure with highly reflective acoustic surfaces. However, it repurposing as a conference center allows the sidewalls to contain acoustic panels. These make a significant improvement in the clarity.

Clarity is also helped by using directional speakers that focus the sound energy on the audience area to avoid reverberation from multiple reflections off the ceiling and uninsulated walls. For this reason, overhead speaker arrays like the HX-5 and HX7 are poor choices. Multiple HS-1200 speakers which contain a line array are better but not as good as column speakers like the LBC-32xx or SR-Hxx column arrays. These are all professional grade loud speakers and expensive new. However, used ones are occasionally offered for sale on Ebay. Two SR-H3S and two SR-H2S speakers were found and ordered.

Changes made to the interior design including the addition of a glass partition and projection screen changed the acoustic model after the speakers were ordered. It was also decided to use the acoustic panels as temporary display surfaces for artwork. The result was an increase in the panel area from 18 to 29 sq m. Further analysis now showed that the performance goals could be met with just two or the ordered loudspeakers.

The display/acoustic panels were built on site using readily available material in a couple days. There are 10 large panels (4x8 ft or 1.2x2.4 m).

Clarity was measured at 5 locations along the centerline of the audience area with and without the panels. It was between 2 and 3 dB (fair) without the panels and between 3 and 6 dB (good) with the panels. This was without any audience present.

The speakers arrived without the transformers so they are currently wired in parallel for 4 ohms. There is some consideration for adding the smaller SR-H3S speakers for overflow crowds in the vestibule. This will require adding transformers to all four speakers and making some minor wiring changes so the rear speakers can be switched on or off from the PAM245 amplifier.