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Acoustical renovation of "Nuestra Señora de la Paz"

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Church "Nuestra Señora de la Paz" is located in Pilar, province of Buenos Aires, Argentina. It has an octagonal floor plan and an internal volume of 2500 m^3 with bare sidewalls and little ornamentation. Excessive reverberation (4 seconds at mid-band frequencies), and an inappropriate sound system impaired speech intelligibility making ceremonies almost unintelligible. The church also suffered from thermal problems due to insufficient thermal insulation on the roof. Measurements (reverberation time, impulse responses and STI) were carried out and subsequent analysis revealed the significance of these problems. A holistic acoustical and thermal renovation was proposed and a new sound system was designed to address these issues. Subsequent measurements validated the effectiveness of the proposed renovations.

1 INTRODUCTION

Catholic church "Nuestra Señora de la Paz" is located in Pilar, province of Buenos Aires, Argentina. The worship space had several acoustical flaws and an inappropriate sound reinforcement system which rendered ceremonies almost unintelligible. Complaints from the congregation arose soon after inauguration. The building's thermal insulation was unsatisfactory as well, making it hot in summer and cold in winter. A combined solution for these two problems was requested by the parish priest.

A team composed of an acoustician and two students from the Electrical Engineering Department of Instituto Tecnológico de Buenos Aires (ITBA) was hired to consult and propose an efficient design that would address these problems, while preserving aesthetics and functionality.

2 HISTORICAL AND ARCHITECTURAL OUTLINE

"Nuestra Señora de la Paz" opened to the public on Christmas Eve 2003. The construction was funded by members of the "Estancias del Pilar" community, where the temple is located. It can house 400 worshipers seated in 40 unpadded wooden pews. Its internal volume is 2500 m^3 approximately.

The floor plan is almost a perfect octagon (Figure 1) and walls are hard and sound-reflecting with little ornamentation. The wooden roof forms an octagonal-based pyramid with its apex rising to almost 13 meters.

Ceremonies usually consist on the homily, delivered by the priest from the altar or the ambo, and musical accompaniment by a small group of singers and folk guitarists on one side of the altar. Occupancy varies greatly, ranging from full occupancy on Sunday masses to a dozen people during baptisms. The church doesn't have an organ.

The sound system used in ceremonies (loudspeakers are indicated with red arrows in Figure 2) was inappropriate because it lacked sufficient directivity and it excited excessively the reverberant field, resulting in very low speech intelligibility.

3 INITIAL MEASUREMENTS

3.1 Reverberation Time

Reverberation time was measured in octave-bands following ISO 3382[1] guidelines. Source and receiver positions are shown in Figure 1. Source positions are marked S1 and S2. Receivers are marked R1 to R5. Temperature and relative humidity values at the time of the measurement were recorded.

Measurements were performed with the interrupted noise method using a 15-inch Yamaha BR-15 two-way loudspeaker. The loudspeaker's frequency response is -10 dB from 20 Hz to 20 kHz. This source doesn't comply with the recommendations of directionality dictated by ISO 3382. In an effort to counter back this limitation, different loudspeaker orientations were used. According
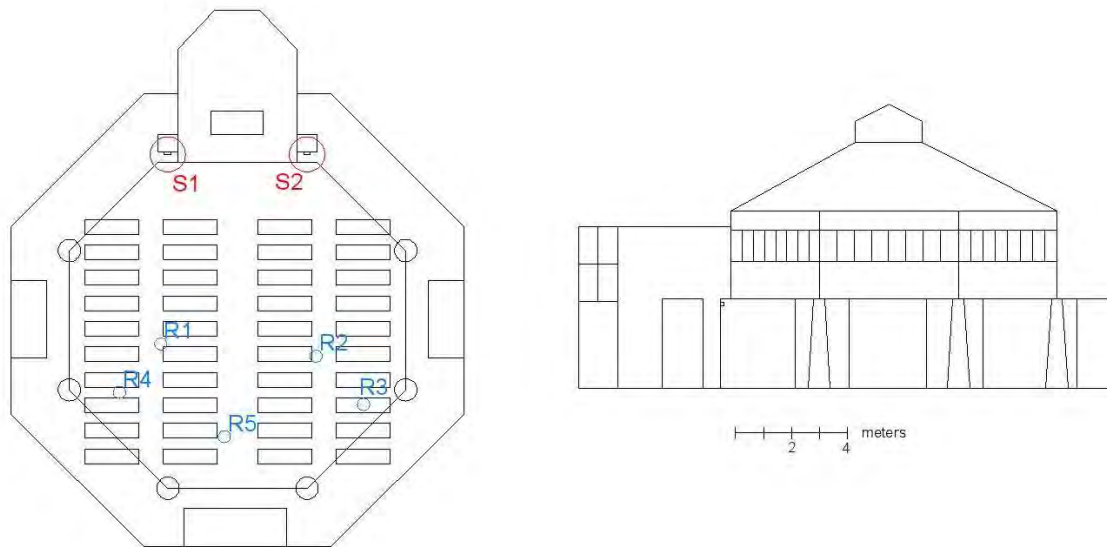
Figure 1: Plan and side view. Red points indicate source positions and blue points receiver positions.

Figure 2: Interior. Arrows indicate pre-renovation loudspeakers.

to Wallace[2], averaging values using different orientations yields more accurate results. Three orientations were used: loudspeaker pointing to the ceiling, to the congregation and to the altar. Signals were recorded with a laptop computer using a Brüel & Kjaer 2250 G4 sound level meter.

Results in Table 1 show the room average (mean of all measurement points, all orientations and both source positions) and the standard deviation across all these values. Standard deviations were also computed for different orientations. By calculating the standard deviation of the mean of all measurement points for each orientation, the influence of the source orientation could be studied. Results in Table 1 show that standard deviations for different orientations were within the JND for reverberation time[1], indicating that source orientation had a small impact on the results.

Reverberation time values were checked with the Reverberation Time Measurement Application BZ-7227 of the sound level meter (which is compliant with the relevant parts of ISO 3382), using the Impulsive Excitation method. Impulsive sources were balloon bursts. Less

measurement points were used in this case. Reasonable agreement was found between the two methods. Results are shown in Table 1.

Table 1: Measured reverberation time.

Method	Octave Band [Hz]	125	250	500	1000	2000	4000	8000
Interrupted noise	T30 [s] Room average	3.14	3.00	3.84	4.05	3.82	2.90	1.85
	STDEV [s] Room average	0.15	0.14	0.09	0.11	0.11	0.11	0.08
	STDEV [s] Different orientations	0.14	0.11	0.04	0.08	0.08	0.05	0.05
Impulsive excitation	T30 [s]	3.21	3.1	3.71	3.87	3.55	2.83	1.88
	STDEV [s]	0.18	0.02	0.05	0.02	0.10	0.01	0.03

3.2 Speech Intelligibility

In order to quantify the level of speech intelligibility impairment, an STI measurement was carried out using the existing sound reinforcement system. To perform the measurement, the iSTI ("Standard" version) iOS App (developed by Embedded Acoustics and fully compliant with the 4th edition of IEC 60268-16) was used. The STIPA signal was fed to the church's sound system and analyzed with the iOS device connected to the sound level meter. Constant values of 0.20 where obtained throughout all measurement locations, which according to Bradley[3] yield 60% intelligibility.

3.3 Thermal Control

A heat load analysis was performed on the building by an HVAC engineer, who quickly identified the wooden roof as the area with least thermal insulation. Proper insulation of the roof would be crucial in lowering the heat load on the building.

3.4 Acoustical Defects

The presence of parallel, sound-reflecting walls in the area of the congregation motivated the analysis of Room Impulse Responses (RIRs), in the search for echoes and coloration. RIRs were obtained through impulsive excitations (balloon bursts and firecrackers) in several combinations of source-listener pairs.

4 RENOVATION PROPOSAL

Long[4] recommends a reverberation time of 1.4 seconds for a house of worship with emphasis in speech and an internal volume matching that of "Nuestra Señora de la Paz" (the metric assumes full occupancy). Measured reverberation time was thus excessive for these purposes.

Fiberglass is a well-known acoustical material. It has a high absorption coefficient in the speech frequencies and can be used in conjunction with other materials to obtain high transmission

loss in partitions. Fiberglass is also an efficient thermal insulator, and boards with sufficient thickness and density can provide a thermal resistance of 20 mK/W (Concrete's thermal resistance ≈ 0.7 mK/W).

The aforementioned properties of fiberglass hinted a possible joint solution for the thermal and acoustical problems of the church: to apply fiberglass boards on the wooden roof to lower the reverberation time while providing the necessary thermal insulation in that area.

Thermal insulation and sound insulation follow similar rules: heat travels through the path of least resistance. Points in the building where heat conduction occurs are called "thermal bridges". Uninsulated areas are prone to become thermal bridges. Thus, covering the total area of the roof with fiberglass boards was necessary from the thermal point of view.

The acoustical consequence of this decision is that reverberation time would be controlled in a coarse manner, only hoping to reach the RT values quoted previously.

An additional outcome of this design decision is that the absorption would be irregularly distributed in the room and the sound field would depart from Sabinean diffuse-field assumptions[4]. Two issues arise from this: the reverberation time will be different from that predicted by Sabine's formula and the sound field will be composed of a vertical and a horizontal reverberant field, each one with a different attenuation. The vertical reverberant field will be highly attenuated by the absorption of the roof and the congregation and the horizontal field will have much less attenuation. It is also possible that decay curves exhibit double slopes[5], but Ermann[6] has shown that there is no subjective preference between this condition and pure exponential decays. (None of the pre-renovation measurements indicated double-sloped decays. ISO 3382 proposes a metric for measuring the linearity of decays: the correlation coefficient. If this metric exceeds 1%, the decay can be considered non-linear. Only the 63 Hz band of one decay exceeded this threshold with a 1.27% correlation coefficient value).

Without a computer simulation (which was beyond the scope of this project), predicting the reverberation time with uneven absorption is difficult. Some authors have proposed alternative reverberation time formulas[7-11] for these situations, but Bradley[12] points out that they do not in general lead to greater accuracy. Applying one of these formulas to the geometry of this space would be guesswork.

Since the thermal requirements dictated that all of the roof should be treated with insulation, we deferred quantifying the effect of it on the reverberation time until it was measured after the renovation. If the measured value was still too high, additional absorption could be placed in the upper areas of the walls.
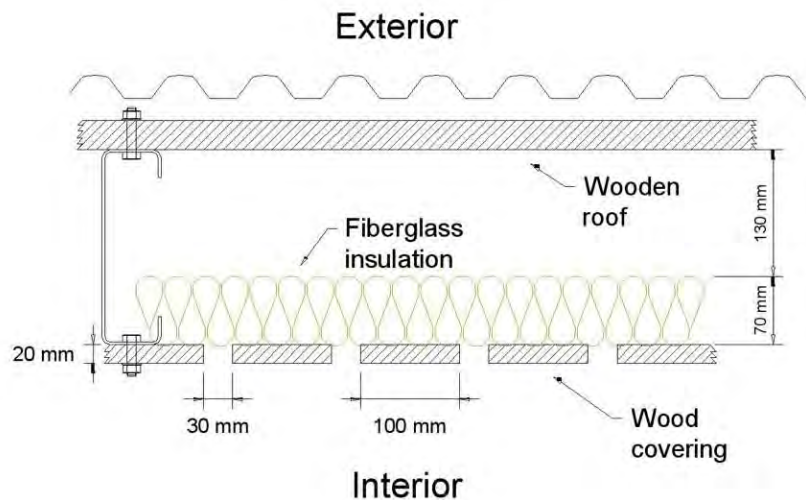
5 CEILING TREATMENT DETAILS

Fiberglass insulation is available in Argentina in different formats, mainly as rectangular boards and rolls of material that can be cut to a desired length. Different thicknesses and density of material are available to some extent.

Being a porous absorber, fiberglass produces maximal sound absorption where the particle velocity is highest. If reflecting from a rigid surface, the particle velocity of a sound wave has its maximum at a distance of ¼ wavelength from the surface. To obtain significant absorption in the lower speech octave bands (500 Hz) the thickness of the absorber should be at least 17 cm. The same effect can be obtained with a thinner material if it is placed separated from the backing surface.

Available fiberglass boards had a higher NRC (Noise Reduction Coefficient) than material sold in rolls (equal thickness), but cost of boards per square meter tripled that of rolls. Thus, a 70 mm thick material, sold in rolls, with a NRC of 0.83, was selected and placed on the roof providing a 130 mm air cavity to increment low-frequency absorption. Rooms for speech should have a flat distribution of reverberation time across the frequency spectrum, so, by looking at Table 1, sound absorption was most needed in the mid-frequency bands. The selected product could provide for this absorption.

The wooden roof of the church is supported by cold-formed steel beams, and fiberglass was secured using this structure, as depicted in Figure 3. A covering, composed of 20 mm thick, 100 mm wide wood strips, separated by a 30 mm gap, was installed to visually conceal the fiberglass. This arrangement provides more than 20% of fiberglass area exposed to sound, which is the value usually quoted in the literature[4] to provide the same absorption as an uncovered porous absorber.

Figure 3: Ceiling treatment details

6   SOUND SYSTEM DESIGN

The primary goal we set for the new sound system was to raise speech intelligibility scores to acceptable values. In order to accomplish this, the system should maximize the amount of direct sound that reaches the congregation and have a uniform coverage. Also, the listener should have the impression that the sound is coming from the source (in this case the speaking priest).

The first step of the design process is to select the type of loudspeaker system. Our initial suggestion was a distributed system or single cluster located above the altar, hung from a chain. This last configuration can maintain the impression that the sound comes from the priest in the altar. Both options were turned down due to aesthetic reasons. Our next suggestion was a double cluster, with the speakers located in the same columns where the former system's loudspeakers were located. The client accepted this option. The drawback of this type of system is that the sound image snaps to whichever side of the center aisle one is sitting on[4].

Three candidate loudspeakers were studied, all of them two-way speakers with an 8 inch woofer. They differ in the power handling capacity and directivity factor (Q). All of them had an acceptable bandwidth for reproducing speech, which is the most significant part of the program.

Long[4] proposes the following design criteria for indoor sound reinforcement systems: to have a less than 2 dB standard deviation on the direct sound distribution in the 500 to 2000 Hz octave

bands and to attain a satisfactory speech intelligibility in most seats, allowing some fair seats on the rear and sides. Speech intelligibility was estimated with a signal-to-noise ratio proposed also by Long[4]. The signal is the direct sound from all loudspeakers and the noise is the reverberant sound. Positive values (in dB) of signal-to-noise are uncommon in rooms and values higher than -9 dB provide good intelligibility.

Table 3: Predicted direct sound and intelligibility

Octave Band (Hz)	Direct sound standard deviation (dB)	Average intelligibility - S/N (dB)	Intelligibility standard deviation (dB)
500	2.39	-6.81	2.39
1000	2.18	-6.10	2.26
2000	2.13	-6.38	2.13

A spreadsheet was developed to calculate the direct sound distribution. Calculations were performed for two points per pew: one located at ¼ and another at ¾ of the pew's length. Energy contributions from both speakers in each point were incoherently added. The height of the loudspeakers was a design variable and the effect of changing it on the obtained coverage was studied. Off-axis directivities were calculated from the anechoic vertical and horizontal polar plots provided by the loudspeaker manufacturer using an elliptical interpolation formula proposed by Long[4].

The coverage criteria couldn't be met with any of the three loudspeakers. Even coverage is difficult to achieve in a room with this layout without a distributed system. Rising the height of the loudspeakers improved coverage, but diminished intelligibility. One loudspeaker model provided the best coverage, and Table 3 shows the calculated standard deviation of the direct sound as well as the average and standard deviation of the signal-to-noise ratio (which quantifies intelligibility) on the congregation area, for the three octave bands (500, 1000 and 2000 Hz) for this loudspeaker. Figure 4 shows the predicted intelligibility on this area, averaged over the three octave bands. Loudspeaker height was set to 3.9 meters, which balanced coverage and intelligibility within the available space in the room.

7   DETECTABILITY OF ECHOES AND COLORATION

Rooms with sound reflecting parallel walls, such as "Nuestra Señora de la Paz", are prone to create periodic reflections between these walls which can cause undesirable coloration in their impulse responses[13]. Also, isolated intense echoes due to long delayed reflections are perceptually undesirable[13].

Room impulse responses were obtained for 32 different source and receiver combinations (before installing the insulation on the roof) following the guidelines for acoustical measurements in churches proposed by Martellota[14]. Two different detection criteria were employed: the echo criterion proposed by Dietsch and Kraak[15] and the autocorrelation technique proposed by Bilsen[16]. The first one can detect individual audible echoes and the second one coloration due to flutter echoes. Both tested negative for all 32 impulse responses (in the case of the echo criterion, no echo exceeded the threshold for 10% listener detectability).
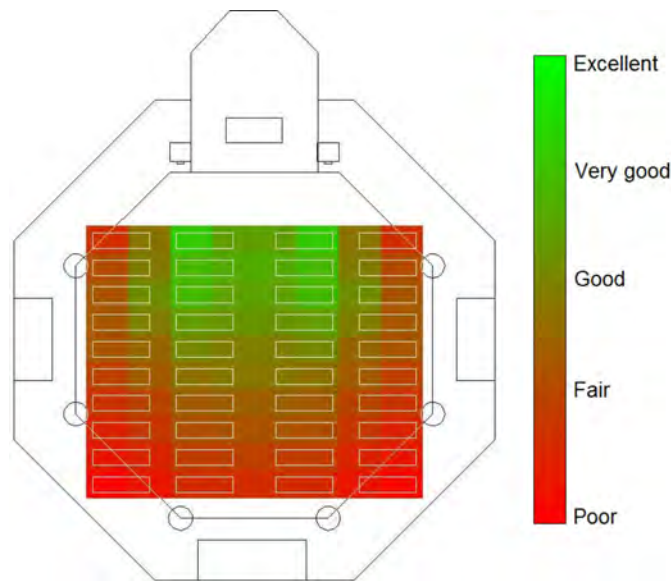
Figure 4: Predicted speech intelligibility (average over 3 octave bands)

8   FINAL MEASUREMENTS

Reverberation time was measured after placing the insulation on the roof, using the same source and receiver positions as in the pre-renovation measurements. Pre-renovation and post-renovation values are shown in Figure 5 (error bars show standard deviation). An estimation of the reverberation time with full occupancy (congregation's absorption was estimated with Beranek's method[17] using absorption coefficients for persons seated in wooden pews[18]) is also shown in this figure. It matches very closely the target value of 1.4 seconds with flat frequency distribution. None of the measured decays exhibited double slopes in the unoccupied measurements. Double sloped decays might appear with full occupancy.

Room impulse responses were measured in search of coloration using the same source and receiver positions. The echo criterion and the autocorrelation method tested negative in all impulse responses. We believe that reverberation, after the addition of insulation, is still high enough to mask flutter echoes in the congregation area.
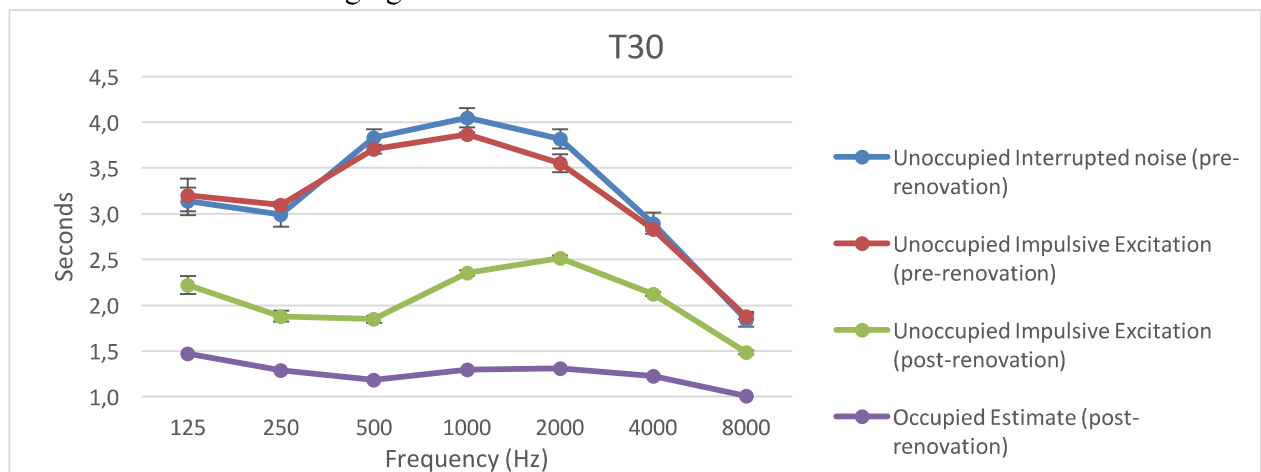

Figure 5: Pre and post-renovation reverberation time and occupied estimated.

Energy savings in air conditioning due to the added insulation were estimated in 20%, using ISOVER's Energy Saving Calculator software.

At the time of writing this report the selected loudspeakers hadn't been installed due to insufficient funding, so no measurements could be performed to validate the coverage and intelligibility predictions.

9   CONCLUSIONS

A holistic solution for the acoustical and thermal deficiencies of a worship space was described.

Significant improvements in speech intelligibility and energy consumption were attained with an efficient architectural design which preserved aesthetics and functionality.

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