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Sound, Noise and Speech at the 9000-Seat Holy Trinity Church in Fatima, Portugal

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This paper presents the interior acoustical characterization of the 9,000-seat church of the Holy Trinity in the Sanctuary of Fátima, Portugal, inaugurated in 2007. *In situ* measurements were held regarding interior sound pressure levels (with and without the HVAC equipment working), NC curves, RASTI (with and without the installed sound system) and reverberation time. The results are presented and commented according to the design values. A comparison is made with other churches in the world, also with a very large volume (for instance the Basilica Mariacka in Gdańsk). The measured data are also used to calculate a global index of this church acoustic quality using Engel's and Kosała's Index Method.

Keywords: church, acoustics, RASTI, reverberation time.

1. Introduction

The Catholic church of the Holy Trinity, inaugurated in 2007 in the Sanctuary of Fátima, was pioneer in Portugal because it is the largest church in the country (in number of seats) and deserved a profound and previous acoustic study (Carvalho, Freitas, 2003). The goal of this paper is the characterization of its interior acoustics through objective parameters and checking of the fulfillment of the acoustic goals, previously stated by the owner. *In situ* measurements were done regarding several objective acoustic parameters (HVAC background sound levels, Noise Criteria – NC, Rapid Speech Transmission Index – RASTI and Reverberation Time – RT).

2. The Holy Trinity Church

Since May 13, 1917 when Virgin Mary appeared to three children shepherds, Fátima (120 km northeast from Lisbon) became a world-wide known center of peregrination with the cult of Our Lady of Fátima. In 1919 the construction of a small chapel on Her place of appearance was initiated. A basilica was built in 1953 where the mortal remains of the three little shepherds rest. Soon, even this large basilica started to be insufficient to receive the thousands of pilgrims (Fig. 1a). In 2007 the Holy Trinity church was inaugurated (Fig. 1b and 2).

a) b)

Fig. 1. Typical May 13$^{\text{th}}$ peregrination (a) and the new Holy Trinity church (b).

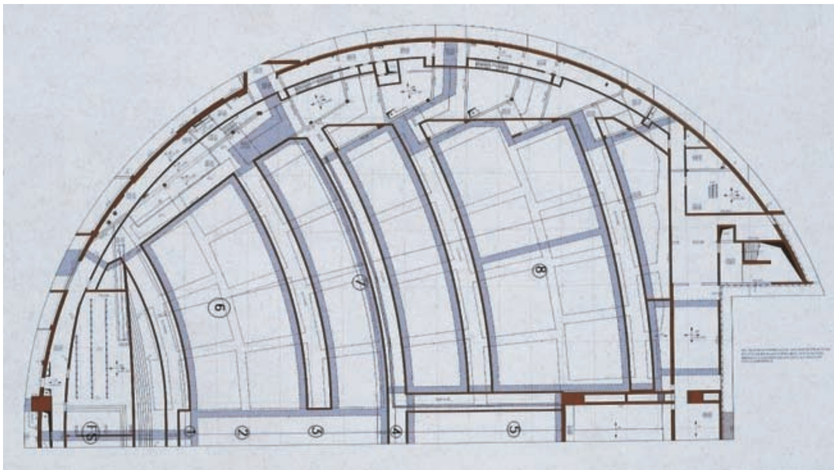

Fig. 2. Holy Trinity church floor half plan with RASTI measuring positions (altar at bottom left).

The church of the Holy Trinity is at the Southwestern top of the Sanctuary of Fátima (blank spot at the top of Fig. 1a). This mega-church (with a seating capacity of about 9,000 people) was designed by the Greek architect Alexandros Tombazis in a 125 m diameter, circular form. Its main dimensions are:

Volume – 130,000 m^3	Minimum height – 9 m	Average length – 85 m
Area – 8,700 m^2	Maximum height – 20 m	Maximum width – 115 m
Average height – 15 m	Maximum length – 95 m	Average width – 105 m

The main goal for the acoustics of this church was to guarantee very good speech intelligibility without compromising the quality of a good environment for music. As such, the owner established several acoustic goals to be fulfilled in the design phase (Table 1) (Carvalho, Freitas, 2003). Those limits reflect the concern in privileging the speech intelligibility, without relinquishing a musical minimum comfort and keeping a propitious environment for meditation and the individual prayer.

Table 1. Limit conditions for the acoustical requirements set by the Owner (Carvalho, Freitas, 2003).

Parameters	Objectives of project [Ideal goals]	Acceptable limit conditions
RT 100% occupied (500-1k Hz) 100% occupied (250 Hz)	$\leq$ 1.6 s $\leq$ 2.4 s	$\leq$ 2.0 s $\leq$ 2.8 s
RT unoccupied (500-1k Hz)	$\leq$ 2.1 s	$\leq$ 2.6 s
unoccupied (250 Hz)	$\leq$ 2.8 s	$\leq$ 3.4 s
NC	$\leq$ 25 dB	$\leq$ 30 dB[1]
RASTI[2]	$\geq$ 0.50	$\geq$ 0.45[1]
ΔL *mean spectral (45–11.200 Hz)*[2] (between any two seats in the congregation area)	$\leq$ 4 dB	$\leq$ 6 dB
ΔL *maximum at 1/3 octave band (141–5.620 Hz)*[2] (between any two seats in the congregation area)	$\leq$ 6 dB	$\leq$ 8 dB

[1] – at least on 95% of the seats; [2] – with Sound Reinforcement System (SRS).

In a church of this dimension (Fig. 4b) and with the chosen coverings (for instance the marble on the floor), an acoustic disaster could be foreseen. However, strong measures were taken to oppose the unfavorably designed architectural characteristics of the church and to provide the space with the acoustic comfort demanded by the Owner. A very short list of some of these measures is presented:

- Pews in wood with acoustically tested soft cushions (Fig. 3a);
- Interior faces of the twelve entrance doors with a perforated wooden finishing (grouped resonators) (Fig. 3b);

a) b)

Fig. 3. Cushioned pews (a) and perforated panels (b).

a) b)

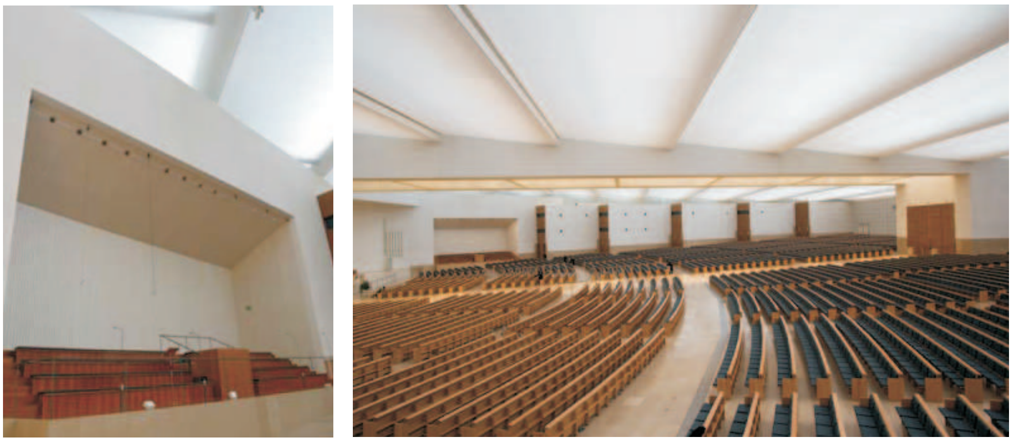

Fig. 4. Choir real wall (a) and church overview (b).

a) b)

Fig. 5. Diffusers (on the congregation rear wall) (a) and wall with absorptive *Acoustaplan* (white on photo at b)).

- Choir rear wall and rear assembly wall with diffusers (Fig. 4a and 5a);
- Presbytery wall with a slight inclination;
- Sidewalls covered with acoustical material *Acoustaplan* (Fig. 5b).

To all these, joins an electro-acoustic sound reinforcement system (SRS) with *Bose* loudspeakers and BSS processing. There are two columns with five loudspeakers, suspended at the center of the altar (Fig. 6a), responsible for the speech diffusion. At the altar's right-hand side six columns and four for low frequency, responsible for the organ amplification and also six wave cannons for extension of organ sound (Fig. 6b).

a) b)

Fig. 6. Suspended loudspeakers (a) and loudspeakers and *Wave Cannons* for the organ (b).

3. Measurements

Several parameters were measured *in situ*, on March 2009, at the unoccupied church:

– L (sound pressure levels) (and Noise Criteria NC) of the background noise with and without the HVAC equipment working (five measure points used);
– RASTI (Rapid Speech Transmission Index) noise with and without the use of the sound reinforcement system (eight measure points used, Fig. 2);
– Reverberation Time (RT) by octave bands (125 to 4k Hz) (nine measure points used).

The equipment used was a B&K sound level meter 2260 with a 1/2″ microphone B&K 4189, a sound source B&K 4224 and the RASTI analyzer (B&K 4225+4419).

4. Results and discussion

Background noise – The results regarding the sound pressure levels (L) for the background noise (with and without the HVAC system) are presented in

Table 2. The HVAC system has a fairly low sound level (about 39 dBA) but it increases the initial low church background noise level between 13 and 19 dB(A). All positions had the NC values from 30 to 35, what shows an increase of about 15 dB in the noise environment within the church.

Table 2. Mean values of the sound pressure levels (L) and sound levels (L_A) of the background noise, with and without the HVAC and the NC rating for each measuring position.

Point	L [dB]		L_A [dB]		ΔL [dB]	ΔL_A [dB]	NC [dB]		ΔNC [dB]
	with HVAC	without HVAC	with HVAC	without HVAC			with HVAC	without HVAC	
1	51.5	35.0	38.3	24.2	16.5	14.1	32	18	14
2	51.4	34.7	37.3	24.0	16.7	13.3	30	17	13
3	52.2	34.4	38.0	23.8	17.8	14.2	31	18	13
4	52.7	30.9	41.0	23.5	21.8	17.5	35	17	18
5	52.8	30.6	40.6	21.7	22.2	18.9	35	16	19
Average	52	33	39	23	19	16	33	17	15

RASTI – The results regarding the RASTI (with and without the use of the church sound reinforcement system – SRS) are presented in Table 3 and Fig. 7. On average the RASTI within the church is about 0.67 with the SRS on (an increase of 0.10 from the situation with the SRS off). These values show that the church has very good speech intelligibility and all the requirements set by the Owner are fulfilled.

Table 3. RASTI values with and without the sound reinforcement system (SRS).

Measuring points	SRS off	SRS on	ΔRASTI (on-off)
1	0.66	0.65	−0.01
2	0.61	0.62	+0.01
3	0.56	0.68	+0.12
4	0.53	0.70	+0.07
5	0.53	0.73	+0.20
6	0.59	0.64	+0.05
7	0.56	0.71	+0.15
8	0.51	0.66	+0.15
RASTI avg	0.57	0.67	+0.10

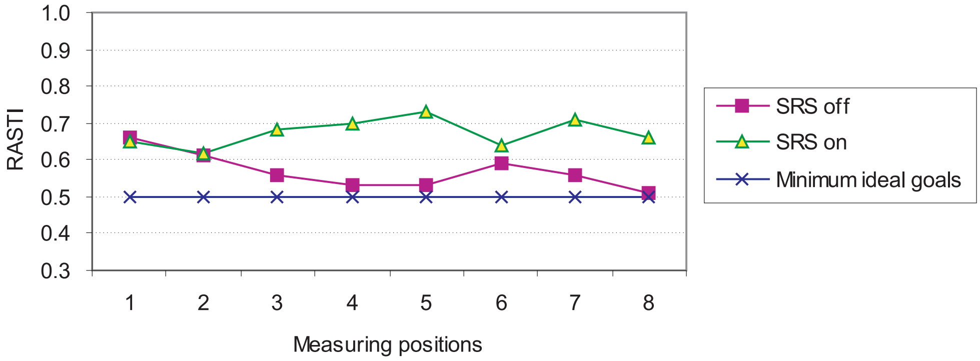

Fig. 7. RASTI values within the church with and without the SRS, compared with the minimum ideal goals.

Reverberation time – The results regarding RT are presented in Table 4 and Fig. 8. The 500-1k Hz RT values are between 1.7 and 2.5 s with an average of 2.1 s. Those values fulfil the ideal goals in 2/3 of the church and entirely for the acceptable limits. The 250 Hz RT values fulfil all the rules set.

Table 4. Summary of RT values vs design RT goals.

Parameter	Measured values within the church	Average of measured values	Ideal project goals*	Acceptable design limits*
RT (500-1k Hz) (s)	1.7 to 2.5	2.1	≤ 2.1	≤ 2.6
RT (250 Hz) (s)	1.7 to 2.4	2.0	≤ 2.8	≤ 3.4

* for every position within the church

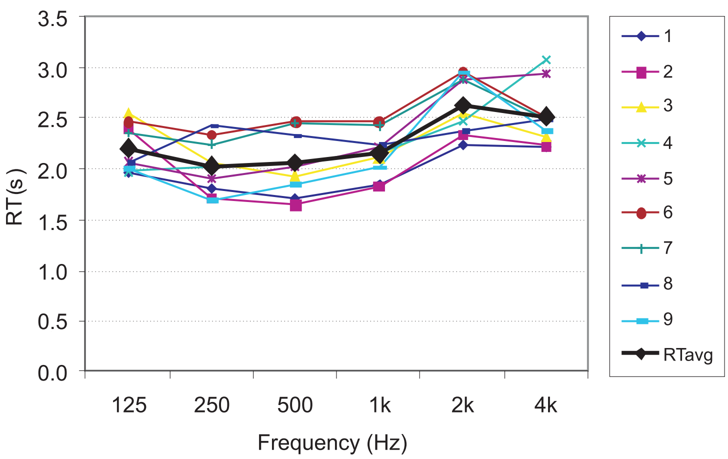

Fig. 8. Spectra of RT values in all the 9 measured points and the RTaverage.

5. Index method of the acoustic quality assessment of sacral buildings

The Index Method of the Acoustic Quality Assessment of Sacral Buildings developed by Engel and Kosała (2007) was tested in this church. It finds a global ndex W_{AQS} which is a function of partial indices as shown below:

$$W_{AQS} = \frac{\sum_{i=1}^{n} W_i \eta_i}{\sum_{i=1}^{n} \eta_i},$$

where W_i are five partial indices and η_i their weights ($\eta_1 = 1$; $\eta_2 = 0.5$; $\eta_3 = 0.3$; $\eta_4 = 0.3$; $\eta_5 = 0.2$). These indices are: *Wr (Reverberation index), Wis (Intelligibility of speech index), Wed (External disturbances index), Wul (Uniformity of loudness index)* and *Wm (Music sound quality index)*. All are rated in a scale from 0 to 1.

The scale for the acoustic quality of a church according to the W_{AQS} is: *bad* ($0 \leq W_{AQS} < 0.5$); *poor* ($0.5 \leq W_{AQS} < 0.65$); *good* ($0.65 \leq W_{AQS} < 0.80$) and *very good* ($0.80 \leq W_{AQS} \leq 1$).

The *Wr* (*Reverberation index*) is found from: $Wr = Wr_1.\beta 1 + Wr_2.\beta 2 + Wr_3.\beta 3$, where Wr_1 – reverberation-volume index, Wr_2 – reverberation index for organ music and Wr_3 – reverberation index for speaking.

$$Wr_1 = 1 - \left(\frac{|RT_{ZS} - RT_p|}{5}\right),$$

where RT_p is the preferred RT for the church ($= 0.24 \cdot \ln(Volume) - 0.24$ for Catholic churches, which gives, for the Holy Trinity church, 2.6 s) and RT_{ZS} is the measured RT corrected by the presence of people in the church.

For the unoccupied church, the measured RT is 2.1 s. For the occupied church, a RT (not measured) of 1.9 was chosen (RT_{ZS}).

According to the method (Engel, Kosała 2007), in this case RT_{ZS} is 1.9 s and the Holy Trinity church has a Wr_1 of 1.

$$Wr_2 = 1 - \left(\frac{|RT_{ZS500} - RT_{pO}|}{5}\right),$$

where RT_{ZS500} is the measured corrected RT for the 500 Hz ($RT_{pO} = 0.73V^{0.15}$, for the Holy Trinity church = 4.3 s) and the RT_{pO} is the preferred RT for organ music at 500 Hz. For RT_{ZS500} it was used 1.9 s, because the value measured in the unoccupied church was 2.05 s. Following the same approach as in the previous index, this Wr_2 is also 1.

$$Wr_3 = 1 - \left(\frac{|RT_{ZS} - RT_{pM}|}{5}\right),$$

where RT_{pM} is the permissible RT for speech ($RT_{pM} = 0.17 \cdot \ln(Volume) - 0.43$, that gives for the Holy Trinity church 1.57 s). Therefore, $Wr_3 = 0.69$.

For this church was used the $\beta1$, $\beta2$ and $\beta3$ similar to those given in the method for churches about 40,000 m^3 since this is the largest value available there. This does not guarantee the validity of this method for such a large church because it was developed for smaller churches (Holy Trinity church has more than three times that maximum volume). Nevertheless, the following values were used: $\beta1 = 0.6$; $\beta2 = 0.3$; $\beta3 = 0.1$. With those assumptions, $Wr = 0.97$.

The *Wis (Intelligibility of speech index)* is found from:

$$Wis = \left[\frac{(W_{is1}^2 + W_{is2}^2 + W_{is3}^2)}{3}\right]^{1/2}$$

Wis is supported by the parameters ALCons (Percentage Articulation Loss of Consonants) for W_{is1}, C_{50} for W_{is3} and RASTI for W_{is2}. The values chosen (using an educated guess) for W_{is1} and W_{is3} were the medium 0.5 because there were no measured data.

As the average measured RASTI was 0.57, the $W_{is2} = 0.58$ (using figure in (Engel, Kosała, 2007)). Therefore, $Wis = 0.53$.

The *Wed (External disturbances index)* is found from

$$Wed = \frac{3}{(L_A - 27)},$$

where L_A is the noise level of external disturbances, inside the church. The value used (23 dBA) is the average of the background noise level without the use of the HVAC systems (Table 2). Following the method's rules (Engel, Kosała 2007), $Wed = 1$.

Wm (Music sound quality index) is found from:

$$Wm = \left[\frac{(W_{m1}^2 + W_{m2}^2 + W_{m3}^2 + W_{m4}^2)}{4}\right]^{1/2}$$

$W_{m1} = 0.63$ using the RT (500-1k Hz) = 1.9 s and the suitable graph on (Engel, Kosała, 2007). $W_{m2} = 0.46$ using the *Bass Ratio* calculated with a $RT_{125} = 2.0$ s and $RT_{250} = 1.8$ s and (Engel, Kosała, 2007). $W_{m3} = W_{m4} = 1$ using the project average values ($C_{80} = +2.5$ dB and Center Time = 110 ms). Then,

$$Wm = \left[\frac{(0.63^2 + 0.46^2 + 1^2 + 1^2)}{4}\right]^{1/2} = 0.81.$$

For the *Wul (Uniformity of loudness index)* values were needed that were not available, like the sound pressure level decrease coefficient and the surface area on which the uniformity of loudness is investigated. Using an educated guess, a medium value of 0.5 was given to *Wul*.

Finally

$$W_{AQS} = \frac{0.97 \cdot 1 + 0.53 \cdot 0.5 + 1 \cdot 0.3 + 0.5 \cdot 0.3 + 0.81 \cdot 0.2}{1 + 0.5 + 0.3 + 0.3 + 0.2} = 0.803.$$

This value is at the borderline between the *Good* and *Very Good* interior acoustics classes. However, the exact number 0.803 is already in the *Very Good* class and a few options were done, in the method, that were very conservative (to give W_{is1}, W_{is3} and Wul a 0.5). If these were given 0.75, the W_{AQS} would be 0.87, now clearly in the *Very Good* domain.

6. Comparison of Holy Trinity church with churches of similar size

Table 5 and Fig. 9 show twelve mega-churches in the world, their volumes and $RT_{500\text{-}1k}$. Holy Trinity church (#7) is one of the largest but has almost the lowest RT, surpassed only by the Church of Jesus Christ of Latter-Day Saints (this, however, not a Catholic church) built in 2000. The two smallest average RT values are in churches built in the last decade, what means that there seems to be now a concern about the interior acoustics.

Table 5. Comparative analysis of mega-churches.

#	Church	City	Country	People	Volume [m^3]	RT(500-1k Hz) [s]
1	St. Peter	Rome	Vatican	58,000	700,000	7.0
2	Church of Jesus Christ of Latter-Day Saints (2000)	Salt Lake City	USA	21,000	226,000	2.0
3	St. Paul Outs. the Walls	Rome	Italy	38,000	181,000	8.6
4	St. Paul's Cathedral	London	UK	31,000	152,000	10.7
5	S. John in Luterano	Roma	Italy	23,000	150,000	6.2
6	Klosterkirche	Ottobeuren	Germany	*na*	130,000	6.5
7	**Holy Trinity (2007)**	**Fátima**	**Portugal**	**9,000**	**130,000**	**2.1**
8	First Baptist Ch. (1985)	Orlando	USA	6,000	115,000	2.9
9	Monastery S.to Domingo	Silos	Spain	*na*	113,000	6.5
10	Marien Church	Lübeck	Germany	*na*	100,000	5.5
11	St. Mary's Church (*Bazylika Mariacka*)	Gdańsk	Poland	25,000	97,000	11.4
12	Klosterkirche	Weingarten	Germany	*na*	90,000	7.2

na – not available.

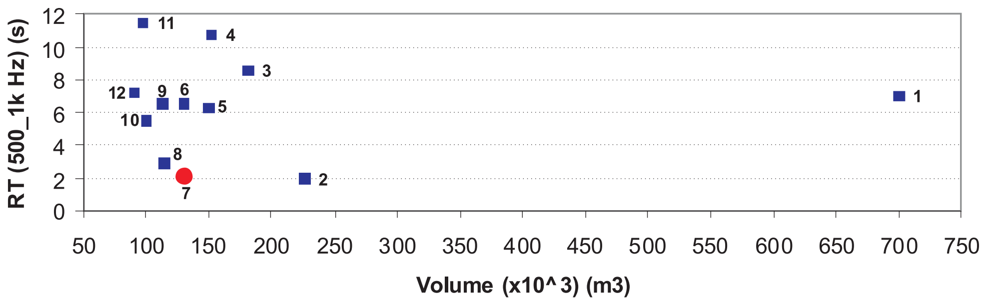

Fig. 9. Average RT (500-1k Hz) for twelve mega-churches (Fátima Holy Trinity: dot 7).

7. Conclusions

Table 6 presents the summary of the measured values. The *NC* values were between 30 and 35 dB, above the acceptable limit of 30 dB. However, these values may be caused only by a few badly connected ventilators' grilles that make an unusual noise (rumble). The HVAC makes the background noise level to increase by about 16 dB(A), reaching a value of about 39 dB(A) that it is not unreasonable.

Table 6. Summary of measured values and comparison with the Owner's previously set goals.

Parameters	Measured values	Avg. meas. values	Project Requirements		Result	
			Ideal	*Acceptable*	*Ideal*	*Acceptable*
NC (dB)	30 to 35	33	≤ 25	≤ 30	ko[3]	OK[2,3]
RASTI with SRS	0.62 to 0.73	0.67	≥ 0.50	≥ 0.45	OK	OK
RT (500-1k Hz) (s)	1.7 to 2.5	2.1	≤ 2.1	≤ 2.6	OK[1]	OK
RT (250 Hz) (s)	1.7 to 2.4	2.0	≤ 2.8	≤ 3.4	OK	OK

[1] – only in 67% of the church; [2] – only in 20% of the church; [3] – pending work in the grilles.

The RASTI values show that all the requirements are largely fulfilled and they reflect the good work in trying to achieve excellent speech intelligibility within the entire space.

The $RT_{500\text{-}1k}$ values show that the acceptable limits are fulfilled in all points. However, 33% of the positions exceed the exigent *ideal* goal. For the RT_{250} all the positions presented the values below the *ideal* goal. It can be concluded that the materials and systems used were capable to transform a very difficult shape and size into a very good space for a church and for its speech intelligibility and religious music.

In general, all the exigent requirements set by the owner were met except the NC values (but in this case, a simple fix of the grilles will transform the situation).

Using the Engel and Kosała's Index Method, this church achieved a rating of *Very Good*, that is in accordance with the previously stated.

Among the largest Christian churches, Holy Trinity stands out as one with the best acoustics for speech and music.

The main conclusion is that a strong and accurate acoustic project that involves the Owner, architect and acoustical consultant will give incredibly good results.

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