ACOUSTIC EVALUATION OF A BAROQUE CHURCH- THROUGH MEASUREMENTS, SIMULATION, AND STATISTICAL ANALYSIS

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ABSTRACT

This paper describes the acoustic evaluation of historical baroque church in Brazil - *Igreja Nossa Senhora do Rosário de São Benedito* (Church of Our Lady of the Rosary of St. Benedict), built in the 18th century. The evaluation was performed in three stages: 1) *in situ* measurements of reverberation time (RT), early decay time (EDT), definition (D_{50}) and clarity (C_{80}); 2) reproduction of field conditions in a computational simulation using ODEON room acoustics prediction software, and 3) statistical analysis of the data. The integrated impulse response method was used here, as recommended by the ISO/3382-1:2009 standard. Results were subjected to an analysis of variance (ANOVA) to test the accuracy of the model. The model can be considered accurate, especially as far as reverberation times are concerned.

RÉSUMÉ

Cet article détaille l'évaluation acoustique d'une église baroque construite au 18e siècle et faisant partie du patrimoine du Brésil - *Igreja Nossa Senhora do Rosário de São Benedito* (église Notre-Dame du Rosaire de St-Benoit). L'évaluation a été réalisée en trois étapes : 1) Mesure sur site (*in situ*) du temps de réverbération (RT), le temps de décroissance initiale (EDT), de la définition (D50) et de la clarté (C80); 2) Simulation numérique à l'aide d'ODEON, un logiciel d'analyse acoustique, à partir des conditions observées sur site, et 3) Analyse statistique des données. Tel que suggérée par la norme ISO/3382-1:2009, la réponse impulsionnelle intégrée a été utilisé pour les fins de la présente étude. Les résultats obtenus ont ensuite été soumis à une analyse de la variance (ANOVA) pour vérifier la précision du modèle. En ce qui concerne les temps de réverbération, le modèle élaborée peut être considéré valide.

1. INTRODUCTION

The development of room acoustic prediction techniques is quite recent. The first efforts in this area emerged in the early 20th century with the works of Wallace Clement Sabine. Until that time, the acoustic quality of a room was determined by trial and error and a little luck, or through the reproduction of successful cases [1, 2].

In the following decades, several investigation techniques to find analysis solutions for room acoustics were developed, including the use of physical scale models. These models were widely employed for testing concert hall designs. Despite their efficiency, however, scale models have gradually been abandoned as modern computer processing capabilities improve.

Digital models often save time and costs for evaluation, and also offer the flexibility to easily change various acoustical parameters such as building materials, room occupancy, etc [3, 4, 5]. However, computer models must still be treated with some care. According to Long [2]: "*The simplifications necessary to be able to carry out* *the calculations in a reasonable time still leave us with an imperfect picture, but as technical sophistication and computing ability increase, the models are improving*".

Computational predictions have become the object of periodic assessments by the international scientific community. Vorländer [6] and Bork [7, 8, 9] conducted international round robin calculations to evaluate the performance of room acoustics simulation software. These authors found that the weaknesses of all the software they evaluated involved the calculations of low frequencies and the treatment of the effects of edge diffraction, especially in seating areas. Other difficulties encountered in these models involved the correct characterization of surfaces in terms of their sound absorption and diffusion properties [10, 11, 12, 13, 14].

A comparison of calculated values and data obtained by measurements is fundamental in checking the quality of the model. According to Bradley and Wang [15]: "…*reverberation time has been the parameter most widely used by academics and industry to calibrate models*". The reasons for this are that this parameter is easy to measure, its sensitivity in relation to positions is low, thus increasing the repeatability of sampling, and the fact that these programs calculate reverberation time consistently, which simplifies its statistical treatment [15].

In addition, predictions should be compared with optimal reference values in order to assess the acoustic quality of the digital prediction model. The ISO/3382-1:2009 [16] standard shows optimum values for several metrics, as well as the perception threshold for mean frequency values in a single position in concert halls and multipurpose auditoriums with volumes exceeding 25,000 m^3 (Table 1).

In Brazil, room acoustics is being standardized and the criteria for acoustic treatments of enclosed spaces are recommended by the Brazilian standard NBR 12179:1992 [17, 18, 19, 20]. This standard considers only reverberation time for acoustic conditioning [18]. It recommends the use of the classical equations of Sabine or Eyring [5, 21, 22].

Subjective impression of the sound field	Objective descriptor	Single number frequency averaging* [Hz]	Perceptible difference	Typical interval **
Reverberation	Early Decay Time	500 to 1000	Rel. 5%	1.0 s to 3.0 s
Perceived sound quality	Clarity, C_{80}, in dB	500 to 1000	1 dB	-5 dB to +5 dB
	Definition, D_{50}	500 to 1000	0.05	0.3 to 0.7
	Center time, Ts, in ms	500 to 1000	10 ms	60 ms to 260 ms

*The single number frequency averaging denotes the arithmetical average for the octave bands.

**The typical interval is for mean values over the frequency in a single position in concert halls and multipurpose auditoriums with volumes above 25,000 m^3 (ISO3382-1 [16])

Table 1. Values of some acoustic descriptors suggested by ISO 3382-1:2009 (Adapted from ISO3382-1 [16])

2. MATERIALS AND METHODS

The objective of this paper is to present the calibration of a computational model for predicting the acoustic parameters of a baroque church in the city of Curitiba, Brazil. The calibration will be performed based on a statistical comparison of the reverberation time of values measured *in situ* and values obtained by computer simulation. This work was divided into three stages: 1) Characterization of the room and *in situ* measurements of reverberation time (RT), early decay time (EDT), definition (D_{50}) and clarity (C_{80}), 2) Reproduction of field conditions in a computational simulation with ODEON version 9.0 room acoustic prediction software and 3) Statistical analysis of the data.

2.1 Characterization of the room and *in situ* measurements

The *Igreja Nossa Senhora do Rosário de São Benedito* (Church of Our Lady of the Rosary of St. Benedict) is an 18th century building of baroque architecture. This church was constructed on the site of a former colonial-style chapel built for slaves, which was called *Igreja Rosário dos Pretos de São Benedito* (Church of the Rosary of the Blacks of St. Benedict). The original church was inaugurated in 1737 and served as the headquarters of the Catholic Church in Curitiba (Brazil) from 1875 to 1893, during the construction of the Metropolitan Cathedral (Figure 1).

The building is made of stone masonry and its interior walls are plastered and painted with water based paint. Stained glass windows illuminate the interior of the church.

The floor is made of parquet laid on concrete and the wooden ceiling is painted with oil-based paint, with no decorations of any kind. The bare wooden benches are unpadded. The benches in the aisles seat approximately 310 people. In the choir above the entrance is a tube organ. Table 2 describes the main dimensions of this enclosed space.

Figure 1. Inside view of the Church - *Nossa Senhora do Rosário de São Benedito*

Architectural characteristics	Dimensions
Maximum width – including side chapels	13.5 m.
Maximum length– measured in front of the altar	28 m.
Maximum height– measured from floor to ceiling at the highest point of the arch, vault or flat ceiling	8.6 m.
Height of the altar – measured from the floor of the altar to the highest point of the ceiling	8.5 m.
Total volume	2488.6 m^3
Total floor area	305.4 m^2

Table 2. Interior dimensions of *Nossa Senhora do Rosário de São Benedito* Church

2.2 *In situ* measurements

The following equipment was used for the measurements of the interior of the church: 1) A omnidirectional sound source connected to a power amplifier; 2) A omnidirectional microphone connected to a sound level meter; 3) DIRAC 3.1 signal generating and decay curve recording software installed in a microcomputer; 4) RME *Fireface* 800 - firewire audio interface circuit board used for connecting the equipment to the microcomputer.

The loudspeakers were positioned at two points in the presbytery (Figure 2 - Source position S1, S2), one on the axis of symmetry of the main chapel and the other on the lectern facing the congregation. The receiver points were distributed around the naves in a regular 5x5 meter grid, making a total of six points in the principal nave and two points in the lateral nave (Figure 2). The microphone (Figure 2 – Microphone position - MP - 1 to 8) was sequentially positioned in the seating between the benches, at a height of 1.2 m from the floor, which reproduces the condition of the seated audience [16]. At each position impulse response was measured using exponential sweep signal to excite the air volume inside the room and then the various acoustical parameters were calculated by DIRAC 3.1 [23]. Triplicate measurements were also taken in for each combined loudspeaker and microphone pair, which yielded the average for the analysis.

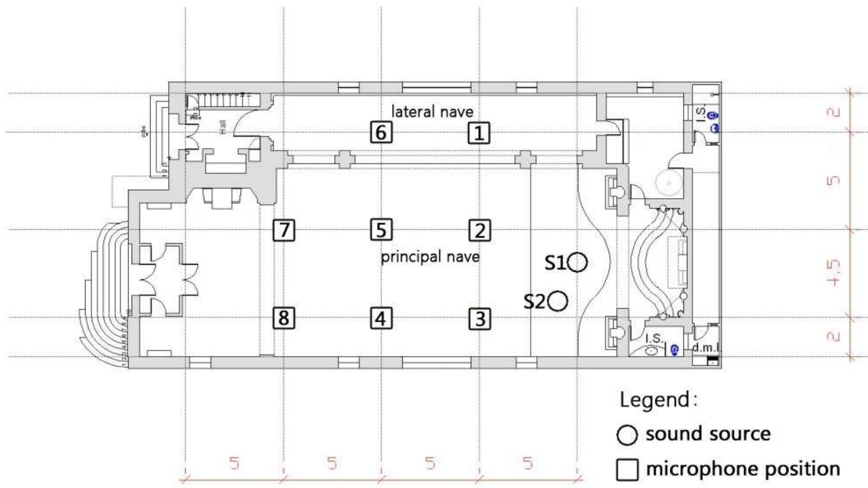

Figure 2. *Nossa Senhora do Rosário* Church – floor plan of the nave and presbytery

2.3 Computational Model

The acoustic simulation was performed using the Odeon 9.0 software [24] and consisted of the following steps: 1) Test of the geometry – identification of errors of the three-dimensional surfaces; 2) Positioning of the loudspeaker and receiver points according to the field survey; 3) Characterization of the surfaces as a function of the sound absorption and diffusion coefficients of the finishing materials found in the room. The digital three-dimensional model was created using VectorWorks 11.5 software [25] and, albeit simplified, it reproduces the main geometric characteristics of the enclosed space under study. Most of the sound absorption coefficients used here were available in the library of the software ODEON. The absorption coefficients used in the model are listed in Table 3 [26].

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Materials	**Frequency in octave bands (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Wood sheathing, pine	0.10	0.11	0.10	0.08	0.08	0.11
Chairs, lightly upholstered concert hall chairs, average	0.35	0.45	0.57	0.61	0.59	0.55
Lime cement plaster	0.02	0.02	0.03	0.04	0.05	0.05
Single pane of glass, 3mm	0.08	0.04	0.03	0.03	0.02	0.02
Solid wooden door	0.14	0.10	0.06	0.08	0.10	0.10
Ceilings, plasterboard ceiling on battens with large air-space above	0.20	0.15	0.10	0.08	0.04	0.02
Floors, wood parquet on concrete	0.04	0.04	0.07	0.06	0.06	0.07
Windows, window glass	0.35	0.25	0.18	0.12	0.07	0.04

Table 3. Absorption coefficients of finishing materials used in churches [26]

Another important acoustic characteristic of surfaces is their property of diffusing reflected rays. Due to the scantiness of data on the diffusion coefficients of materials and because their applicability is based to a large extent on the experience of technicians and researchers [27, 28], the diffusion coefficients used in this model are the ones suggested by the manufacturer of the simulation program used here [29]. Table 4 describes the practical rules for its application.

Characteristics of surfaces	Sound diffusion coefficient
Large rigid or solid surfaces	0.1
Highly diffusive surfaces such as audiences in concert halls	0.7
Rooms with many small items, such as classrooms and offices, that are ignored in the modeling process	0.3

Table 4. Practical criteria for application of the sound diffusion coefficient – characterization of surfaces (Adapted from Christensen [29])

The ODEON software has three precision levels to calculate acoustical parameters [24]: 1) Survey, 2) Engineering, and 3) Precision. These three levels of precision have been associated to two methods of computing diffusion – total diffusion and Lambert´s cosine law (Lambert´s oblique) – and have been applied to two distinct situations: 1) all materials, or 2) soft material only. From these parameters, 12 different calculation combinations are possible, with each one producing a set of results - as can be seen in Table 5. In view of the innumerable/diverse possibilities of the software, the results should be compared to determine which level of precision and method of calculation is the most accurate.

2.4 Statistical treatment

Statistical treatments were applied as an auxiliary tool for the calibration of the models. Only data for the reverberation time (RT) were analyzed. Statistical analysis of the reverberation time by octave band facilitates the application of analysis of variance tests, because values vary very little with the position and its distribution throughout the room tends to normality [30, 31, 32, 33].

As mentioned in Section 2.3, 12 groups were obtained through computational predictions, and one group from measurements taken in the *Nossa Senhora do Rosário* church. For purposes of comparison, this is the control group against which all the other groups were compared. The prediction groups were numbered 2 to 13. The groups were created from the combinations provided by the software Odeon (Table 5), and were subjected to Kolmogorov-Smirnov, ANOVA, Tamhane and LSD tests [30, 31, 32, 33].

Data have been subjected to the ANOVA (Analysis of Variance). According to Vieira [32]: "*One ANOVA should only be applied to a set of observations if the conditions of Independence, equality of variances and normality of the samples are met. In practical terms, however, these 3 assumptions are hardly all met.*"

One of the most widespread test for verification of sample normality is that of Kolmogorov-Smirnov [32]. This test assesses the correlation between the observed distribution of the sample and a particular theoretical distribution. If the hypothesis of normality of data is confirmed, the analysis of variance (ANOVA) can be performed.

The ANOVA is employed in order to compare the means of more than two groups at the same time. It is an extension of the Student´s t-test [32]. According to Bisquerra et.al [33]: "*The null hypothesis can be so named: there are no diferences between the observed means, that* *is, the observed differences are a result of random phenomena. Thus, one can consider that the different samples belong to a single population. With the ANOVA, one can conclude whether the hypothesis of difference between a pair of groups can or cannot be accepted*".

With ANOVA, one comes to the conclusion, to accept or reject the hypothesis of difference between the means of the groups, as a result of a certain source of variation. But in order to localize the differences between the groups, multiple comparison tests are then performed (*post hoc* tests). In this work we used Tamhane and LSD tests [30, 31, 32, 33]. Tamhane's test is applied to not homoscedastic samples, i.e., those having non-homogeneous variance. With the same purpose, samples with homogeneous or homoscedastic variance were treated with LSD test [30, 31, 32, 33].

The 12 groups of prediction are presented in Table 5.

3. RESULTS AND ANALYSIS

First, the *in situ* measurements were analyzed and compiled. Then, the predicted reverberation time for each Group were compared against the measured ones to determine which prediction Group agrees more with the on-site results. Afterwards, the predicted and measured values for the other acoustical parameters were compared.

3.1. Reverberation time inside *Nossa Senhora do Rosário Church*

From the analysis of the measured impulse response, the following reverberation times were obtained for each source and microphone position.

Group description	Group no.
Measured values	**1**
Survey + Lambert + soft materials only	2
Survey + Lambert + all materials	3
Survey + full diffusion + soft materials only	4
Survey + full diffusion + all materials	5
Engineering + Lambert + soft materials only	6
Engineering + Lambert + all materials	7
Engineering + full diffusion + soft materials only	8
Engineering + full diffusion + all materials	9
Precision + Lambert + soft materials only	10
Precision + Lambert + all materials	11
Precision + full diffusion + soft materials only	12
Precision + full diffusion + all materials	13

Table 5. Statistically tested acoustic prediction group

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	3.05	2.99	3.29	3.18	2.94	2.44
S1-MP2	2.83	3.05	3.32	3.16	2.89	2.40

S1-MP3	3.00	3.17	3.35	3.12	2.91	2.32
S1-MP4	2.86	3.05	3.37	3.21	2.96	2.48
S1-MP5	2.92	3.15	3.32	3.17	2.96	2.46
S1-MP6	3.04	2.98	3.27	3.23	2.96	2.43
S1-MP7	2.97	3.15	3.28	3.20	3.01	2.48
S1-MP8	2.93	3.03	3.36	3.26	3.03	2.39

Table 6. Measured Reverberation Time T_{30} for sound source in position S1

Combination Source/Microphone Position (S-MP)	**Frequency in octave bands (Hz)**					
	125	250	500	1000	2000	4000
S2-MP1	3.06	3.02	3.23	3.21	2.94	2.38
S2-MP2	3.17	3.04	3.23	3.14	3.00	2.43
S2-MP3	2.94	2.93	3.31	3.21	2.96	2.48
S2-MP4	3.03	3.05	3.28	3.21	3.02	2.50
S2-MP5	2.64	3.01	3.31	3.32	3.00	2.45
S2-MP6	2.98	2.99	3.34	3.14	2.97	2.41
S2-MP7	2.84	3.11	3.39	3.21	2.98	2.42
S2-MP8	2.87	3.07	3.31	3.20	2.97	2.48

Table 7. Measured Reverberation Time T_{30} for sound source in position S2

3.2. Statistical analysis between predicted and measured results

The 12 prediction groups along with the measured group were statistically analyzed, based on T_{30}, as follow. The normality test (Kolmogorov-Smirnov applied respectively to each group) showed a p-value higher than 0.05 for all the groups analyzed in the *Nossa Senhora do Rosário* church. This shows that within each groups the reverberation times are distributed normally in all the loudspeaker frequencies and positions.

From the homogeneity of Variance test apply to the reverberation time of all predicted groups (Table 8), it appears that the span of the results from group to group is dependant of the source position. With p-value higher than 0.05 except at 125 Hz, the predictions with the loudspeaker in position S1 provided samples with homogeneous variance, meaning small differences from group to group results. In contrast, for all the prediction groups and at all the frequencies, the variances in position S2 of the loudspeaker were inhomogeneous (Table 8); the difference between the results of each prediction group is then significant for this source position.

In addition to being inhomogeneous, the null hypothesis for significant differences among the groups was not accepted for any of the samples subjected to analysis of variance (Table 9) – p-value is lower than 0.05. There are then quite possibly large differences between the means of the reverberation time predicted by Odeon while varying the calculation parameters (12 different calculation combination, see table 5).

The multiple comparison tests detected significant differences between all the prediction groups and the measured values. These differences were concentrated mostly at the frequencies of 250 Hz and 4000 Hz, and were distributed more uniformly among the others. In a comparison of the different positions of the loudspeaker, the simulations for the speaker in position S2 showed a significantly better performance (Table 10).

As one can see in the table 10, Group 7 showed the best reproduction of the measured values (p-value > 0.05) in the largest number of octave bands, and therefore has been used for the following steps of the study.

Loudspeaker position	**p-value per Frequency in octave bands (Hz)**					
	125	250	500	1000	2000	4000
S1	0.007	0.087	0.116	0.123	0.212	0.363
S2	0.019	0.006	0.000	0.000	0.003	0.003

Table 8. Homogeneity of Variance Test

Loudspeaker position	**p-value per Frequency in octave bands (Hz)**					
	125	250	500	1000	2000	4000
S1	0.000	0.000	0.000	0.000	0.000	0.000
S2	0.000	0.000	0.001	0.000	0.000	0.000

Table 9. ANOVA Test

Group description	**Group no.**	**Frequency in octave bands (Hz)**					
		125	250	500	1000	2000	4000
Survey + Lambert + soft materials only	2	▪	▽	●	▪	▪	▽
Survey + Lambert + all materials	3	●	▽	●	●	▪	▽
Survey + full diffusion + soft materials only	4	▪	▽	▪	▽	●	▽
Survey + full diffusion + all materials	5	●	▽	▪	▪	▪	●
Engineering + Lambert + soft materials only	6	▪	▽	●	▪	●	▽
Engineering + Lambert + all materials	7	▪	▽	▪	▪	▪	▽
Engineering + full diffusion + soft materials only	8	▪	▽	▪	▽	▽	▽
Engineering + full diffusion + all materials	9	●	▽	●	▪	▪	▽
Precision + Lambert + soft materials only	10	●	▽	▪	▪	●	▽
Precision + Lambert + all materials	11	▪	▽	●	▪	▪	▽
Precision + full diffusion + soft materials only	12	▪	▽	▪	▽	▽	▽
Precision + full diffusion + all materials	13	●	▽	▪	▪	▪	▽

Legend:

p-value < 0.05 for S1 and S2	▽
p-value < 0.05 for S1	●
p-value < 0.05 for S2	□
p-value > 0.05	▪

Table 10. Multiple Comparison Test between all the Prediction Groups and the Measured T_{30} Values

3.3. Comparison between measured and predicted reverberation time

Figures 3 and 4 indicate the measured and calculated/predicted (Group 7 – reverberation times). The best statistical performance for the prediction of Speaker S2 is shown in Figure 4. In this case the calculated best mach the measured data. The standard ISO/3382-1 [16] recommends that the results for (RT) are presented as a "single number frequency averaging", according to Table 1: "*The single number frequency averaging denotes the arithmetical average for the octave bands, 500 to 1000 Hz*".

It was found that the simulated results of Group 7 for this enclosed space presented differences of less than 0.16 seconds, i.e., differences of less than 5% from the T_{30} measured from point to point in the room. This performance meets the value proposed by ISO/3382-1:2009 [16] which recommends a tolerable difference of 5%. In view of this finding, the modeling of Group 7 was taken as representative of the existing room. Moreover, since the remaining calculated parameters originated from the room's reverberant field, the results of the other three metrics (EDT, C_{80} and D_{50}) will be presented and compared with their respective measured values.

Tables 11 and 12 show the results for the predicted reverberation time (RT).

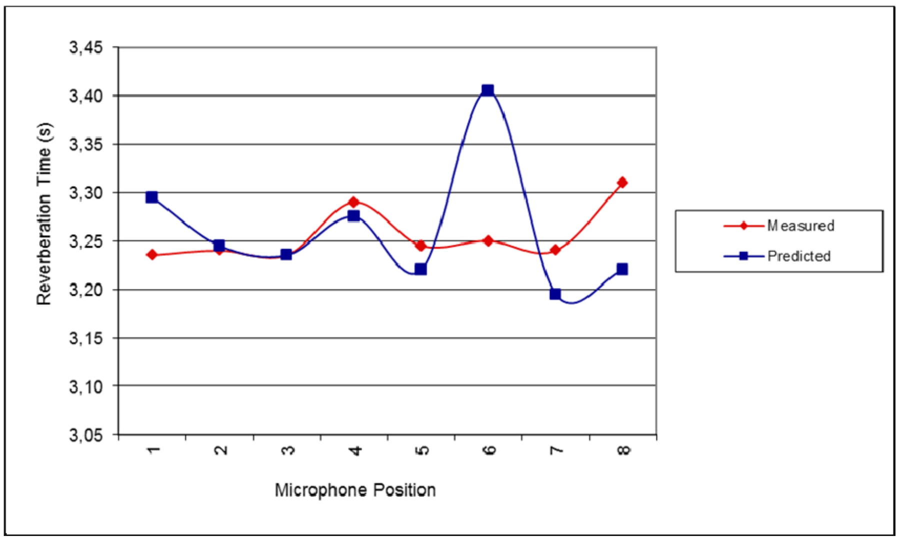

Figure 3. Measured and predicted reverberation time ($T_{500+1000Hz}$) for Loudspeaker position S1

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	2,98	3,27	3,19	3,16	2,89	2,05
S1-MP2	2,80	3,23	3,19	3,17	2,79	2,17
S1-MP3	2,71	3,41	3,34	3,37	2,96	2,15
S1-MP4	2,88	3,49	3,27	3,26	2,98	1,99
S1-MP5	2,74	3,41	3,40	3,36	2,95	2,04
S1-MP6	2,65	3,24	3,17	3,21	3,01	2,16
S1-MP7	2,82	3,68	3,26	3,33	3,00	2,02
S1-MP8	2,70	3,32	3,18	3,33	2,94	2,01

Table 11. Predicted Reverberation Time T_{30} for sound source in position S1

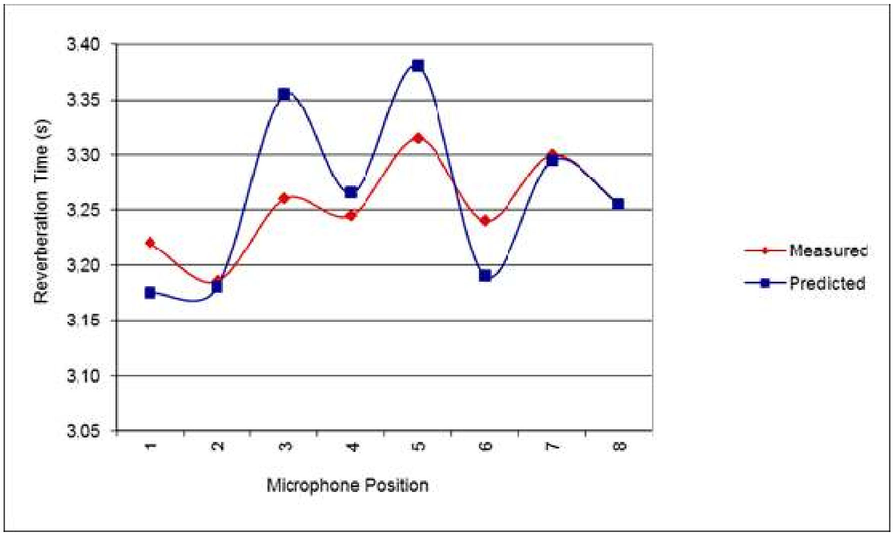

Figure 4. Measured and predicted reverberation times ($T_{500+1000Hz}$) for Loudspeaker position S2

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	2,92	3,36	3,31	3,28	3,06	2,14
S1-MP2	2,97	3,38	3,21	3,28	3,01	2,07
S1-MP3	2,88	3,35	3,27	3,2	2,91	2,14
S1-MP4	2,92	3,49	3,23	3,32	3,05	2,13
S1-MP5	3,14	3,47	3,23	3,21	3,01	2,15
S1-MP6	3,53	3,63	3,42	3,39	2,98	1,96
S1-MP7	3,1	3,35	3,3	3,09	2,92	2,1
S1-MP8	3	3,18	3,26	3,18	2,87	2,11

Table 12. Predicted Reverberation Time T_{30} for sound source in position S2

3.4. Comparison of the measured and calculated results for EDT

The prediction of Early Decay Time (EDT) for the *N. Sra. Do Rosário* Church produced results which deviated by 5% to 16% from the measured values. These results indicate a random dispersion of the data with respect to the tendency of the measurements. Although the difference between the values is less than 5% for most of the points linked to Loudspeaker S1, the calculated results do not show a tendency consistent with the measured results (Figures 5 and 6). Tables 13 and 14 show measured levels of EDT and Tables 15 and 16 show predicted levels for EDT. The standard ISO/3382-1 [16] recommends that the results for (EDT) are presented as a “single number frequency averaging”, according to Table 1: “*The single number frequency averaging denotes the arithmetical average for the octave bands, 500 to 1000 Hz*”.

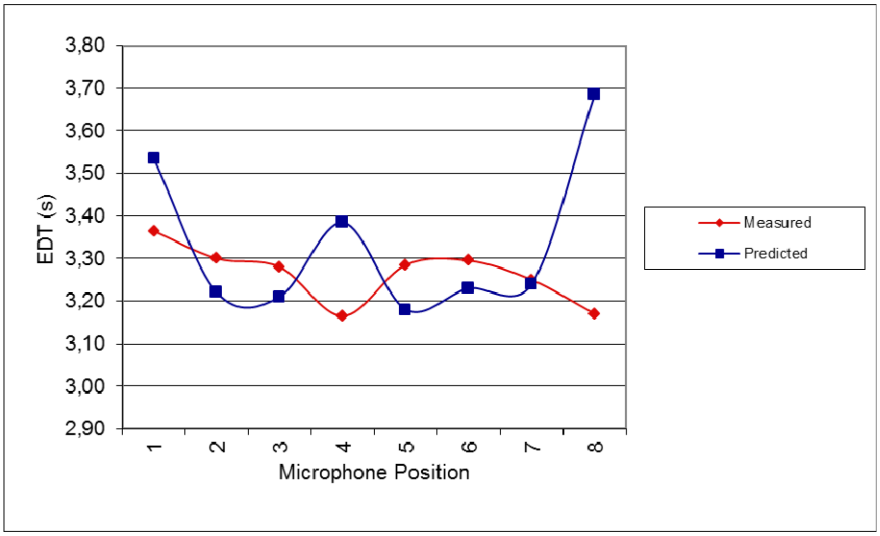

Figure 5. Measured and predicted Early Decay Times ($EDT_{500+1000Hz}$) for Loudspeaker position S1

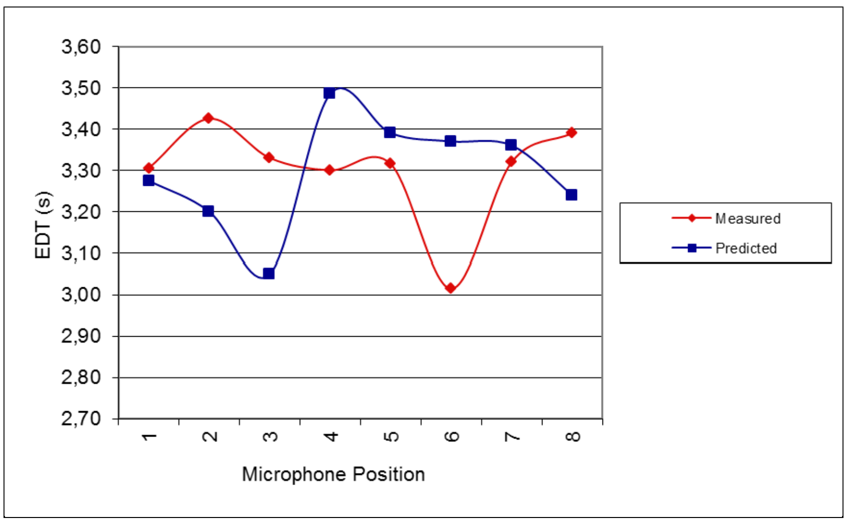

Figure 6. Measured and predicted Early Decay Times ($EDT_{500+1000\ Hz}$) for Loudspeacker position S2

Combination Source/Microphone Position (S-MP)	**Frequency in octave bands (Hz)**					
	125	250	500	1000	2000	4000
S1-MP1	3.12	3.24	3.59	3.14	3.05	2.40
S1-MP2	3.38	3.36	3.21	3.39	2.94	2.27
S1-MP3	3.18	2.71	3.34	3.22	2.98	2.29
S1-MP4	2.84	3.12	3.10	3.23	3.02	2.35
S1-MP5	2.93	2.90	3.23	3.34	2.91	2.34
S1-MP6	3.23	3.14	3.31	3.28	3.12	2.38
S1-MP7	3.20	2.79	3.30	3.20	2.98	2.50
S1-MP8	2.31	3.04	3.10	3.24	2.95	2.43

Table 13. Measured Early Decay Time EDT for sound source in position S1

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S2-MP1	2.75	3.05	3.50	3.11	3.17	2.48
S2-MP2	2.57	3.05	3.48	3.37	2.86	2.20
S2-MP3	2.37	2.88	3.28	3.38	2.96	2.25
S2-MP4	2.81	2.94	3.36	3.24	2.97	2.33
S2-MP5	3.48	3.31	3.45	3.18	2.95	2.34
S2-MP6	3.12	3.21	3.10	2.93	3.02	2.31
S2-MP7	2.85	3.01	3.03	3.61	3.28	2.47
S2-MP8	2.95	3.03	3.42	3.36	3.22	2.55

Table 14. Measured Early Decay Time EDT for sound source in position S2

Combination (Source-Microphone Position) (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	3.22	3.78	3.53	3.54	3.13	2.22
S1-MP2	2.62	3.40	3.10	3.34	3.04	2.06
S1-MP3	2.87	3.42	3.21	3.21	2.88	2.18
S1-MP4	3.01	3.53	3.39	3.38	2.93	2.04
S1-MP5	2.88	3.45	3.19	3.17	2.94	2.11
S1-MP6	2.75	3.38	3.27	3.19	3.03	2.24
S1-MP7	3.10	3.56	3.28	3.20	3.16	2.20
S1-MP8	3.20	3.97	3.77	3.60	3.12	2.20

Table 15. Predicted Early Decay Time EDT for sound source in position S1

Combination (Source-Microphone Position) (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S2-MP1	2.93	3.44	3.27	3.28	3.00	2.07
S2-MP2	2.90	3.40	3.26	3.14	3.02	2.20
S2-MP3	2.48	3.15	3.09	3.01	2.83	2.05
S2-MP4	2.96	3.49	3.42	3.55	3.09	2.28
S2-MP5	2.77	3.60	3.45	3.33	2.98	2.07
S2-MP6	2.87	3.42	3.45	3.29	2.85	2.05
S2-MP7	3.00	3.58	3.33	3.39	3.20	2.10
S2-MP8	2.87	3.51	3.33	3.15	3.11	2.35

Table 16. Predicted Early Decay Time EDT for sound source in position S2

Large deviations in the simulations of Early Decay Time were also observed by other authors [8, 9, 15]. This descriptor of reverberation, unlike reverberation time, is significantly dependent on early sound (direct sound and early reflections), thus resulting in overestimated values for the points further away from the loudspeaker and, inversely, underestimated values for the closest points. The results indicate that, insofar as reverberation descriptors are concerned, computer models perform better in the calculation of reverberation time T_{30} than of Early Decay Time.

3.5. Comparison of the measured and calculated results for (C_{80})

For Clarity (C_{80}), the differences between the calculated values of (C_{80}) and the ones existing in the real room were described in Figures 7 and 8. The computer model overestimated most of the points for the configuration of loudspeaker S1. Nevertheless, the reproduction of the calculated values presented a difference of about 1 dB, the limit of the perceptible difference for this parameter, which characterizes a good performance of the model [16]. The predicted data for loudspeaker S2 presented a higher deviation at the points more distant from the loudspeaker (above 10 meters) and a better reproduction of the closer points. Tables 16 and 17 show measured values for C_{80}, and Tables 18 and 19 show predicted C_{80} values. The standard ISO/3382-1 [16] recommends that the results for (C_{80}) are presented as a "single number frequency averaging", according to Table 1: "*The single number frequency averaging denotes the arithmetical average for the octave bands, 500 to 1000 Hz*".

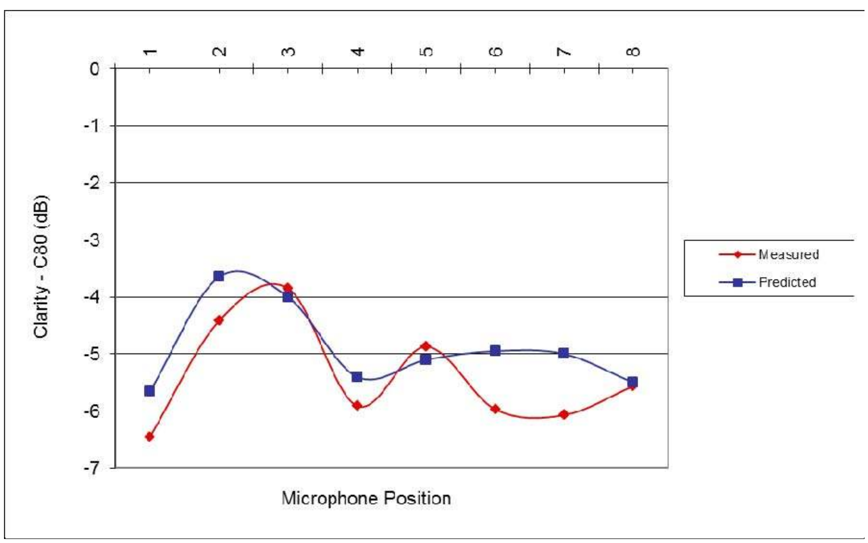

Figure 7. Measured and predicted values of Clarity (C_{80}) $_{(500+1000\ Hz)}$ for Loudspeaker position 1

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	-2.81	-6.16	-5.44	-7.46	-6.85	-3.82
S1-MP2	-3.00	-3.13	-4.68	-4.15	-3.25	-1.51
S1-MP3	-2.44	-2.21	-3.32	-4.38	-4.20	-1.55

S1-MP4	-4.92	-5.26	-6.55	-5.26	-4.25	-2.47
S1-MP5	-4.72	-3.82	-5.50	-4.24	-3.69	-1.47
S1-MP6	-4.77	-4.54	-5.91	-6.02	-4.84	-2.88
S1-MP7	-4.95	-6.99	-5.96	-6.18	-5.49	-2.80
S1-MP8	-4.35	-6.25	-6.74	-4.37	-4.97	-3.40

Table 16. Measured Clarity C_{80} for sound source in position S1

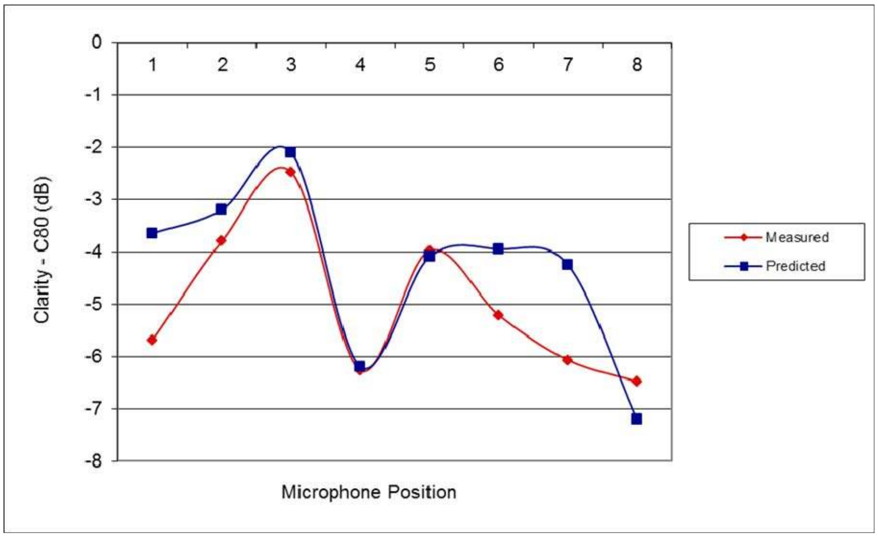

Figure 8. Measured and predicted values of Clarity (C80) (500+1000 Hz) for Loudspeaker position 2

Combination Source/Microphone Position (S-MP)	**Frequency in octave bands (Hz)**					
	125	250	500	1000	2000	4000
S2-MP1	-0.86	-4.26	-4.99	-6.39	-5.06	-3.18
S2-MP2	1.76	-3.11	-4.07	-3.52	-3.29	-1.20
S2-MP3	-7.13	-4.16	-2.18	-2.75	-3.15	-1.66
S2-MP4	-3.93	-7.64	-7.02	-5.52	-3.89	-2.75
S2-MP5	0.18	-3.43	-3.21	-4.74	-4.50	-2.53
S2-MP6	-1.12	-2.82	-6.11	-4.31	-3.72	-3.14
S2-MP7	-8.13	-4.42	-7.02	-3.95	-4.13	-2.63
S2-MP8	-6.05	-5.22	-6.25	-6.70	-5.76	-3.71

Table 17. Measured Clarity C_{80} for sound source in position S2

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	-4.50	-5.70	-5.70	-5.60	-5.20	-3.40
S1-MP2	-2.40	-3.70	-3.70	-3.60	-2.90	-1.00
S1-MP3	-2.80	-4.00	-4.00	-4.00	-3.50	-1.70
S1-MP4	-4.50	-5.60	-5.40	-5.40	-5.00	-3.30
S1-MP5	-4.10	-5.20	-5.10	-5.10	-4.70	-2.80
S1-MP6	-4.20	-5.20	-5.00	-4.90	-4.40	-2.50
S1-MP7	-4.50	-5.60	-5.10	-4.90	-4.30	-2.40
S1-MP8	-4.90	-6.10	-5.60	-5.40	-4.90	-2.90

Table 18. Predicted Clarity C_{80} for sound source in position S1

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S2-MP1	-2.70	-3.80	-3.70	-3.60	-3.20	-1.50
S2-MP2	-2.10	-3.30	-3.20	-3.20	-2.80	-0.70
S2-MP3	-1.00	-2.10	-2.10	-2.10	-1.60	0.30
S2-MP4	-5.20	-6.30	-6.20	-6.20	-5.70	-3.60
S2-MP5	-3.20	-4.30	-4.10	-4.10	-3.60	-1.60
S2-MP6	-3.10	-4.20	-4.00	-3.90	-3.40	-1.30
S2-MP7	-3.70	-4.80	-4.30	-4.20	-3.60	-1.60
S2-MP8	-6.50	-7.70	-7.20	-7.20	-6.50	-4.50

Table 19. Predicted Clarity C_{80} for sound source in position S2

3.6. Comparison of the measured and calculated results for (D_{50})

The simulation of Definition (D_{50}) presented lower deviations from the measured values than those obtained in the prediction of C_{80}. Differences of less than 0.05 (Figure 9 and 10) were observed between the measured and calculated data for both loudspeaker S1 and S2. The performance of the simulations for the second position of the loudspeaker, however, presented two points with differences of 0.05 to 0.10. In both these cases, the tolerance for the prediction was exceeded (Figure 10). Tables 20 and 21 show measured D_{50} values, and Tables 22 and 23 show predicted D_{50} values. The standard ISO/3382-1 [16] recommends that the results for (D_{50}) are presented as a "single number frequency averaging", according to Table 1: "*The single number frequency averaging denotes the arithmetical average for the octave bands, 500 to 1000 Hz*".

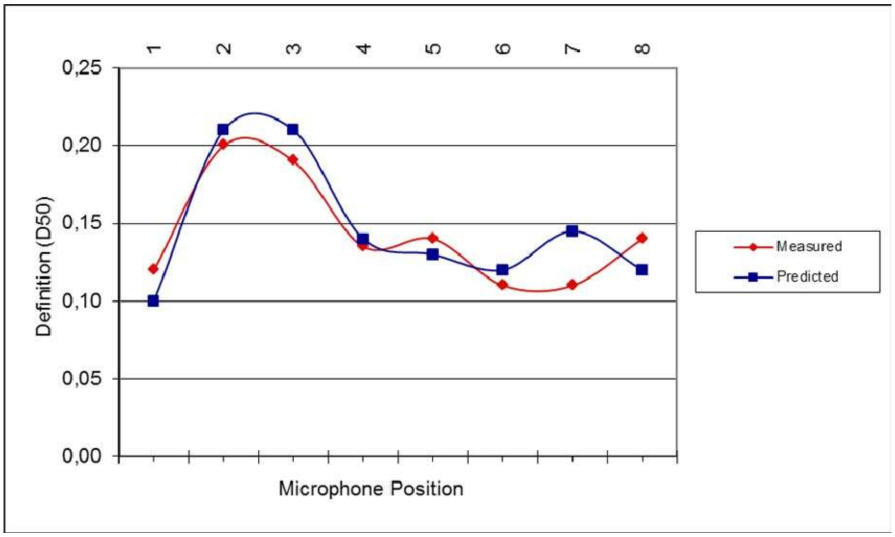

Figure 9. Measured and predicted values of Definition (D_{50}) $_{(500+1000\ Hz)}$ for Loudspeaker position 1.

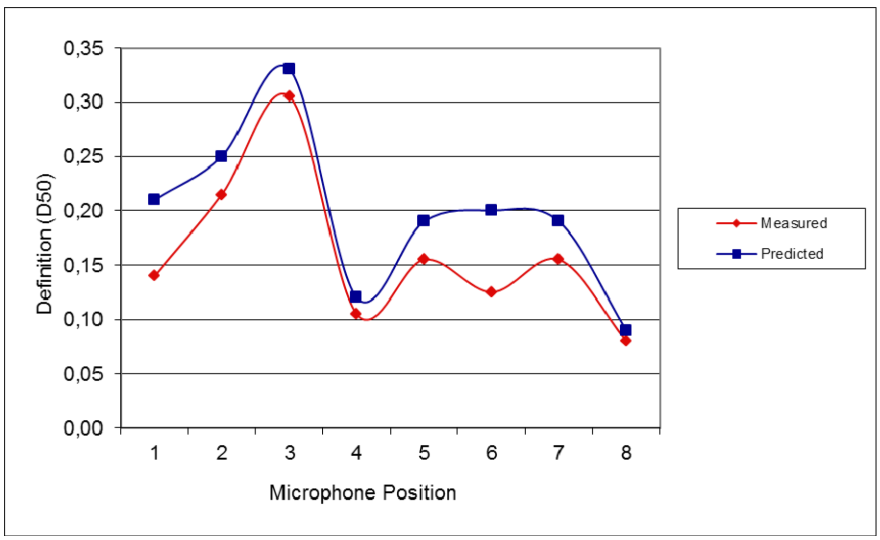

Figure 10. Measured and predicted values of Definition (D_{50}) $_{(500+1000\ Hz)}$ for Loudspeaker position 2.

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	0.20	0.13	0.15	0.09	0.09	0.18
S1-MP2	0.21	0.24	0.21	0.19	0.23	0.30
S1-MP3	0.26	0.27	0.20	0.18	0.19	0.31
S1-MP4	0.17	0.16	0.12	0.15	0.17	0.23
S1-MP5	0.15	0.19	0.11	0.17	0.21	0.29
S1-MP6	0.20	0.19	0.09	0.13	0.17	0.22
S1-MP7	0.07	0.04	0.12	0.10	0.15	0.25
S1-MP8	0.19	0.14	0.12	0.16	0.13	0.22

Table 20. Measured Definition (D_{50}) for sound source in position S1

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S2-MP1	0.42	0.18	0.17	0.11	0.14	0.23
S2-MP2	0.49	0.19	0.21	0.22	0.21	0.32
S2-MP3	0.10	0.19	0.33	0.28	0.23	0.31
S2-MP4	0.24	0.09	0.07	0.14	0.21	0.25
S2-MP5	0.34	0.15	0.17	0.14	0.16	0.24
S2-MP6	0.38	0.17	0.10	0.15	0.19	0.22
S2-MP7	0.07	0.11	0.09	0.22	0.20	0.24
S2-MP8	0.09	0.14	0.09	0.07	0.12	0.19

Table 21. Measured Definition D_{50} for sound source in position S2

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S1-MP1	0.13	0.10	0.10	0.10	0.11	0.16
S1-MP2	0.26	0.21	0.21	0.21	0.24	0.33
S1-MP3	0.26	0.21	0.21	0.21	0.23	0.30
S1-MP4	0.17	0.14	0.14	0.14	0.15	0.21
S1-MP5	0.16	0.13	0.13	0.13	0.14	0.20
S1-MP6	0.15	0.12	0.12	0.12	0.14	0.19
S1-MP7	0.15	0.12	0.14	0.15	0.17	0.23
S1-MP8	0.13	0.11	0.12	0.12	0.14	0.19

Table 22. Predicted Definition D50 for sound source in position S1

Combination Source/Microphone Position (S-MP)	Frequency in octave bands (Hz)					
	125	250	500	1000	2000	4000
S2-MP1	0.25	0.20	0.21	0.21	0.22	0.29
S2-MP2	0.30	0.25	0.25	0.25	0.28	0.38
S2-MP3	0.39	0.33	0.33	0.33	0.36	0.46
S2-MP4	0.15	0.12	0.12	0.12	0.14	0.20
S2-MP5	0.22	0.18	0.19	0.19	0.21	0.28
S2-MP6	0.23	0.19	0.20	0.20	0.22	0.31
S2-MP7	0.20	0.17	0.18	0.19	0.21	0.29
S2-MP8	0.11	0.08	0.09	0.09	0.10	0.15

Table 23. Predicted Definition D50 for sound source in position S2

4. CONCLUSIONS

This study reports an evaluation of the acoustics of a Brazilian baroque church - *Nossa Senhora do Rosário* Church. The evaluation was performed in three stages: 1) *in situ* measurements of reverberation time (RT), early decay time (EDT), definition (D_{50}) and clarity (C_{80}); 2) reproduction of field conditions in a computational simulation using ODEON room acoustics prediction software, and 3) statistical analysis of the data.

The results were subjected to an analysis of variance (ANOVA) to test the accuracy of the model and can be considered accurate, especially insofar as reverberation times are concerned. The models tested here performed better in the calculation of reverberation time (RT) than of (EDT).

Statistical analysis is a useful tool for the selection of the best prediction. In this work, the prediction obtained by simulation of Group 7 (Table 8), which used the *engineering level of precision combined with Lambert's sound diffusion method applied to all materials*, produced results, when compared to the *in situ* measurements, within the deviation limits of ISO 3382-1:2009 for (RT_{60}) and (C_{80}), and relatively good correlations for (EDT) and (D_{50}).

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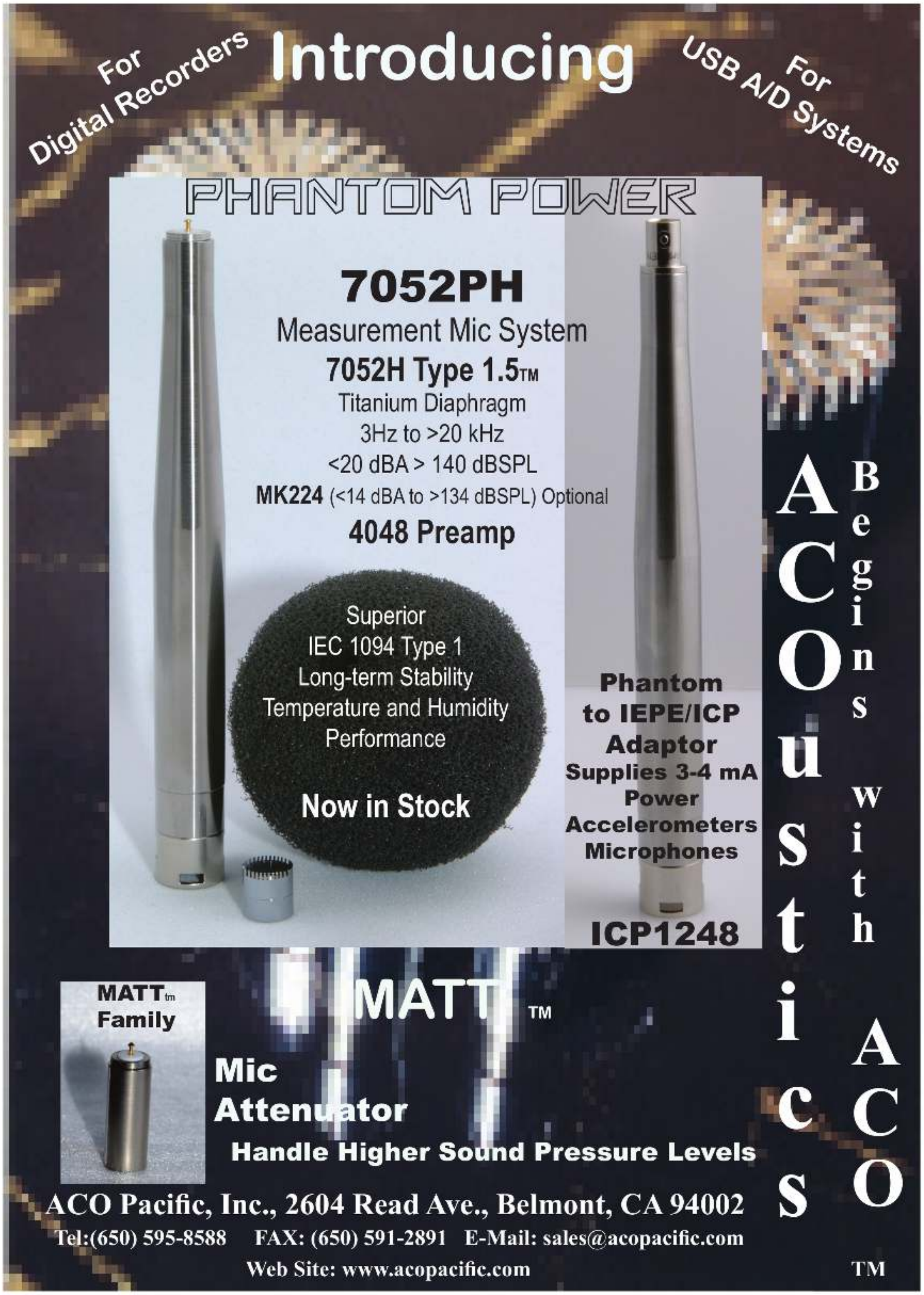
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