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Acoustic Characterization of Historic Cloisters in Portugal

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ABSTRACT
This paper presents the results of field measurements in 20 cloisters of old monasteries in Portugal (length: 15 to 55 m and height: 3.7 to 8.5 m) regarding their acoustic behavior to some objective parameters: *RT*, *RASTI* and background sound level. The individual results show, for instance, that the mean measured values in each cloister for *RASTI* were from 0.33 to 0.64 (with a global mean value of 0.50 for all rooms) and for the *RT* (1 kHz) were from 1.0 to 4.5 s (with a global mean of 2.5 s for all rooms). The evaluation of the sound level difference between cloister and exterior (L_{A95}), found values up to 24 dB(A) with a global average of a 7 dB(A) for all rooms. The sound level decrease from one corner to the opposite one (diagonal) was also measured and values from 4 to 15 dB(A) were found (with a global average of 9 dB(A) for all spaces). A small group of rooms with a covered patio or glass-closed galleries was tested to check for differences in their acoustic behavior regarding the typical cloister nature. Simple formulas were obtained that relate among the objective acoustic parameters and between the acoustic and architectural parameters.

1. INTRODUCTION

The cloisters integrated in historic monasteries are very special and traditional places where the acoustics can be very interesting. These spaces are characterized by a long corridor (or galleria) with one side almost totally open (colonnade) for a garden (usually with a water fountain) and with walls and floor made with very sound reflective materials.

The goal of this work was to check the overall acoustic conditions of these spaces by the use of objective acoustic parameters concerning their interior conditions: Reverberation Time (*RT*), Rapid Speech Transmission Index (RASTI), airborne sound insulation to the exterior and sound level decrease within the long galleries.

The among-room variations of acoustic objective parameters can be viewed as differences that result from the architectural proprieties of the rooms that experience shows actually exist. Therefore strategies to measure and predict these variations would be helpful to acoustical consultants.

2. METHOD

A. The Sample

The investigation is focused on cloisters of former Catholic monasteries of Portugal. Portugal is one of the oldest European countries with a strong Catholic influence and played a prominent role in some of the most significant events in world history. It presents a very good location to characterize this type of Catholic buildings in the world. Portuguese cloisters can be considered a representative example of ancient cloisters in the world.

This study reports on acoustical field measurements done in a major survey of a selected group of 20 historic cloisters integrated in former Catholic monasteries in Portugal that were built between the 9th century and the 18th century. The cloisters were selected to represent the main architectural styles found throughout Portugal and to represent the evolution of this type of construction in Portugal. Figures 1 to 4 show four photos of some of the cloisters tested (BJ - Batalha, MJ - Jerónimos, TP - Tomar. and SP - Porto). The sample used is entirely listed in Table 1 and the statistical summary of their main architectural characteristics is shown in Table 2.

Four cloisters of this group of twenty rooms had specific characteristics. Three cloisters have closed patios (*CB* and *BV* on Table 1) or closed galleries with glass (*CA* on Table 1) and one has a circular plan shape instead of the traditional rectangular shape (*MP* on Table 1). Therefore, a main group of 16 standard cloisters was formed to be the core of this study. The others were used to check (or test) same specific particularities.

Figures 1 to 4 - Four examples of the cloisters tested (BJ, MJ, TP, and SP - Table 1).

B. Methodology and Equipment

In each cloister, several measuring points were used for each parameter under scrutiny:

- For the Reverberation Time analyses, four measure points were used (named 1, 2, 4, and 6 in Figure 5) and two sound source positions (*S* and *S** in Figure 5). Position 1 was only used with sound source *S* (not for *S**). All room average *RT* values are the mean of seven point measures. Octave band results from 125 to 4000 Hz were used. However in many of the analyses only the 1000 Hz octave band results were used not only because this is the method usually employed in this type of work by many of others researchers but also because this band relates well with the subjective acoustic impression in rooms as several studies show[1];

- For the *RASTI* measurements, thirteen measure positions (*A* to *M*) and two sound source locations were used (*S* and *S**) as seen in Figure 6. All room average *RASTI* values are the mean of 25 measures;

- For the characterization of the background noise and its relationship with the exterior noise level, three measure positions were used in the interior (1, 3, and 6 - Figure 5) and one in the exterior of the building. In each of these, the parameters measured were L_{A10}, L_{A50}, L_{A95} and L_{Aeq};

- For the characterization of the sound decrease within the cloisters' galleries, five measure positions were used (1 to 5 in Figure 5) and two sound source positions (*S* and *S** in Figure 5). Position 1 was only used with sound source *S* (not for S*). In each of these, a fifteen-second L_{Aeq} was determined.

All measurements in each position were done with three consecutive measures per point.

The equipment used was a sound level meter B&K 2231 with a filter set B&K 1625, a microphone B&K 1/2", a sound source B&K 4224, software B&K BZ 7109 or 7144, and *RASTI* set B&K 3361.

Table 1 - List of the sample of 20 cloisters used.

Cloister	Code	Town	Length (m)
See of Porto	SP	Porto	26.5
Monastery of Grijó	MG	Vila Nova de Gaia	28.5
Monastery of Cete	MC	Cete	16.8
Monastery of S. Gonçalo	SG	Amarante	26.2
Monastery of Santa Maria da Vitória, Cloister of D. João I	BJ	Batalha	52.5
Monastery of Santa Maria da Vitória, Cloister of D. Afonso V	BA	Batalha	44.0
Old See of Coimbra	VC	Coimbra	31.6
Convent of Cristo, Cloister of the Cemetery	TC	Tomar	19.0
Convent of Cristo, Cloister of the Hospedaria	TH	Tomar	27.0
Convent of Cristo, Main Cloister	TP	Tomar	35.4
Convent of Cardais	CC	Lisboa	14.8
Monastery of Jerónimos	MJ	Lisboa	55.0
Monastery of Arouca	MA	Arouca	31.0
Monastery of Lorvão	ML	Penacova	29.6
Monastery of Tibães	MT	Tibães	33.5
Monastery of Vila Boa do Bispo	MB	Marco de Canaveses	25.1
Convent do Beato	CB	Lisboa	34.6
Convent of São Bento da Vitória	BV	Porto	35.5
Convent of Alpendurada	CA	Marco de Canaveses	26.8
Monastery of Serra do Pilar	MP	Vila Nova de Gaia	29.0*

* Diameter

Table 2 - Main architectural characteristics of the entire sample of 20 cloisters used.

Parameter	Minimum value	Medium value	Median	Maximum value	Standard deviation
Length of galleries (m)	14.8	31.0	29.3	55.0	10.3
Width of galleries (m)	2.2	3.7	3.5	6.2	1.0
Maximum height of galleries (m)	3.7	5.4	5.4	8.5	1.3
Average height of galleries (m)	3.3	4.6	4.4	7.4	1.0
Surface area (entire cloister incl. garden) (m^2)	218	1053	844	3025	741
Surface area of all 4 galleries (m^2)	123	436	381	1210	280
Sound absorption of two contiguous gallerias (m^2)	47	137	128	262	60

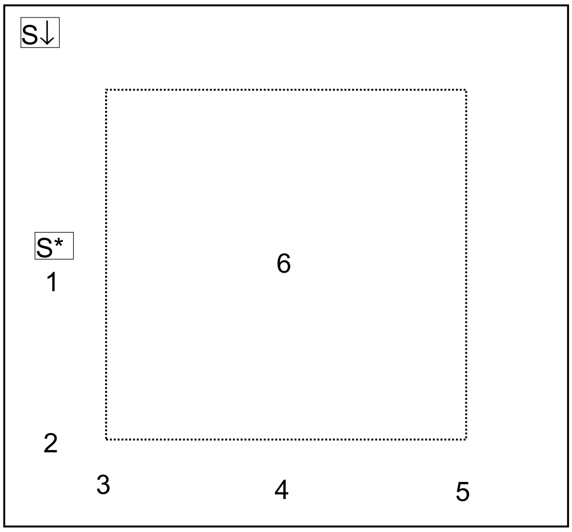

Figure 5 - Standard locations of the measuring points (1 to 6) and sound source (*S* and *S**).

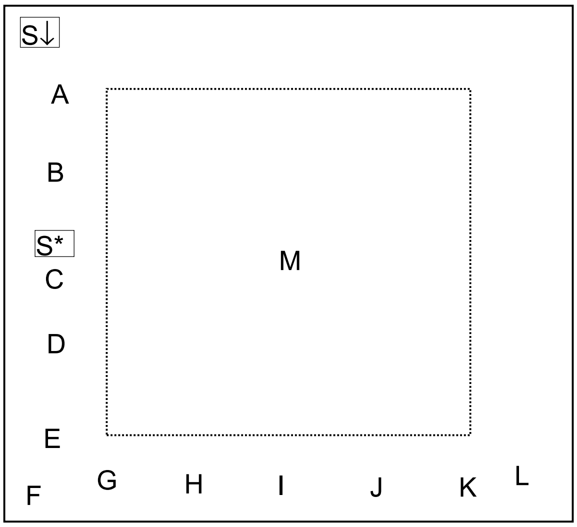

Figure 6 - Standard locations of the thirteen measuring points (*A* to *M*) and two sound sources (*S* and *S**) for the *RASTI* measurements.

3. ANALYSIS

A. General Comments

The Table 3 shows the summary of the results found in the 20 cloisters sampled for the parameters tested. The results show that the majority of the cloisters have good or acceptable acoustical conditions for many (new) purposes. In general, they were not very reverberant achieving the conditions for a reasonable quite space. For the *RASTI* values, about 50% of the rooms have values about 0.5 what indicates these as places with reasonable or good speech intelligibility.

The inclusion of measure position number 6 (on the middle of the patio-garden) does not affect the *RT* values significantly. The relative relation between the *RT* (galleries positions only: 1 to 4) and the *RT* (all position including patio, n. 6) show values, in general, from 0.99 to 1.05 with an average of 1.02. Therefore the inclusion of measure position n. 6 (patio) in the room average calculation increases about 2% the mean *RT* values (or 0.04 s on average, in its absolute value).

Table 3 - Summary of results regarding the 20 averaged values (one for each cloister).

Parameter	Minimum	Mean value	Median	Maximum	Standard error
RT 125 Hz (s)	1.1	3.0	2.9	5.6	1.2
RT 250 Hz (s)	0.8	2.6	2.5	5.1	1.2
RT 500 Hz (s)	1.0	2.5	2.2	5.1	1.0
RT 1 kHz (s)	1.0	2.5	2.4	4.5	0.9
RT 2 kHz (s)	1.0	2.1	2.1	3.3	0.7
RT 4 kHz (s)	0.9	1.7	1.6	2.6	0.5
RASTI	0.33	0.50	0.48	0.64	0.08
Sound decrease within a cloister diagonal dL=L1-L5* (dBA)	4.3	9.3	8.9	15.5	3.1
L95 exterior – L95 interior (dBA)	-1.3 #	7.0	6.9	24.5	5.8

* Opposite corner (diagonal); # due to water fountain noise

B. Relationships among Acoustical Parameters

Using the 16 averaged values for each cloister (using the core main group of 16 cloisters) and for each objective acoustic parameter, some good simple models were found to relate among pairs of parameters as seen in Table 4 (Figures 7 to 9 show graphical examples). Very high values of R^2 (about 0.9) were found for some relationships. Therefore these formulas can be used with confidence to predict the *RT125Hz* and the *RASTI* (averaged room values) from the room averaged *RT1kHz*.

Table 4 - Relationships found between pairs of objective acoustic parameters with the squared correlation coefficient (R^2) using the main core of 16 cloisters sample.

MODEL	R^2
$RT\ 125 = 0.1127(RT1k)^2 + 0.7421(RT1k) + 0.448$	0.93
$RASTI = 0.0113(RT1k)^2 - 0.157(RT1k) + 0.800$	0.92
$dL = 0.775(RT1k)^2 – 2.381(RT1k) + 10.27$	0.29

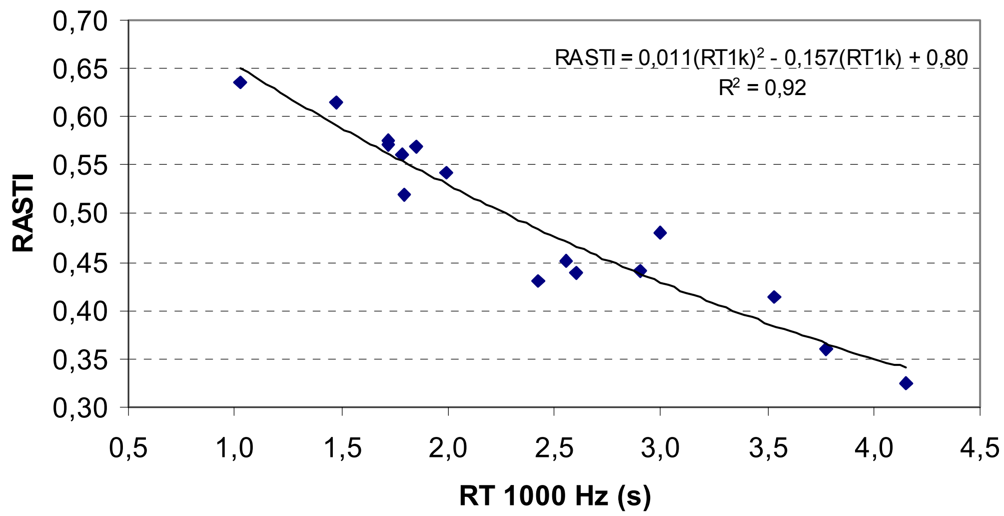

Figure 7: Example of a regression model for the relationship between the *RASTI* and the *RT1k* room averaged values (16 data points).

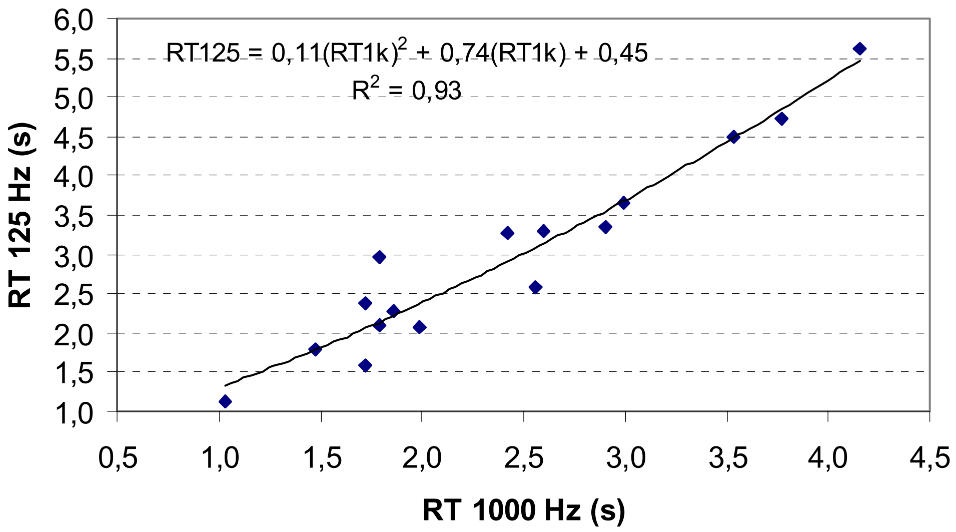

Figure 8 Example of a regression model for the relationship between the *RT125* and the *RT1k* room averaged values (16 data points).

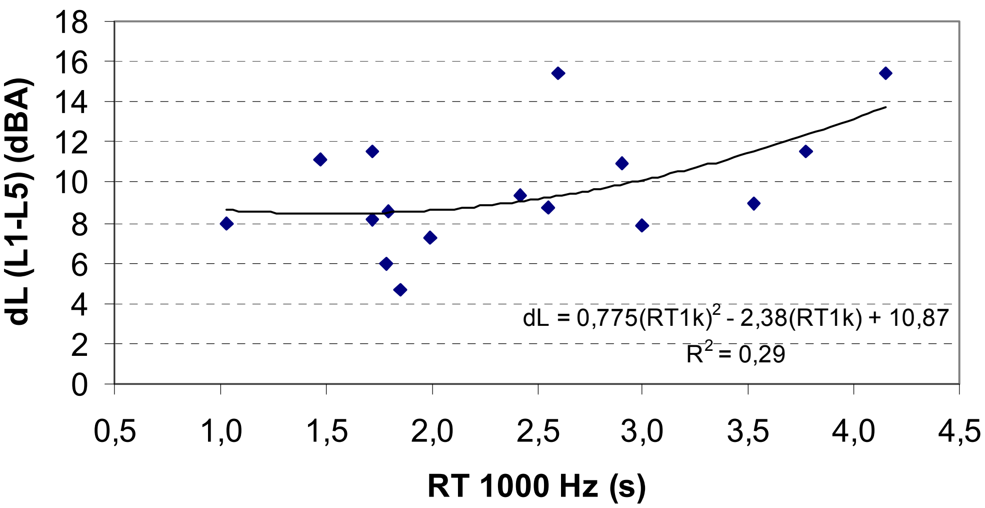

Figure 9: Example of a regression model for the relationship between the dL (=L1-L5) and the *RT1k* room averaged values) (16 data points).

C. Relationships between Acoustical Parameters and Architectural Features

Simple models

The Table 5 displays simple models to predict the mean room value for the tested objective acoustic parameters (*RT1k* and *RASTI*) using only one architectural feature of the room (Figures 10 to 13 show graphical examples).

It was found that about 78% of the variance in the acoustic parameters *RT1k* and *RASTI* is explained by the *Width* (or about 66% by the *Length*) of the cloisters' galleries, being that, the most important single architectural feature.

Table 5 - Best simple models to predict objective acoustic parameters (room mean values) using one architectural feature with the squared correlation coefficient (R^2) found (*Hm* - maximum height of galleries, m; *L* - length of galleries, m; *W* - width of galleries, m; SG - Total surface area of the galleries, m^2).

MODEL	R^2	MODEL	R^2
RT 1k = $0.0829\ W^2 - 0.0146\ W + 1.1434$	0.74	*RASTI* = $0.8711\ e^{-0.1524\ W}$	0.81
RT 1k = $0.1645\ Hm^2 - 1.1472\ Hm + 3.609$	0.69	*RASTI* = $0.747\ e^{-0.0137\ L}$	0.68
RT 1k = $0.0003\ L^2 + 0.0383\ L + 0.8587$	0.63	*RASTI* = $0.7036\ e^{-0.0039\ SG}$	0.60

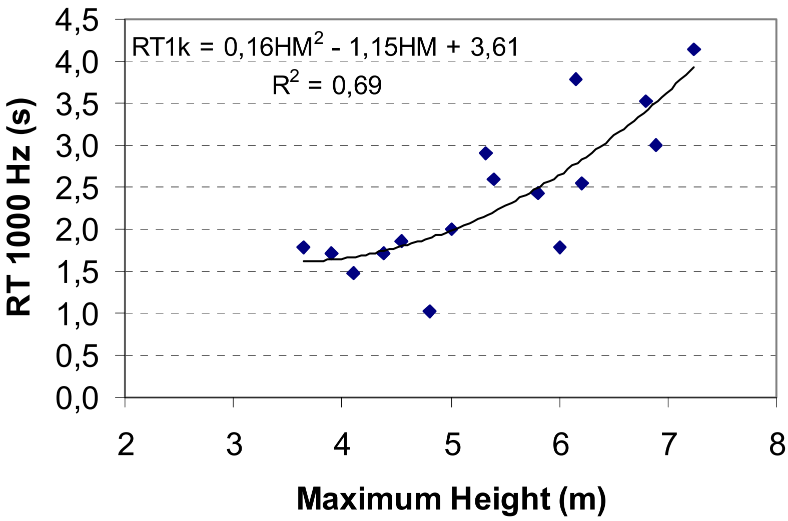

Figure 10: Example of a regression model for the relationship between the *RT 1 kHz* and the *Maximum Height* (16 data points).

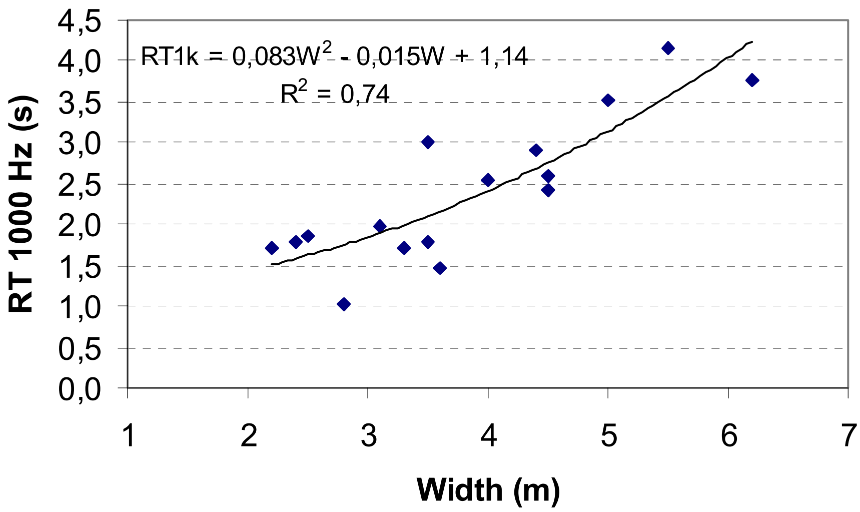

Figure 11: Example of a regression model for the relationship between the *RT 1 kHz* and the *Width* (16 data points).

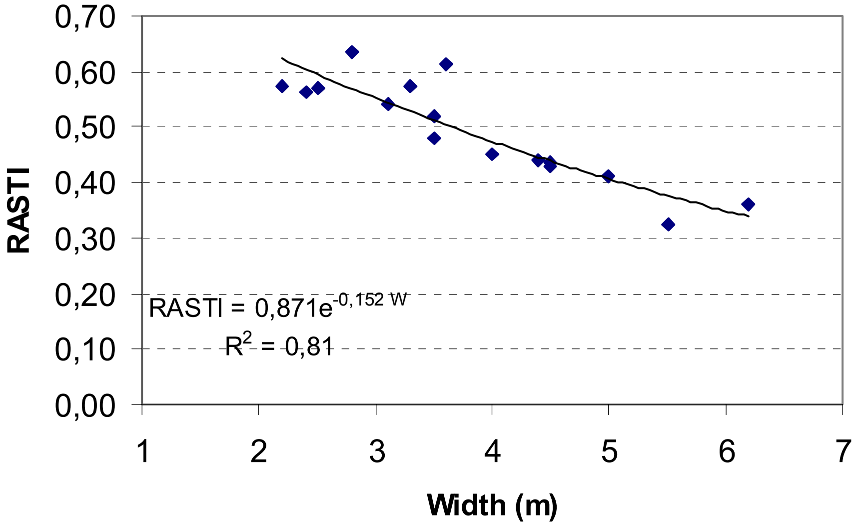

Figure 12: Example of a regression model for the relationship between the *RASTI* and the *Width* (16 data points).

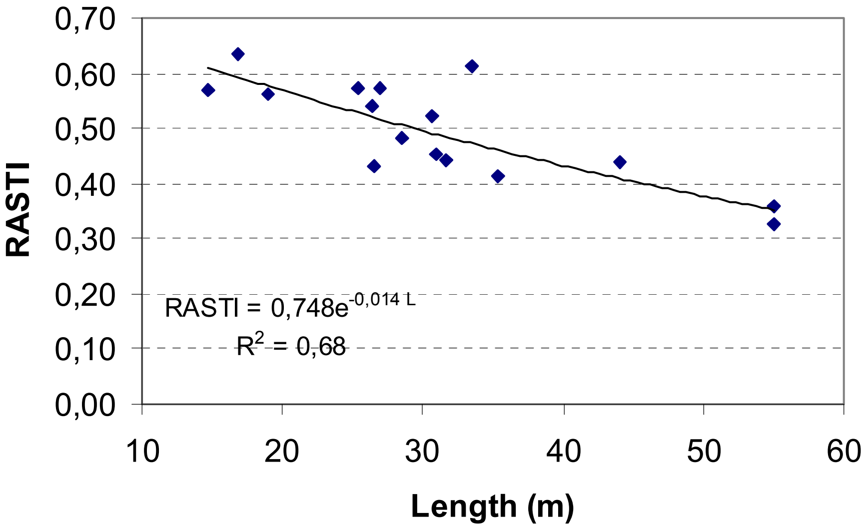

Figure 13: Example of a regression model for the relationship between the *RASTI* and the *Length* (16 data points).

General linear models

To improve the simple models of Table 5, general linear models were tested and the results are shown in Table 6. Using five architectural features: *H* - maximum height of galleries, *L* - length of galleries, *W* - width of galleries, *Sr* - Relative area of gallerias (= area 4 gallerias / total area of cloister), and *A* - Total sound absorption of two contiguous galleries, the variance explained by the models increases now to about 90%.

Table 6 - Best general linear models to predict objective acoustic parameters (room mean value) by the use of some architectural features with the squared multiple correlation coefficient (R^2) found: *H* - maximum height of gallerias, m; *W* - width of galleries, m; *A* - Total sound absorption of two contiguous gallerias, m^2; *Sr* - relative area of galleries (=area of 4 galleries / total cloister area).

GENERAL LINEAR MODEL	R^2
$RT\ 1k = -0.411 + 0.414\ W + 0.397\ H - 2.06\ Sr$	0.89
$RASTI = +0.707 - 0.0718\ W - 0.0261\ H + 0.000495\ A + 0.305\ Sr$	0.90

D. Analysis Controlling for Specific Particularities

Two groups of rooms were formed concerning their type of construction: "traditional" rooms (open galleries and patio) and "closed" rooms (see Table 7). The hypothesis that the acoustical parameters had different mean values for each of these groups was statistically tested. The statistical analysis did not support the hypothesis.

As seen in Figures 14 and 15, only one of the four cloisters (CB) distinguishes itself from the main core of the standard 16 cloisters. This CB is a covered patio cloister (Figure 16) and it has a 2 s increase in its mean *RT* value (Figures 14 and 15). This is due to the presence of the high glass ceiling that covers the entire interior patio and also partly by the increased room volume caused by the opening of all the windows in the second floor (Figure 16).

In cloister BV (also with a covered patio) this effect is not revealed. The expected increase in the *RT* mean value is compensated by the use of sound absorptive materials that were put on some surfaces to use the patio as a music room.

Therefore, the only room in this 20-room study that had been object of acoustic treatment (cloister BV) had values considered not to be statistically distinct from the others due to the acoustic correction done.

Table 7 - Summary of the analysis regarding the mean values for the groups of cloisters controlled by geometric particularities with ± 1 standard error.

Type	Number of rooms	*RT1k* (s)	*RASTI*
Open rooms	16	2.4 ± 0.9	0.50 ± 0.09
Closed patios	2 (CB and BV)	3.7 ± 0.4	0.48 ± 0.01
Room with closed gallerias w/ glass	1 (CA)	2.3	0.46
Room with circular shape (open)	1 (MP)	1.6	0.59

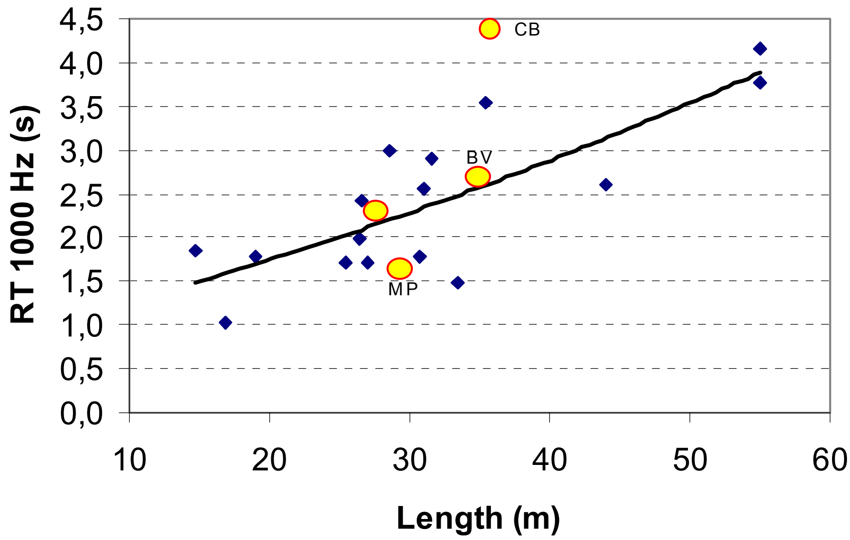

Figure 14: Cloisters with specific particularities compared with the main core group of 16 standard rooms (16+4 data points).

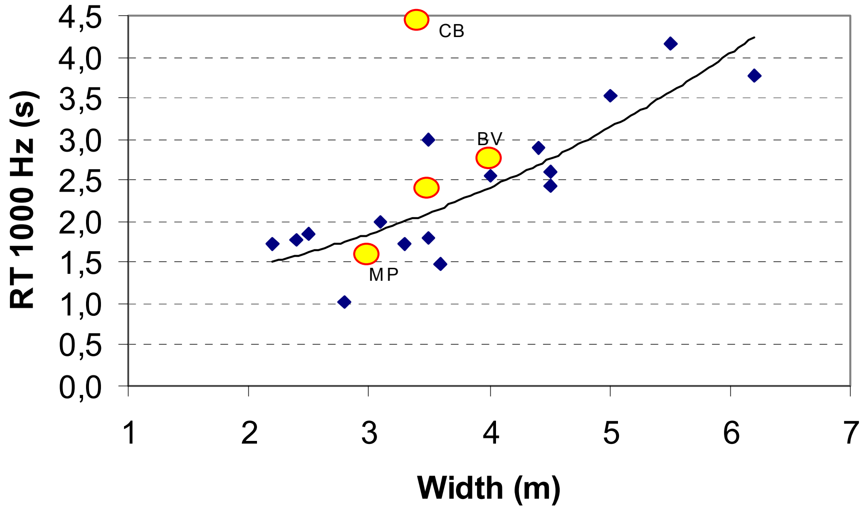

Figure 15: Cloisters with specific particularities compared with the main core group of 16 standard rooms (16+4 data points).

Figure 16: Photo of cloister CB (Beato Convent) with specific particularity (closed patio).

4. DESIGN RULES

In the pursuit of the best dimensions for cloisters (for new, modern uses), a set of "ideal" values was defined (see Table 8) and they were used to propose the range of ideal values for the main architectural parameters. Table 9 shows these ranges of values regarding ideal values for the length, width and, maximum height. These values were found using the relationships presented above.

Table 8 - Ideal range of values for new uses of open cloisters (museums, music, etc.).

Parameter	*RT1k* (s)	*RASTI*
Ideal conditions	1.0 to 2.0	≥ 0.50

Table 9 - Ideal values for the main architectural features in cloisters (with standard sound reflective materials) determined using the relationships found in this study (if no specific acoustic project is considered).

Architectural feature	Length (m)	Width (m)	Maximum Height (m)
Ideal range of values	< 26	< 33	< 5

5. CONCLUSION

This work (a preliminary study of ongoing research) was centered in a selected 20-room sample and confirmed that the cloisters in Portugal have very distinct characteristics.

Simple formulas were found for the relationships among objective acoustic parameters and also to predict the mean room values using some of the main architectural features. In this case, relationships were found that could explain about 90% of the variance in the measured mean values.

No statistical evidence was found to support the hypothesis that "closed" rooms behave acoustically better than the traditional ones.

However, one room with closed ceiling had a *RT* mean value considered to be statistically distinct from the others and showed a 2-s increased mean *RT (1 kHz)* that was found possible to be controlled (in a similar cloister with covered patio) by the correct use of sound absorptive materials.

A set of ideal values for the objective acoustic parameters was proposed and a desired range for the main architectural features (length, width, and maximum height) was defined that can be useful in the design of new cloisters (for new uses).

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References

1. António Carvalho, *Influence of Architectural Features and Styles on Various Acoustical Measures in Churches* (University of Florida, 1994).