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OBJECTIVE ACOUSTICAL ANALYSIS OF ROOM ACOUSTIC MEASUREMENTS IN PORTUGUESE CATHOLIC CHURCHES

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INTRODUCTION

This study reports on acoustical field measurements in a major survey of Roman Catholic churches in Portugal that were built in the last 14 centuries. Series of monaural acoustical measurements were taken at several source and receiver locations in each church. The measurements included Reverberation Time, Early Decay Time, Early to Late Sound Index, Early to Total Energy Ration, Center Time and Loudness. This paper concentrates on the relationships among these six room acoustic measures using linear and non-linear models.

PROCEDURE

1) Churches

This paper reports on acoustical field measurements in a major survey of 41 Roman Catholic churches in Portugal that were built from the sixth century until 1993. The churches were chosen to represent the evolution of the architectural styles in church construction in Portugal. Therefore, we measured 12 Visigothic or Romanesque churches (6th-13th centuries), 16 Gothic or Manueline churches (13th-16th centuries), 13 Renaissance, Baroque or Neoclassic churches (16th-19th centuries) and 4 Contemporary churches (20th century). The main architectural features of those churches are displayed in the following table:

ARCH. FEATURE	Minimum	Maximum	Mean	Median	Skewness
VOLUME (m^3)	299	18674	5772	3918	0.99
AREA (m^2)	56	1031	450	427	0.41
Max. HEIGHT (m)	6.5	39.0	14.8	13.4	1.67
Max. LENGTH (m)	11.5	62.2	33.1	30.8	0.31

2) Measurements Methods

Six Room Acoustics Parameters were calculated in each church using the Impulse Response Method. A sound source generates sound within the room and a receiving section acquires the sound pressure signal after the sound source ceases emit.

The six Room Acoustic Parameters are:

RT - Reverberation Time (using the integrated impulse-response method described by Schroeder) RT30 (from -5 to 35 dB);

EDT - Early Decay Time EDT10 (from 0 to -10 dB);

C80 - Early to Late Sound Index or Clarity with a time window of 80 ms $C80 = 10 \log E(0,80)/E(80,\infty)$;

D - Early to Total Energy Ratio (Early Energy Fraction, Definition or *Deutlichkeit*) with a time window of 50 ms. $D = E(0,50)/E(0,\infty)$;

TS - Center Time (point in time where the energy received before this point is equal to the energy received after this point);

L - Loudness or Total Sound Level (measure of the room's ability to amplify sound from the source position).

The method used is based on the integrated impulse-response method described by Schroeder. A limited-bandwidth noise-burst is generated and transmitted into the church by a loudspeaker via an amplifier. The response of the room to the noise-burst (the *impulse response*) is then sampled from the RMS detector output of the sound level meter (time constant 5 ms). A loudspeaker emitting short pulses-noise bursts in 3/2 octave frequency bands (to ensure that the received noise-burst is of 1/1 octave bandwidth) was used as sound source. The receiving section consisted of one 1/2" microphone and a sound level meter with a 1/1-octave filter set. All the procedure was controlled by a specific software using, *in loco*, a notebook computer. In each church, two sound source locations were used for the loudspeaker (in front of the altar and in the center of the main floor). The sound source was positioned at 0.8 m above the floor and making a 45^{o} angle with the horizontal plane. Each measurement was calculated from an ensemble of 3 or 4 pulse responses in each position. Five receiver positions were, in average, used depending on the width of the church. The microphone, at each location, was placed at 1.30 m above the floor. In total, near 8000 values were determined (all combinations of the six octave-frequency bands, 125 to 4000 Hz, and source-receiver locations). The equipment used consisted of Sound Level Meter "Brüel & Kjær" (B&K) type 2231, 1/3-1/1 Octave Filter Set B&K-1625, Module *Room Acoustics* B&K-BZ7109, Sound Source B&K-4224, Microphone 1/2" B&K, Notebook computer *Compaq* LTE and Application Software *Room Acoustics* B&K-VP7155.

RELATIONSHIPS AMONG ROOM ACOUSTIC MEASURES

1) Procedure

Statistical analysis was used to determine relationships among those 6 Room Acoustic Measures (RT, EDT, C80, D, TS and L). Two approaches were followed:

a) Using ALL DATA

Statistical analysis done with near 2030 data-points obtained considering all positions and all 6 frequency-bands (125 to 4000 Hz) measured. Each data-point is the result of the average of the 3 or 4 "shots" in that location and for that particular octave-band.

b) Using AVERAGED DATA

For each church, one value was calculated, as the average of all source-receiver position results and using all 6 octave frequency bands. Therefore, 41 data-points were calculated (one for each church).

Linear and non-linear models were used in order to determine the best regression line for the correspondence between each two Room Acoustic Parameters. The models tested were the Linear ($y=a+b.x$) and some Non-linear: logarithmic ($y=a+b.log_n x$), quadratic ($y=a+b.x+c.x^2$), cubic ($y=a+ b.x^3$) and exponential ($y=a+b.e^{c.x}$).

2) Statistical Analysis Using All Data

Using all data (around 2030 points), the following table presents the absolute values for the correlation coefficients (R) regarding the relationships among the 6 Room Acoustic Parameters. For each case there are two R values shown (|R1|[|R2|type). The left one is using the *linear* regression model and the right one is with the *best-fit* model (linear, logarithmic or quadratic smooth).

|R|	RT	EDT	C80	D	TS
EDT	0.99[**0.99**lin	-	-	-	-
C80	0.68[**0.75**log	0.70[**0.78**log	-	-	-
D	0.51[**0.59**log	0.53[**0.62**log	0.92[**0.94**qu	-	-
TS	0.91[**0.91**lin	0.94[**0.94**lin	0.85[**0.93**log	0.71[**0.84**log	-
L	0.08[**0.19**qu	0.09[**0.21**qu	0.35[**0.35**lin	0.35[**0.35**qu	0.21[**0.31**qu

Figure 1 presents each one of the previous relationships studied, in scatterplot matrixes (casement plots), with the best fit applicable. The equations for each of the *best-fit* regression line are as follows:

$EDT = 0.043 + 0.941\ RT$
$EDT = 0.219 + 0.013\ TS$
$C80 = 2.876 - 5.572\ Log_n\ (RT)$
$C80 = 2.784 - 5.735\ Log_n\ (EDT)$
$C80 = 30.937 - 6.422\ Log_n\ (TS)$
$C80 = - 7.071 + 0.308\ L$
$D = 0.439 - 0.190\ Log_n\ (RT)$
$D = 0.439 - 0.197\ Log_n\ (EDT)$
$D = 0.347 + 0.048\ C80 + 0.0016\ (C80)^2$
$D = 1.562 - 0.25\ Log_n\ (TS)$
$D = 0.140 + 0.0011\ L + 0.00045\ (L)^2$
$TS = 17.821 + 64.203\ RT$
$L = 16.683 - 1.828\ RT + 0.190\ (RT)^2$
$L = 16.790 - 1.926\ RT + 0.201\ (EDT)^2$
$L = 18.148 - 0.035\ TS + 0.000047\ (TS)^2$

From these results the following was observed:
- The highest correlation was between RT and EDT (|R| = 0.986);
- Very high correlations (|R| = 0.94) were also found between C80 and D or EDT and TS;
- The correlations between L and the other parameters are very low (|R| < 0.36) representing a significant poor relationship among them.

3) Statistical Analysis Using Averaged Data For Each Church

Using just 1 single number for each church (only 41 points are now used), the following table presents the absolute values for the correlation coefficients (R) regarding the relationships among the 6 Room Acoustic Parameters. For each case there are two R values shown. The left one is using the *linear* regression model and the right one is with the *best-fit* model (linear, logarithmic, cubic, exponential or quadratic).

|R|	RT	EDT	C80	D	TS
EDT	1.00[**1.00**lin	-	-	-	-
C80	0.90[**0.97**log	0.90[**0.97**log	-	-	-
D	0.80[**0.84**log	0.80[**0.85**ex	0.97[**0.97**lin	-	-
TS	0.99[**0.99**lin	1.00[**1.00**lin	0.92[**0.99**log	0.84[**0.94**log	-
L	0.26[**0.32**ex	0.26[**0.32**ex	0.33[**0.36**cu	0.25[**0.32**qu	0.27[**0.31**log

Figure 2 presents each one of the previous relationships studied, in a scatterplot matrix (casement plot). Each case shows 41 data-points (41 churches). The equations for each of the *best fit* regression line are as follows:

$RT = -0.0010 + 1.047\ EDT$
$RT = -1.853 - 3.396\ Log_n\ (D)$
$RT = -0.179 + 0.015\ TS$
$EDT = 0.837 + 11.362\ e^{-7.574\ D}$
$EDT = -0.173 + 0.014\ TS$
$C80 = 2.868 - 5.49\ Log_n\ (RT)$
$C80 = 2.605 - 5.48\ Log_n\ (EDT)$
$C80 = -9.612 + 27.574\ D$
$C80 = 27.978 - 5.822\ Log_n\ (TS)$
$C80 = -4.099 + 0.0004\ (L)^3$
$D = 1.274 - 0.194\ Log_n\ (TS)$
$D = 0.363 - 0.025\ L + 0.0011\ (L)^2$
$L = 11.969 + 8.902\ e^{-0.632\ RT}$
$L = 12.093 + 9.361\ e^{-0.722\ EDT}$
$L = 22.915 - 2.504\ Log_n\ (TS)$

From these results the following was observed:
- The highest correlations are now stronger than when using all the available data (the 2030 points);
- The (remarkably) highest correlations are now between RT and EDT ($|R| = 0.999$), EDT and TS ($|R| = 0.995$), RT and TS ($|R| = 0.993$) or D and C80 ($|R| = 0.969$);
- The correlations between L and the other parameters are now not as low as in the previous situation (*all points*) but nevertheless still markedly low ($|R| < 0.37$) maintaining a non significant relationship among them.

CONCLUSIONS

As presented above, the correlations among six Room Acoustic Parameters have been studied. The following conclusions apply:
i) Non-linear models seem to give a slight better prediction line than the linear models in the majority of the cases studied (70%). Among these, the logarithmic smooth presents a better fit in many cases, especially those regarding the C80 parameter. This is due to the logarithmic mathematical characteristic of many of those parameters (by their definition).
ii) Concerning the two approaches for this study (*all data* or *averaged data*), it was found that there are significant differences between the $|R|$ results (1 to 68% higher $|R|$ in the *averaged data* option). Depending on the situation in study (a single point measure or a room averaged value) the corresponding prediction equation should be used.
iii) This study suggests that there is no need to use simultaneously those 6 Room Acoustic Measures due to their relationships. Three groups, among them, seem to appear: RT/EDT/TS, C80/D and L.

- RT and EDT present a very high correlation ($|R| > 0.99$) as expected because they are similar quantities with comparable physical meaning. EDT and TS also show a strong relationship between them ($|R| > 0.94$). These two factors suggest that just one of those 3 parameters (RT, EDT or TS) should be used to predict the other two. The RT looks to be the reasonable choice due to its clear physical meaning and traditional use in this area.

- C80 and D are highly correlated ($|R| > 0.94$) mainly due to their comparable physical and mathematical design.

- The correlation between L and the other 5 parameters is markedly low ($|R| < 0.37$) confirming to this parameter its individuality among those 6 and indicates that this quantity should be included as one of the main Room Acoustic Parameters.

Therefore, we conclude that regarding the acoustical analysis of churches, the main and most significant parameters to be used are: RT, C80 and L.

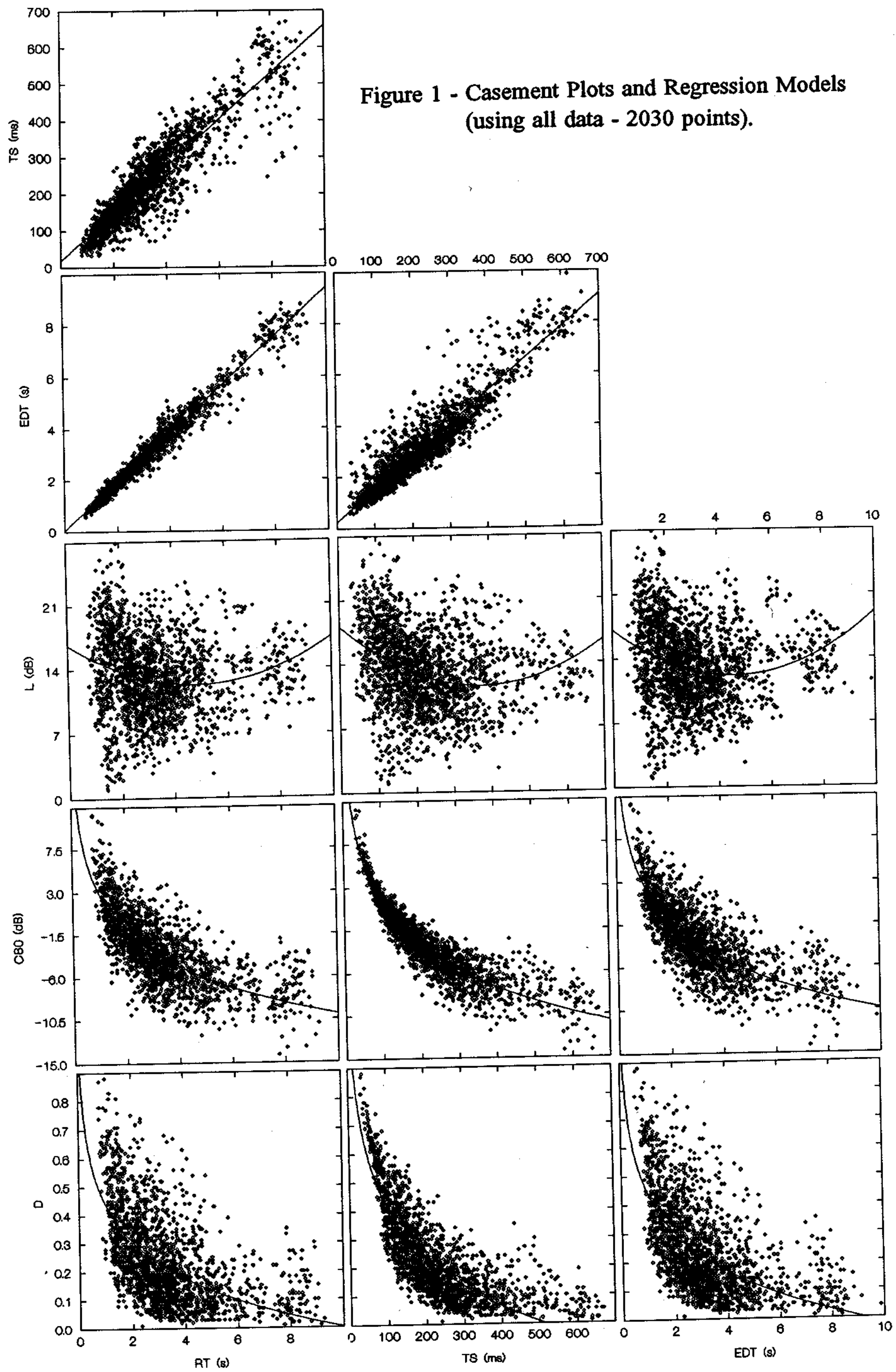

Figure 1 - Casement Plots and Regression Models
(using all data - 2030 points).

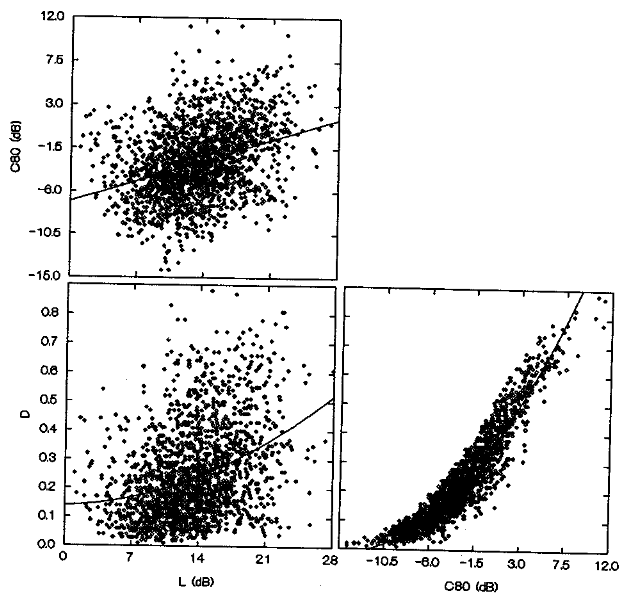

Figure 1 (cont.) - Casement Plots and Regression Models (using all data - 2030 points).

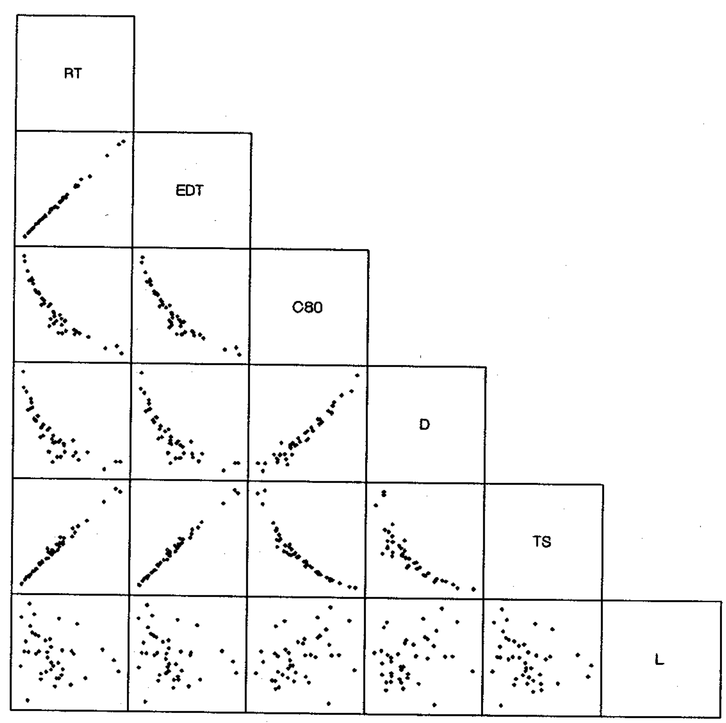

Figure 2 - Scatterplot (casement plot) for the 6 Room Acoustic Parameters (using averaged data - 41 points=41 churches).