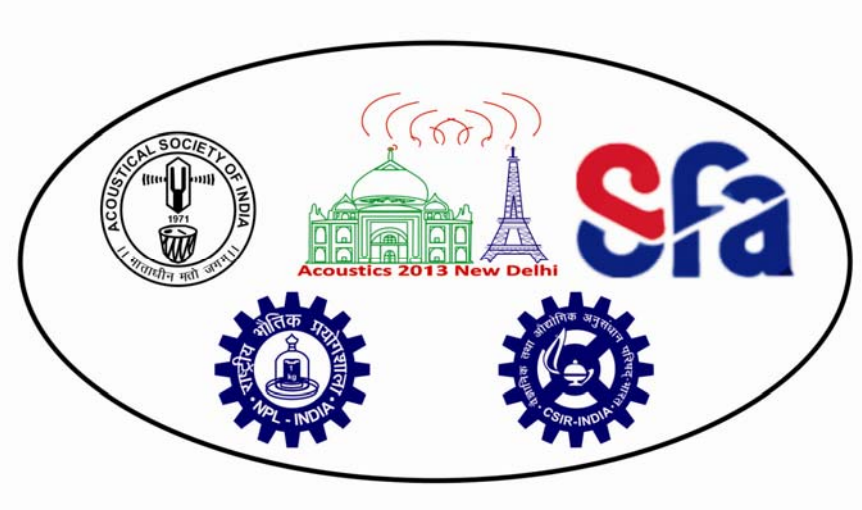

PORTUGUESE CATHOLIC CHURCHES AS REFERENCE ACOUSTICAL MODELS FOR HERITAGE CATHOLIC CHURCHES IN GOA, INDIA

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The architectural genres of the churches built in Goa (a Portuguese colony in India) during the 16th - 19th century period, are partial derivatives of the Portuguese style considering the affinity of the latter's architecture and worship ambience with that of the Goan churches. Therefore reference ranges used for the normalization of the measured objective acoustical parameters in the Goan Catholic churches of values for Reverberation Time (RT) and Loudness (G) (both regarding the medium octave frequency bands of 500 Hz and 1000 Hz); Objective speech intelligibility parameters such as RASTI and D_{50}; Objective music intelligibility parameters such C_{80}, Center Time (TS) and Early Decay Time (EDT), were obtained through a regression on the total volume of the church of the reported measured values of the same in Portuguese churches. Reverberation Time was found to linearly relate with the total volume of the church ($R^2 = 0.42$) with significant probability ($p < 0.01$). Mid-frequency Loudness (G) showed exponential decay of the first order with the total volume of the church ($R^2 = 0.76$). A range was constructed using the standard deviation of the mean RT which would be the range of the optimal values of RT. A range of optimal values of Loudness was also constructed using the predicted value and the chi square value. If the measured value of Reverberation Time or Loudness belonged to their respective reference range of values then, their maximum normalized value was equal to 1. In case of RASTI, D_{50} and C_{80} the lower limit of the optimal reference range was fixed. The values of RASTI without the Sound Reinforcement System in the Portuguese churches were found to range from 0.22 to 0.56. The upper limit of this range was fixed as the lower limit of the optimal reference range for the normalization of the measured RASTI values. Thus if the measured value of RASTI belonged to this optimal reference range of 0.56 to 1 than the normalized value of RASTI was equal to 1. Definition for speech (D_{50}) showed exponential decay of the first order with the total volume of the church ($R^2 = 0.56$). Therefore, if the measured value of D_{50} belonged to its optimal reference range of values (0 - 1) then the normalized value was

equal to 1. Center Time for music (TS) showed a linear regression with the total volume of the church ($R^2 = 0.40$) ($p < 0.01$). Early Decay Time (EDT) showed exponential decay of the first order with the total volume of the church ($R^2 = 0.41$). If the measured values of TS and EDT were found to be equal to or less than this lower reference limit, then their respective normalized values were considered to be equal to 1. The values of the optimal reference limits were dependent on volume and therefore gave unique results for the different acoustical parameters in each sample church.

1. Introduction

During the Portuguese era in Goa (1510 - 1961) a number of churches were built [1][2]. The architectural styles of these churches ranged from the Neo-Roman, Mannerist to the uniquely Goan Indo-Baroque motif [3]. The genres of the churches in Goa, in a broad sense, can be considered as partial derivatives of the architectural styles of the churches in Portugal.
The Portuguese churches (as represented in Figure 1) share architectural affinity (on the exterior and the interior) and similarity in functionality of the encompassed worship space (for the celebration of Catholic liturgy) with their Goan counterparts.

Figure 1. The facade and the interior nave space of Basílica da Estrela, Lisbon, Portugal.

The typical 18th century baroque wood altar pieces, paintings and the other many adorning wood artworks inside the churches in Portugal and Goa also indicate a similar acoustical utility.

2. Sample and Reference Churches

A few sample Catholic churches (shown in Table 1) (representative of the diverse styles available in Goa) were chosen to be studied.

Table 1. Primary details of the Churches surveyed.

No	CHURCH	PLACE	BUILT	STYLE
CH1	Capela do Monte	Old Goa	1557	Mannerist
CH2	Bom Jesus Basilica	Old Goa	1594-1605	Jesuit Classic
CH3	Our Lady of Pilar	Pilar	1613	Mannerist
CH4	Divine Providence	Old Goa	1656-1661	Renaissance
CH5	Holy Spirit	Old Goa	1661-1668	Indo-Baroque
CH6	Holy Trinity	Benaulim	2005	Contemporary

The simple statistical data related to the volume and the acoustical parameters measured in the sample Goan churches and the referred Portuguese churches are provided in Table 2 and Table 3 respectively.

Table 2. Simple Statistics in Goan churches.

Simple Statistics of volume and acoustical measures in Goan churches							
Statistics	VOLUME	TS	G	D50	C80	RT (500-1k Hz)	EDT (500-1k Hz)
	(m3)	(ms)	(dB)	0 - 1	(dB)	(s)	(s)
MINIMUM	2974	250	8.30	0.16	-5.03	3.02	3.51
MEAN	10106	279	11.88	0.21	-3.91	4.36	4.21
MAXIMUM	18858	294	16.79	0.27	-2.88	5.17	4.66
MEDIAN	7691	281	12.05	0.21	-3.75	4.48	4.51
STD_DEVIATION	7631	17	3.62	0.05	1.01	0.81	0.55
SKEWNESS	0	-2	0.35	0.13	-0.20	-1.36	-0.64
KURTOSIS	-3	3	-1.47	-2.47	-2.92	2.41	-2.80
CONFIDENCE	6688	15	3.17	0.04	0.88	0.71	0.48

Table 3. Simple Statistics in Portuguese churches.

Simple Statistics of volume and acoustical measures in Portuguese churches							
Statistics	VOLUME	TS	G	D50	C80	RT (500-1k Hz)	EDT (500-1k Hz)
	(m3)	(ms)	(dB)	0-1	(dB)	(s)	(s)
MINIMUM	299	80	6.00	0.08	-10.00	1.20	1.06
MEAN	5772	250	13.66	0.20	-3.90	3.39	3.29
MAXIMUM	18674	577	21.90	0.46	2.50	8.14	8.07
MEDIAN	3918	242	13.70	0.17	-4.50	3.09	3.06
STD_DEVIATION	5161	117	3.59	0.10	2.89	1.64	1.60
SKEWNESS	1	1	0.31	0.90	0.29	1.14	1.23
KURTOSIS	0	1	-0.26	0.06	-0.47	1.47	1.82
CONFIDENCE	1580	36	1.10	0.03	0.89	0.50	0.49

Skewness - Measure of asymmetry, Positive: long right tail, Negative: long left tail
Kurtosis - Measure of normality, Significance greater than zero: the variable is longer tailed than a normal distribution
Confidence - Measure of confidence around the mean. The value obtained is used to construct a 95% confidence interval for the *mean*.

The values of the mean and standard deviation in Portuguese churches in comparison with the values of the mean in the Goan churches justifies the selected Portuguese churches (within tolerable limits) as reference churches.

3. Purpose and Methodology

The work presented below is part of a study to acoustically characterize the worship ambience of worship spaces [4][5][6]. The measured acoustical data for RT, EDT, TS, G, RASTI, D_{50} and C_{80} from 41 Catholic churches of Portugal was used as reference data [7]. Regression models for each parameter on Volume were tested and the regression analysis was done using *Origin 6.1*

and *Origin 8*. These values of Portuguese churches are not all from "acoustically good" churches, hence, these reference values were considered only as standard (but not optimal) values. Thus the optimal reference range (= Prediction value ± 1 Standard Deviation) were calculated using the regression equations.

The normalized value of *RT* or *G* was calculated using Equation 1.

$$
\begin{cases}
nY = 1 & \forall\ Y_{meas} \in (Y_{ref(LOW)}, Y_{ref(HIGH)}) \\
nY = 1 - \left| \dfrac{\Delta Y}{Y_{ref}} \right| & \forall\ Y_{meas} \notin (Y_{ref(LOW)}, Y_{ref(HIGH)}) \\
nY = 1 - \left| \dfrac{\Delta Y}{Y_{ref\ (LOW)}} \right| & \forall\ Y_{meas} < Y_{ref(LOW)} \\
nY = 1 - \left| \dfrac{\Delta Y}{Y_{ref\ (HIGH)}} \right| & \forall\ Y_{meas} > Y_{ref(HIGH)} \\
nY = 0 & \forall\ \Delta Y \geq Y_{ref}
\end{cases}
\tag{1}
$$

Where,
Y_{meas} is the measured value of either *RT* or *G*
nY is the normalized value of either *RT* or *G*
$(Y_{ref(LOW)}\ ,\ Y_{ref(HIGH)})$ is the optimal reference values range for either *RT* or *G*
$Y_{ref(LOW)} = Y_{regression} - SD$
$Y_{ref(HIGH)} = Y_{regression} + SD$
$Y_{regression}$ is the predicted value of either *RT* or *G*, obtained through the regression equations given in Table 4
SD denotes the standard deviation from the mean of $Y_{regression.}$
$\Delta Y = \left| Y_{meas} - Y_{ref} \right|$ ~ where $\left|\ \right|$ denotes the absolute value.

In case of RASTI, D_{50} and C_{80} the lower limit of the optimal reference range were fixed. The optimal reference range for RASTI was decided using measurements in the Portuguese churches. The values of RASTI without the Sound Reinforcement System (SRS) in the Portuguese churches were found to range from 0.22 to 0.56. Therefore the upper limit of this range was fixed as the lower limit of the optimal reference range for the normalization of the measured RASTI values in the present study. Thus the normalized value of RASTI (nRASTI) was calculated as follows:

$$
\begin{cases}
nRASTI = 1 & \forall\ RASTI_{meas} \in [0.56, 1] \\
nRASTI = 1 - \dfrac{0.56 - RASTI_{meas}}{0.56} & \forall\ RASTI_{meas} < 0.56
\end{cases}
\tag{2}
$$

Where,
$RASTI_{meas}$ is the measured value of RASTI.
nRASTI is the normalized value of RASTI
[0.56, 1] is the optimal range of values for RASTI
The lower reference limit for optimal values of RASTI = 0.56

The normalized value (nC_{80}) was calculated as follows:

$$\begin{cases} nC_{80} = 1, & \forall\ C_{80\,meas} \geq C_{80ref} \\ nC_{80} = 1 - \left| \dfrac{\Delta C_{80}}{C_{80\,ref}} \right| & \forall\ C_{80\,meas} < C_{80ref} \\ nC_{80} = 0, & \forall\ \Delta C_{80} \geq C_{80ref} \end{cases} \quad (3)$$

Where,
$C_{80\,meas}$ is the measured value of C_{80}
nC_{80} is the normalized value of C_{80}
$C_{80ref} = C_{80regression}$ = lower reference limit for optimal values of C_{80}.
$C_{80regression}$ is the predicted value of C_{80} obtained through the regression equation. (Table 4)
$\Delta C_{80} = \left| C_{80\,meas} - C_{80\,ref} \right|$ ~ where $\left|\ \right|$ denotes the absolute value.

The normalized values of D_{50} (nD_{50}) was calculated as follows:

$$\begin{cases} nD_{50} = 1, & \forall\ D_{50meas} \in [D_{50ref}, 1] \\ nD_{50} = 1 - \dfrac{D_{50ref} - D_{50meas}}{D_{50ref}}, & \forall\ D_{50meas} < D_{50ref} \end{cases} \quad (4)$$

Where,
D_{50meas} is the measured value of D_{50}
$[D_{50ref}, 1]$ is the optimal range of values for D_{50}
nD_{50} is the normalized value.
$D_{50ref} = D_{50regression}$ = lower reference limit for optimal values of D_{50}.
$D_{50regression}$ is the predicted value of D_{50} obtained through the regression equation. (Table 4)

The lowering of the values of *TS* and *EDT* was reported to improve the clarity of music. Therefore incase of *TS* and *EDT* the upper reference limit for optimal values was calculated.

The normalized values were calculated as follows:

$$\begin{cases} nZ = 1, & \forall\ Z_{meas} \leq Z_{ref} \\ nZ = 1 - \left| \dfrac{\Delta Z}{Z_{ref}} \right| & \forall\ Z_{meas} > Z_{ref} \\ nZ = 0, & \forall\ \Delta Z \geq Z_{ref} \end{cases} \quad (5)$$

Where,
'Z' denotes either *TS* or *EDT*.
Z_{meas} is the measured value.
nZ is the normalized value.
$Z_{ref} = Z_{regression}$ = Upper reference limit for optimal values.
$Z_{regression}$ is the predicted value obtained through the regression equations (Table 4).
$\Delta Z = \left| Z_{meas} - Z_{ref} \right|$ where $\left|\ \right|$ denotes the absolute value.

4. RESULTS

The regression equations for RT, G, C_{80}, D_{50}, TS and EDT are shown in Table 4.

Table 4. Regression statistics of the Best Reference prediction equation

Sr.No	PREDICTION EQUATION	R^2	Adj R^2	SD/Chi square	F Statistic	Prob>F
1	RT (s) = 2.20+ 2.06*10^{-4} V_{TOT}	0.42	0.41	1.26	28.34	<0.0001
2	$G_{MF} = 9.67 + 10.34e^{\frac{-V}{3762.49}}$ (dB)		0.76	3.28		
3	C_{80} (dB) = -1.75 + -3.73*10^{-4} V	0.44	0.43	2.19	30.84	<0.0001
4	$D_{50} = 0.14 + 0.29e^{\frac{-V}{1534.89}}$		0.57	0.0042		
5	TS (ms) =166.99+ 0.01 V	0.40	0.39	92	26.37	<0.0001
6	EDT = 2.15 + 1.98*10^{-4} V	0.41	0.39	1.25	26.81	<0.0001

Thus on a scale of 0 - 1, the normalized values obtained for the different acoustical parameters in the Goan churches (using the counterpart acoustical data from the Portuguese churches as reference data) are shown in Table 5.

Table 5. Normalized values (0 < nX > 1) of acoustical measures in Goan churches

Churches	Volume (m^3)	nRT	$nG_{[MF]}$	nRASTI	nD50	nC80	nTS	nEDT
CH1	2974	0.73	1.00	0.68	0.85	0.35	0.60	0.30
CH2	3457	1.00	1.00	0.73	0.99	0.70	0.85	0.76
CH3	18858	0.99	1.00	0.68	1.00	1.00	1.00	1.00
CH4	7691	1.00	1.00	0.76	0.87	0.77	0.94	0.76
CH5	17549	0.96	1.00	0.79	0.97	1.00	1.00	1.00
CH6	5761	0.26	0.95	0.51	0.97	0.73	0.61	0.24

5. Conclusion

The acoustical data from the Portuguese churches was usable to construct a reference frame for the normalization of the counterpart acoustical measures in the Goan churches.

Reverberation Time was found to linearly relate with the total volume of the church (R^2 = 0.42) with significant probability ($p < 0.01$). Mid-frequency Loudness (G) showed exponential decay of the first order with the total volume of the church (R^2 = 0.76) ($p < 0.01$). Definition for speech (D_{50}) showed exponential decay of the first order with the total volume of the church (R^2 = 0.56) ($p < 0.01$). Center Time for music (TS) showed a linear regression with the total volume of the church (R^2 = 0.40) ($p < 0.01$). Early Decay Time (EDT) showed exponential decay of the first order with the total volume of the church (R^2 = 0.41) ($p < 0.01$).

The values of the optimal reference limits were dependent on volume and therefore gave unique results for the different normalized acoustical parameters in each sample church.

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