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Acoustical behaviour of Colonial Churches in Peruvian Andean Plateau (Puno, Peru)

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ABSTRACT

The paper searches for characterizing the acoustical behavior of nine colonial churches in Puno, a southern city of Peru, surrounding the Titicaca Lake in the Andean Plateau. The Peruvian Andean Plateau was an important extended area through the Spaniard Colonial Era in Peru due to the extractive mining activity of the zone, so several religious orders established in the area and fix the European styles and building process to the geography, geology and available building materials. Through five typical acoustical objective parameters it is defined the acoustical environment in each church. A comparison between several positions in each church analyzed and among churches will be presented.

INTRODUCTION

The establishment of the Spanish dominions in the American territories had one of its most significant events in the founding of cities by the conquerors, and of course all transculturation they have flown since that historic moment, one of these samples are the many buildings within of new colonies. Characterized and printed its stamp on the buildings at that time (called Colonial Period - XVIth to XIX centuries), however, the European architecture, more properly Spanish, experienced some changes for reasons of social, cultural and historical, geographical and climatological conditions especially taking into consideration the architecture of the Inca civilization had different patterns and symbols. Representative element of this historic period is religious architecture. The churches in various cities of Peru is a representative example of this importation of styles, treatises on architecture and construction processes of Europe and its forced merger with some elements of these urban centers and population.

The physical characteristics of the churches of that time held different religious views from the current functional ones. The acoustic requirements were then given to provide a soundscape of grandeur and spiritual elevation and were conducive to a style of music typical of that era. These conditions do not match the current acoustic requirements so that the temples have a high reverberation, lack of clarity of the message and poor speech intelligibility. Currently, many of these churches are in good condition and are widely used for the purpose for which they were designed and built: the liturgical rite. The traditional Catholic churches in Peru often have high ceilings, a large volume of indoor air and highly reflective walls. These architectural and physical characteristics cause a long reverberation time. Also, the aisles and chapels in them, in the great temples generate acoustic coupling, causing problems due to the difference in the reverberation time of two spaces with the central nave. The shape and material of the roof (with semicircular arches, domes, vaults, etc.) can also cause strong echoes or reflections of long delay.

The conditions of the physical environment of the current coastal and highland Peruvian territory modeled two forms of development, imposed technologies and ways of life, and extended the traditional problem of integrating two different realities under a centralized power. Refreshing synthesis process architecture identifies the region of the Peruvian Andean Plateau. Renaissance, Baroque and others styles brought from Europe are interpreted and incredible temples were erected with the contribution of indigenous labor and the action of Spanish craftsmen. The geographic locations are crucial to the availability of building materials and construction techniques consistent. In the territory of the mountains, dominated by the Andes mountain chain, the stone is plentiful but the wood is scarce and is also practiced the use of adobe and brick. The response to an eminently sismic territory is also reflected in the religious architecture: a rigid and massive structure, big stone walls properly locked to withstand earthquakes.

MEASUREMENT TECHNIQUES

In the present study, we have taken into account the objective acoustic parameters used in the study of churches in other researches. Five monaural acoustic measures have been chosen to have a great potential to describe the sound signals of the spoken word and music that are used in churches. The objective acoustic parameters chosen are: Definition (D50) for the spoken word, Clarity (C80) and Central Time (ts) for music, and reverberation time (RT) and Early Decay Time (EDT) for their role in characterize the overall impression of the place.

Acoustical conditions analyzed were carried out in empty rooms, this is no audience because of two main conditions:

the sound pressure level caused by the sound source is high so that the public can be exposed to those levels during prolonged periods time required for acoustic measurements, also the research conducted in churches of other countries have not considered the presence of an audience during his acoustic measurements, so the results could be compared to have the same conditions during the evaluation process.

Measurements were made with an omni-directional sound source (dodecahedron), which was connected to a 400 W amplifier. DIRAC Room Acoustics software from Brüel & Kjaer generated the MLS signal to excite spaces. This signal was captured by a B&K 4007 omni-directional microphone, and saved in a laptop. All measurements and calculations of these parameters were done according to ISO 3382. Two positions of the source were applied in each temple: one in front of the altar on the chancel (called S1) and the other at the central part of the nave (called S2); both positions were on the long axis of the temple. The sound source was at 1.5 m above floor level. Sound receptors were located at up to eight positions in each of the ten churches. In all of them, six positions were at the central nave, and one or two additional positions were in a lateral nave or at one end of the transept. Three positions of sound receptors were located at the front, center and back zones of the listener that was the closest to the long axis of the temple, and the other additional three in the same three zones but at the opposite end of the respective bench. The microphone was located at 1.2m above floor level.

THE CHURCHES SURVEYED

Taking into account the historical conditions of the extensive architectural religious building in Peru, was performed a selection of the most representative of five regional schools of architecture. This paper presents the results of acoustic measurements and analysis carried out in nine colonial churches belonging to the Regional School of the Andean Plateau. The churches were built between the sixteenth and eighteenth centuries. Name and codes of the churches are shown in Table 1. Figure 1 shows comparison of the ten plans tested churches.

Table 1. Churches analyzed

Church	Code	Receiver Positions
Basilica Menor Catedral	PLC	7
Nuestra Señora de la Asuncion	PAY	6
San Francisco de Asis	PSF	7
San Juan Evangelista	PJE	6
San Pedro	PSJ	7
Santa Catalina	PSC	7
Santa Isabel	PSI	6
Santiago Apostol	PST	7
Santo Domingo	PSD	7

As seen on the floor plans of Figure 1, almost all of the churches are similar in shape: cruciform, just the smallest PSD has just a central nave with three lateral chapels. The nine temples analyzed belonging to the architectural styles renaissance, baroque and neoclassical. The characterization of an architectural space necessarily involves the dimensions and volumes of it, its geometry, the interior materials and a combination of some of these aspects. Nineteen architectural parameters were established for the analysis, as shown in Table 2; statistical descriptors of the nine churches are presented too. The range of interior volume is considerable: 3032m^3 to 17 352m^3, the maximum lengths: 39,6m to 74,9m and this because they have been considered in research both rural churches and a basilica.

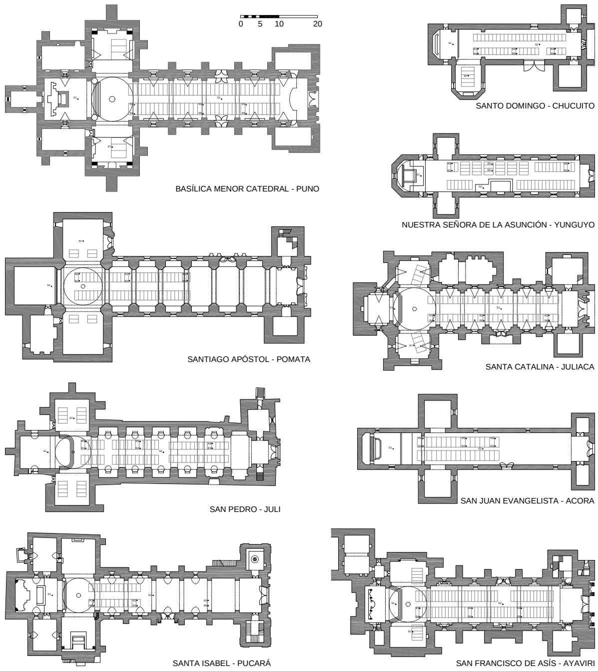

Figure 1. Plans of the nine churches surveyed

Table 2. Statistical Descriptors of Architectural Parameters

Parameter	Code	Max.	Mean	Min.
Total Volume	VT	17352	8784	3032
Central Nave Volume	vnc	13287	7065	2577
Lateral Nave Volume	vnl	4065	1719	344
Total Floor Area	atf	1129	753	354
Central Nave Floor Area	afnc	821	567	294
Total Wall Area	atp	2932	1920	869
Total Ceiling Area	att	1594	940	426
Total Area	AT	5656	3613	1650
Average Length	lp	73,5	58,6	38,6
Maximum Length	LM	74,9	60,5	39,6
Central Nave Heigth	hnc	15,9	12,1	9,0
Lateral Nave Heigth	hnl	15,9	10,9	6,7
Maximum Heigth	HM	26,2	17,2	9,0
Average Heigth	HP	15,4	11,1	8,2
Average Width	Ap	13,3	9,5	7,8
Maximum Width	AM	36,3	26,6	17,2
Pews Floor Area	AS	275	152	54
Total Absorption	ABS	286	194	116
Average ALPHA (α)	ALPHA	0,082	0,057	0,041

ACOUSTIC CHARACTERIZATION OF THE CHURCHES

It was described above that several acoustical measurments where performed in each church, with several sound and receiver positions. Figure 2 and table 3 show the mean values of the five objective acoustic parameters measured in the nine churches analyzed. For each objective acoustic parameter it is plotted for each octave band, the average of the two measurements taken for each of the two sound source positions and six or seven receiver positions in the nine churches. It is possible to observe very similar trends over the five objective acoustic parameters analyzed, with slight variations between them due mainly to the air volume of the churches, as clearly seen with PLC and PSD.

These similar trends recorded mainly in EDT, RT and ts are due to similar features of the nine temples. Greater variation is found between the measures reported for the C80 of the churches, probably due to the different interior decoration, but low levels of D50 are due to air volume and rigidity of the walls and floors of the churches.

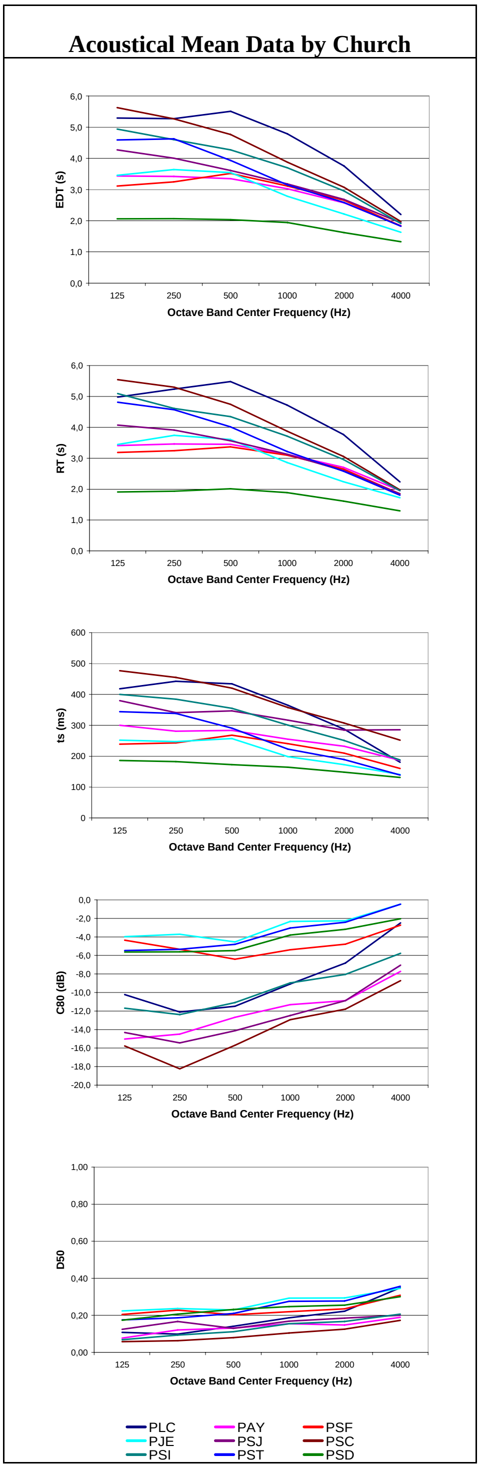

Figure 2. Acoustical mean data by octave band for the nine churches

Table 3. Statistical Descriptors of Acoustical Parameters by church

Church	EDT	RT	ts	C80	D50
PLC	4,5	4,4	355	-8,7	0,18
PAY	2,9	3,0	256	-12,0	0,14
PSF	2,9	2,9	227	-4,8	0,23
PJE	2,9	2,9	211	-2,9	0,27
PSJ	3,3	3,2	326	-12,4	0,16
PSC	4,1	4,1	378	-13,9	0,10
PSI	3,7	3,8	313	-9,7	0,13
PST	3,4	3,5	254	-3,6	0,25
PSD	1,8	1,8	164	-4,3	0,24

ACOUSTIC STATISTICAL ANALYSIS

Through statistical analysis, correlations between different measured parameters were defined, for which it was performed the SPSS 15.0® software; then correlation algorithms (linear or nonlinear models) between these parameters could be defined.

Whereas a single averaged value of two recordings taken at each position tested, a minimum of six receiver positions for each of the two sound source positions in the 9 temples evaluated, as well as the six octave bands considered, 1296 data points are obtained that have been used for acoustic statistical analysis. Table 4 shows the main descriptive statistics obtained for each of the five acoustic parameters considered. You can see not only the mean value obtained for each parameter but also the range of the same (maximum and minimum) and standard deviation.

Table 4. Statistical Descriptors of Acoustical Parameters considering the 1296 data points

Parameter	Max.	Mean	Min.	Std.Dev.
EDT	5,6	3,3	1,3	1,2
RT	5,5	3,3	1,3	1,2
ts	477	276	131	91
C80	-0,5	-8,0	-18,2	4,6
D50	0,36	0,19	0,06	0,08

Under these conditions it is valid to investigate whether there are statistically significant relationships between objective acoustic parameters. The figure 3 shows comparatively dispersion between the objective acoustic parameters evaluated, taking into account a mean single value for each church analyzed, also shows the linear correlation coefficients $|R_{linear}|$ between them and in the right superior box some of the algorithms defined by these correlations (shown only those algorithms which $|R_{linear}|$ is greater than 0.700 and significance level is less than 0.05).

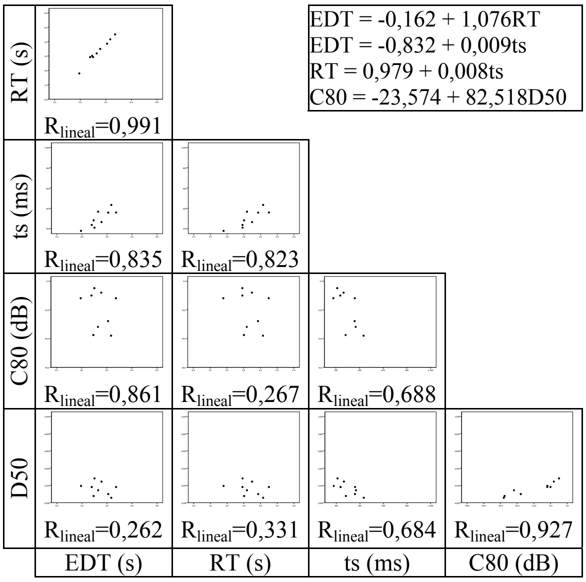

Figure 3. Scatterplot (dot matrix) correlation between objective acoustic parameters considering all source and receiver positions, with data averaged for all octave bands

The Regional School of the Andean Plateau is one of the most prolific and rough in the number of churches built in the colonial period in Peru. As is shown in figure 3, the highest correlation is between EDT and RT ($|R_{linear}|$ = 0.991). For the C80 and D50 will also have a fairly high correlation coefficient ($|R_{linear}|$ = 0.927). Also, between ts and the other four acoustic parameters are significant correlations ($|R_{linear}|> 0.684$). It is therefore possible to establish algorithms for calculating parameters from others with high statistical significance.

Variation of Objective Acoustic Paramaters within the Churches

Having determined the relationship between objective acoustic parameters evaluated in the churches, it is also important to know the variation of these variables within each church. The following statistical analysis will establish some relationships in this regard. The acoustic characteristics of an enclosed space are dependent on their internal physical characteristics (size, volume of air, indoor surfaces: texture and stiffness, etc.), and this is reflected in variations within the same enclosed. Although differences in the measurements values obtained for each parameter evaluated in the churches for the different positions of sound source and receiver are a demonstration of such variability, the standard deviation allows for this range of variation for each church on the mean value. Figure 4 shows the variability analysis this criterion: standard deviation, considering all the registers obtained in all octave bands and source and receiver positions sound. The graphics are displayed for each temple and each objective acoustic parameter evaluated.

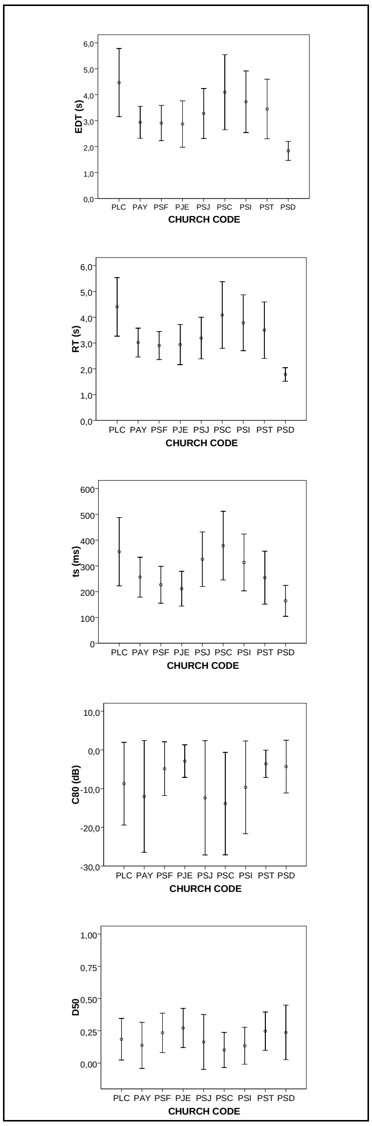

Figure 4. Mean values with one standard deviation interval for churches (all source and receiver positions)

As can be seen, the spatial variation is greater for the case of C80 and in some cases, the EDT and RT. The D50 has a fairly even spatial variation for each temple, when compared between them. EDT and RT present major spatial variations in those large churches. The ts have greater spatial variations in those temples that also have such variations in EDT and RT, possibly due to the large volume of air in the determination of these three parameters.

CONCLUSION

- The characterization of the sound environment of a churche is possible from the five objectives monaural acoustic parameters evaluated.
- The orthogonality found among many of the used acoustic parameters were validated through statistical analysis of correlation, either when the temples were considered individually or grouped.
- Although it is only possible to establish significant values of correlation (R) between those acoustic parameters related (EDT with RT and C80 with D50), it is possible to find algorithms that relate to and define those parameters that could be used as prediction values temples with similar characteristics.

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