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ANALYSIS OF REVERBERATION TIME VALUES IN CHURCHES ACCORDING TO COUNTRY AND ARCHITECTURAL STYLE

Victor Desarnaulds*, António P. O. Carvalho**

*École Polytech. Féd. Lausanne (EPFL), 1015 Lausanne, Switzerland (desarnaulds@monay.ch)
**Univ. of Porto, Faculty of Eng., Acoustics Lab., 4200-465 Porto, Portugal (carvalho@fe.up.pt)

Abstract
This paper presents a simple comparative analysis among the available results for about 400 churches in nine countries: Germany, Greece, Italy, Poland, Portugal, Spain, Switzerland, USA and Yugoslavia (Serbia). The results present a large variability regarding the Volume (V) of the churches and their architectural style. Therefore the relationship between the Reverberation Time values (RT) and V is not powerful ($r^2 \approx 0.45$). However, the regression lines (RT vs. V) controlling for Country are relatively consistent notwithstanding the confession of the churches (Catholic, Protestant and Orthodox). Only the USA and Polish churches show a slightly different regression line. In the comparison of the RT values with the architectural style, a small variation was found in the RT mean values between Romanesque and Gothic churches. However a clear drop in the normalised (to a volume of 5000 m^3) RT values was found between Gothic and Baroque churches. With the exception of the Serbian churches used in the sample, the Neoclassic churches present an increase of the RT values. The spectral RT evolution shows that large church volumes involve a RT decrease at high frequencies and an increase at the low frequencies. This is found mainly in the Romanesque and Gothic churches. A decrease of the RT at the low frequencies is observed in average size churches, in the Baroque and Neoclassic buildings and especially in the Reformed temples.

INTRODUCTION

During the last decade, several studies collected various objective parameters to characterize the churches on several layers of analysis: architectural (time of construction, style, etc.), geometrical (area, height, volume, etc.) and acoustical (reverberation time, intelligibility, etc). The statistical analysis of these data makes it possible to determine the relations between these parameters (for example the dependence of the reverberation time with volume) and to give indications to the architects for the construction or restoration of religious buildings. The small number of churches used however, often limits the relevance of these analyses. In addition, one can question on the generalization of these results, which are obtained for a particular group of churches, representative only of a country, a confession or even a specific time period.

This study proposes to compile the data of several sources [1 - 13] in order to obtain a statistically significant group. This one, in spite of the introduction of bias resulting from the various measuring methods and possible local specificities, should make it possible to study and to compare various parameters, in a way perhaps more relevant than the individual studies (for example for the architectural style) or with a new approach (in particular the analysis of the regional distinctive features). This study will deal particularly with the relations between the reverberation time (average value and evolution with frequency) and the volume, country, confession or architectural style.

METHOD

The studies [1-13], which collected and analysed objective parameters characterizing the churches, use each one a group of different parameters. The processing of these parameters also differs from one study to another. Thus for example, the average value of the Reverberation Time (RT) is sometimes taken only on intermediate frequency bands (500 and 1000 Hz) or, in other situations, on the whole spectrum (125 to 4000 or 8000 Hz). It is consequently difficult to directly compare the results obtained by these various studies. The option taken to carry out this analysis was to return to the rough data (about 400 churches from nine countries) and to gather them in a databank (table 1). As mentioned, the various studies relating to acoustics of churches use each one a group of various parameters. Therefore this comparative analysis can relate only to the few common parameters to these various studies: Country; Confession (Catholic, Reformed or Protestant, Orthodox); Architectural Style (construction time - analysis for the four countries with enough churches); Volume (total volume in m^3) and RT (octave frequency bands from 125 to 4k Hz and mean of the 500 and 1000 Hz frequency bands).

Table 1: Characteristics and origin of the data collected.

Country	Symbol	Churches	Confession	Architectural Style	Source
Germany	D	42	Catholic + Reformed	Yes	[5; 11-12] + various
Greece	G	13	Orthodox	No	[6] + various
Italy	I	14	Catholic	No	[9-10] + various
Poland	PL	9	Catholic	No	[8]
Portugal	P	41	Catholic	Yes	[2]
Serbia	YU	56	Orthodox	Yes	[4]
Spain	E	10	Catholic	No	[3] [13]
Switzerland	CH	178	Catholic + Reformed	Yes	[1] + various
USA	USA	23	Catholic + Reformed	No	[7]

ANALYSIS

Data Description

The various studies used relate to churches with variable sizes and volumes that range from 80 to 700000 m^3 (table 2). The average volume of the majority of the studied churches is about 5000 m^3 (in CH, P, G and E). It is however lower in Serbia (1806 m^3) but larger in the USA (12601 m^3), Germany (17260 m^3) and Poland (26700 m^3). The ones from Italy are particularly large (85247 m^3). All countries put together, the average church volume is about 9800 m^3 with a strong dispersion (standard deviation $\approx$ 39500 m^3). These high figures are primarily due to some particularly large churches (six churches with a volume of more than 100000 m^3). The median value is only 3379 m^3 for the entire sample.

Table 2: Volumes of the churches sampled.

Country	CH	D	E	G	I	P	PL	USA	YU	All
Minimum volume (m^3)	80	1200	3950	230	2183	299	6000	296	115	80
Mean volume (m^3)	4718	17260	5626	6403	85247	5772	26700	12601	1806	9783
Maximum volume (m^3)	54000	130000	9500	22100	700000	18674	97000	114683	20500	700000
Standard deviation (m^3)	6221	27539	1762	8237	185531	5161	29641	22923	2959	39489

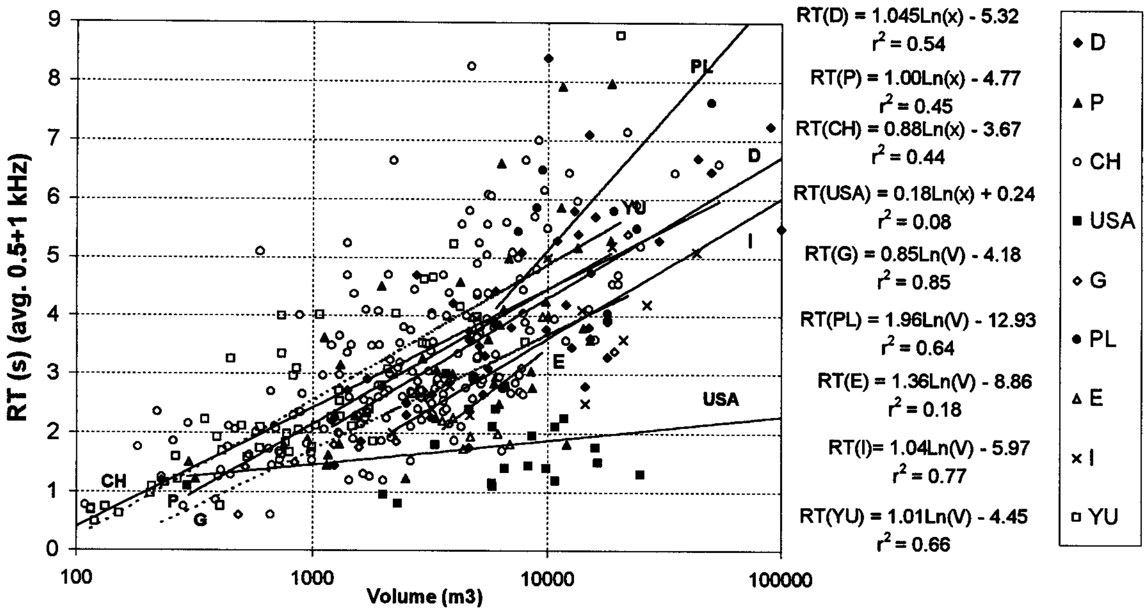
Analysis of the Reverberation Time Regarding Volume

For the analysis of the relation between RT and volume, the average values of the 0.5 and 1 kHz octave frequency bands were used for unoccupied churches.

Dispersion. The results present a great dispersion of the data for the relation of RT with volume ($r^2 \approx 0.45$ for the entire sample as well as in CH and P; see Fig. 1). The Orthodox churches (r^2 = 0.66 in YU and 0.85 in G) present a better correlation between them, probably because of the strong coherence on the architectural style and on the liturgical furniture in this confession. It is also observed a good correlation in the countries where the sampled churches (mainly Catholic) have a large average volume ($r^2 = 0.54$ in D, 0.64 in PL and 0.77 in I). The opposite happens with the churches in the USA ($r^2 = 0.08$) and E samples ($r^2 = 0.18$) that present a large dispersion. In the USA sample, this weak correlation between RT and volume comes from the coexistence of traditional church construction (RT is similar with other countries where it is used a traditional liturgy) with some very dry churches (for the new liturgies supported primarily on sound systems). One also observes a clear separation in the E sample between three churches with a rather high reverberation and the seven others being definitely drier. All these churches are however of the same architectural style (*Mudejar* Gothic) and with a comparable volume.

Regression models. The logarithmic regression functions that model the relationship of RT with Volume, RT = a*ln(V) + b, are coherent for the majority of countries (D, P, CH, I, YU and G) having for slope (parameter a) a value of 0.97 ± 0.08 and for Y-intercept (parameter b) a value of -4.7 ± 0.8 s. In these countries, the RT value calculated for a volume of 5000 m^3 is of 3.5 ± 0.5 s. For a median volume ($1000 < V < 10000$ m^3), RT is approximately one second weaker in G and I (extrapolation from great volumes) compared to the YU. The USA churches present in our sample, are the driest churches, with a weak slope ($a = 0.18$) and a low Y-intercept ($b = 0.24$). As already exposed, in the USA many recent churches are designed dry to obtain a good intelligibility with a sound system. On the contrary, in PL, the RT of the (large) churches is definitely higher than the average of the European churches with a strong slope ($a = 1.96$) and the lowest Y-intercept ($b = -12.9$). The reasons of this high RT, explained by Wroblewska [8], are to be sought in the monumental architectural style after WWII of the Polish religious buildings. With the exception of the USA (very dry churches) and of Poland (very reverberant churches), the regression models for the evolution of the RT with volume are relatively similar for the majority of the countries whatever the confession. There is not true local specificity for the evolution of the RT values with volume.

Figure 1: Reverberation Time (non occupied churches) regarding Volume and Country.



Analysis of the Reverberation Time Regarding Architectural Style

The analysis of the churches in the countries having a great number of sampled churches (> 40 churches, that is CH, D, P and YU) allows us to compare the evolution of the RT with the architectural style. The churches were classified according to their period of construction or significant architectural modification and then gathered in five periods: Romanesque, Gothic, Baroque, Neoclassic and Modern. All styles are in general well represented in the various countries except Romanesque and Neoclassic in D or Neoclassic and Modern in P (table 3).

The average church volume in certain architectural styles and in certain countries is very variable and move away from the value of 5000 m^3 (table 3). In Germany, one has for example, more than 21000 m^3 for the Gothic and Baroque but only 10425 m^3 for the Neoclassic and 4782 m^3 for the Modern style. On the contrary, the Neoclassic is the style with the greatest average volume in the P sample. The volumes are relatively small for all the styles in YU.

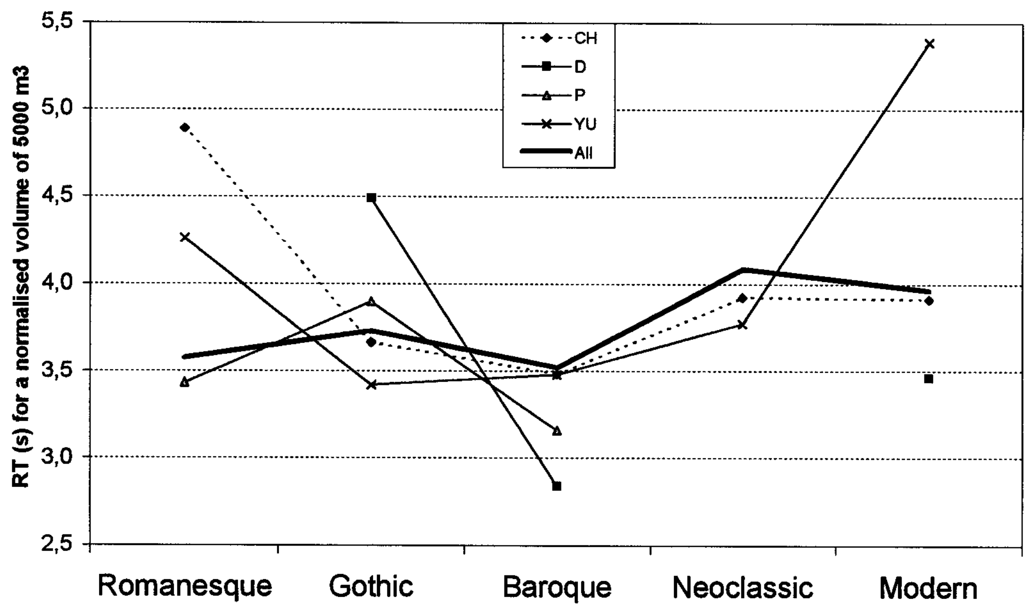
To validly compare the average RT according to the architectural style, it is necessary to transform the various values to a common normalised volume. It was shown previously that the RT values increase with volume, a regression logarithmic model giving a good indication of this relation. The RT values were then standardized by calculating the regression model parameters (*a* and *b*) for each controlled sample (country and style), except for the too small samples (Romanesque in D, Neoclassic in P or D, and Modern in P). These regression equations have then be used to evaluate the normalized RT that correspond to the calculated value for each one of these equations and for a reference volume of 5000 m^3 (Fig. 2).

The Fig. 2 shows a decrease of the RT values from the Romanesque and Gothic in Switzerland and Serbia but a weak rise in Portugal. The passage of the Gothic to the Baroque involves a generalized decrease (particularly marked in Germany), which is explained by the evolution of the liturgy brought by the Reformation and Counter-Reformation, where the speech intelligibility becomes significant. The Neoclassicism sees again an increase in the RT values related to the nostalgia of medieval piety and to a return to a sentimentalism that is better expressed in a largely reverberant atmosphere. The transition at the Modern time introduced more contrasted variations (notable increase in YU but little change in D and CH). The significant variations observed within a country, are explained by the break with tradition and the diversity of the architectural styles of the modern sacred buildings. The drier RT values noted in the USA churches can however predict for a future reduction in RT values in the churches where the liturgy requires excellent speech intelligibility and where the music uses primarily the sound system. The liturgical evolution (in the History and according to the confessions) makes it possible to partly explain the various tendencies observed.

Table 3: Number of churches (*n*) and mean volumes (*Vm*) by architectural style and country.

Country	CH		D		P		YU		All countries	
Style	*n*	*Vm*	*n*	*Vm*	*n*	*Vm*	*n*	*Vm*	*n*	*Vm*
Romanesque	8	4507	-	-	13	3534	4	1880	29	4571
Gothic	33	6410	8	22588	12	6407	12	1226	79	18025
Baroque	32	4876	7	21180	10	6049	9	1873	63	7689
Neoclassic	43	5236	2	10425	2	15049	15	1404	66	5521
Modern	61	3579	18	4782	4	5813	16	2560	124	5482
All styles	177	4718	35	17260	41	5772	56	1806	361	9783

Figure 2: Reverberation Time evolution (normalised for a volume of 5000 m^3) regarding Architectural Style and Country.

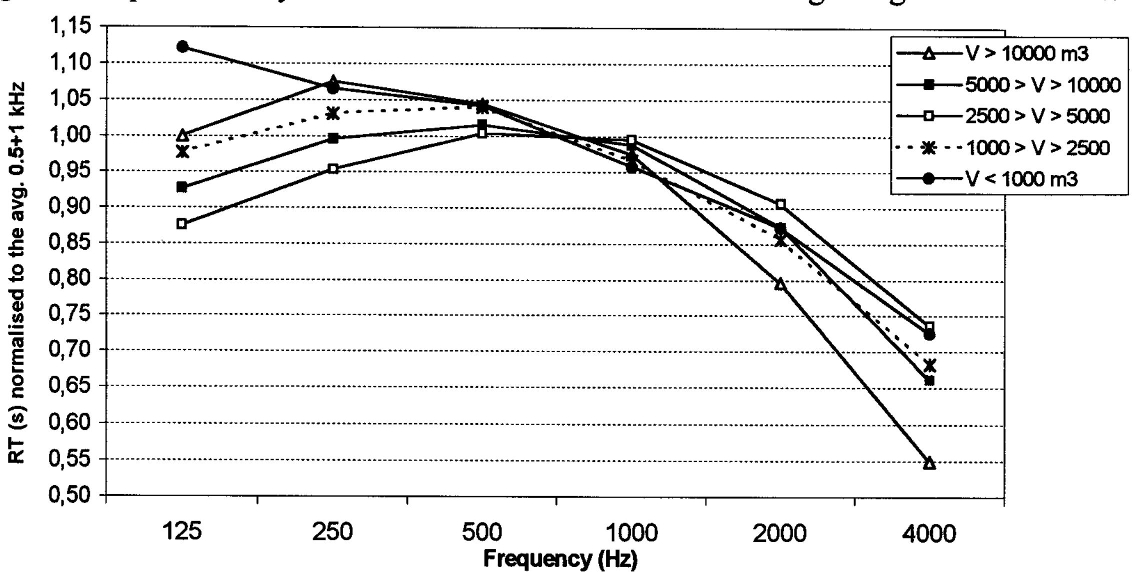


Analysis of the Reverberation Time by Frequency

In order to study the relative frequency evolution of the RT, their values by octave band were normalised. The RT value for each frequency band was divided by the RT average value (average of 500 and 1000 Hz). This makes it possible to study the RT relative differences between the frequency bands and to analyse the importance of various parameters (volume, style, confession and country) on the timbre of the churches.

Volume. To study the influence of volume on the spectral frequency evolution of the RT values five categories of volume, each with a comparable number of churches, were used (fig. 3a). It is noticed that large volumes (> 10000 m^3) involve a significant decrease of the RT at the high frequencies (> 2000 Hz). This effect, which induces a loss of brilliance, is explained by the air absorption, which becomes significant at these frequencies, in particular for great volumes where the free average path between two reflections becomes very large. On the other hand, low volumes (< 1000 m^3) have the RT raised at the low frequencies (< 250 Hz). This effect, which corresponds to a warmth timbre, can be perhaps explained by the presence of room modes still distinct under these conditions. One can finally notice weaker relative RT values at low frequencies (≤ 250 Hz) for volumes of average importance (2500 ≤ V ≤ 5000 m^3).

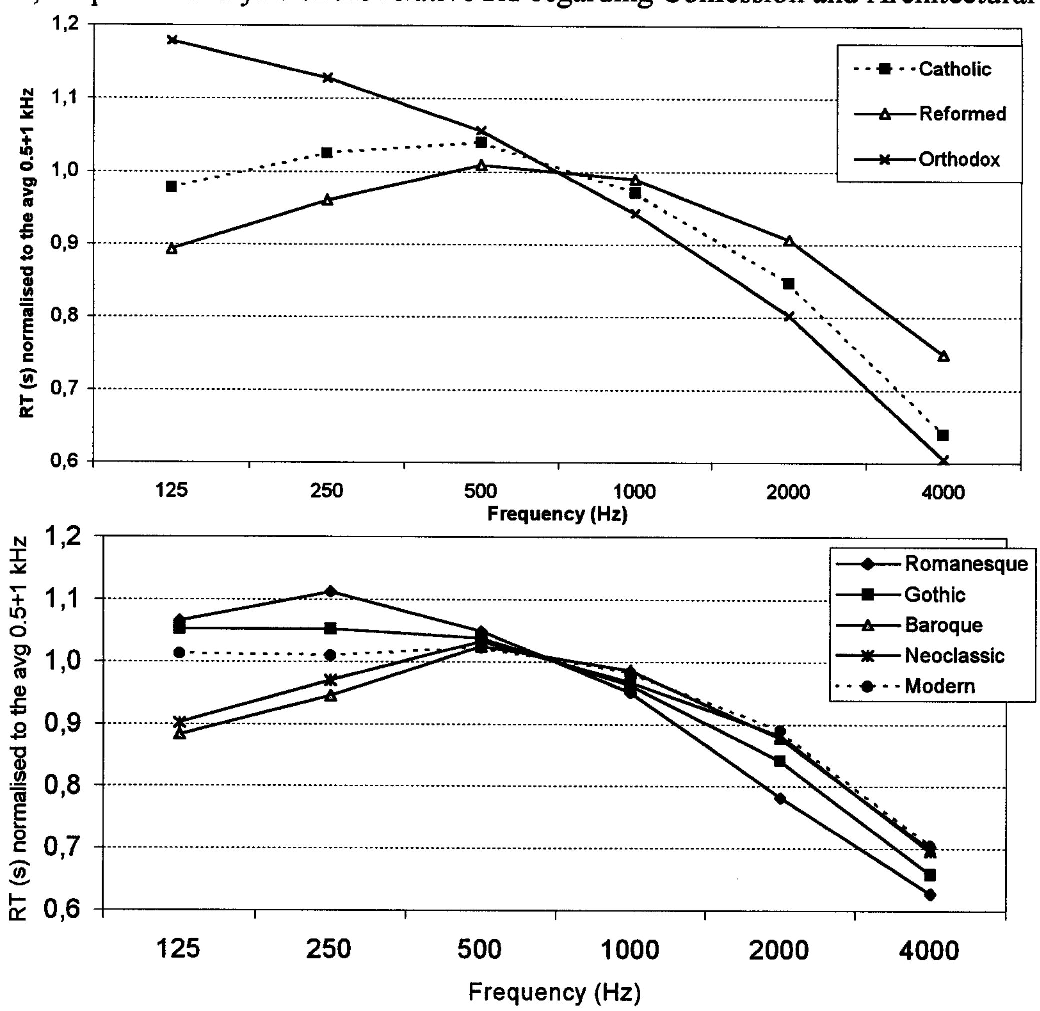
Figure 3a: Spectral analysis of the relative Reverberation Time regarding church Volume.



Confession. Controlling for the confession (fig. 3b), the RT values at high frequencies (≥ 2000 Hz) decrease rapidly for the Catholic and Orthodox churches. In the first case that is explained by the large average volume of these churches (≈ 15000 m^3 against 4500 m^3 for the Reformed churches). This explanation does not apply for the Orthodox churches that present the strongest decrease to the high frequencies in spite of the lowest church average volume (2500 m^3). The liturgical furniture used in the Orthodox churches, often with many hangings, is probably at the origin of this strong sound absorption at the high frequencies. In these churches, on the other hand, one finds an increase in the RT values at low frequencies already noted in the case of the churches of smaller volume. The spectral characteristic for the Reformed churches is, in contrary to the Orthodox churches, a less significant fall at the high frequencies, but a decrease of the RT at the low frequencies (≤ 250 Hz). This one, already observed for the churches of average sizes, is probably still accentuated, in this case, by the regular presence in these churches, of much woodwork, which absorb the low frequencies.

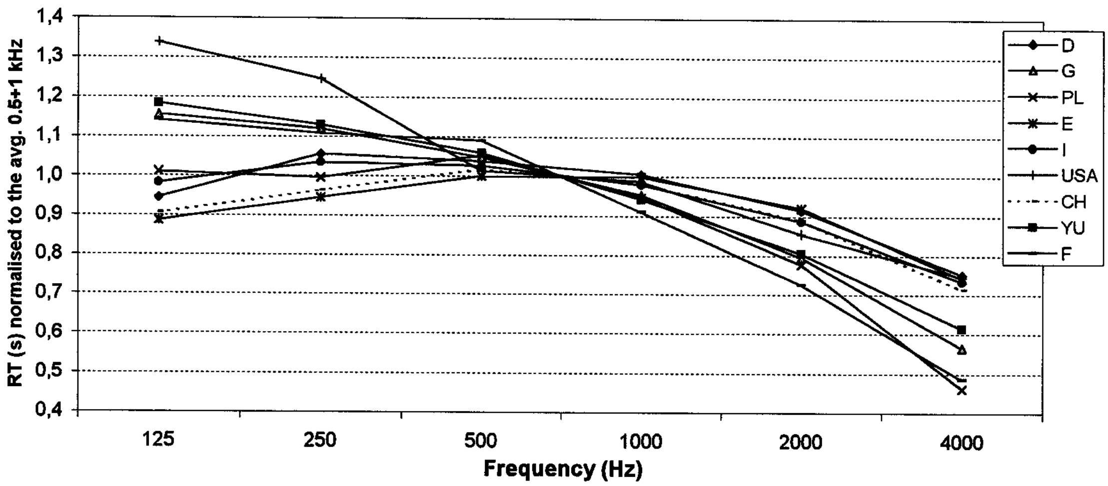
Style. In the spectral analysis of the reverberation controlling for architectural style (fig. 3c), a reduction at the high frequencies (≥ 2000 Hz) for the Romanesque and to a lesser extent, Gothic is noted. This is mainly due to the large average volume of these churches (respectively, ≈ 25500 m^3 and 17700 m^3 against 5000 m^3 or less in the other styles). In addition, in these churches, the stone and the harmony of great spaces are the principal decorations, which can explain the raised RT values at the low frequencies (≤ 250 Hz). These marked characteristics of the Romanesque churches confer a specific acoustics to them. The Baroque and Neoclassic churches have, in contrary, a less significant decrease at the high frequencies, but a fall of the RT at the low frequencies (≤ 250 Hz). The characteristic relative frequency evolution of these religious buildings was already noted down by Venzke [11]. The presence of woodworks in these churches contributes to explain this characteristic, already observed for the churches of average sizes and, in particular, Reformed.

Figure 3b,c: Spectral analysis of the relative RT regarding Confession and Architectural Style.



The Modern churches that present the same relative spectral characteristic on the medium and high frequency bands that the two preceding styles, are dissociated by the larger RT values at the lower frequencies. The considerable use of rough and rigid materials (barely absorbents), like concrete, is probably the principal cause.

Figure 3d: Spectral analysis of the relative Reverberation Time regarding Country.



Country. By studying regional specificities (fig. 3d) it is noted that the Polish churches, with very large volumes and mainly made of concrete, have very high RT values at low frequencies and that decrease in a characteristic way at higher frequencies. The Serbian and Greek churches show the same characteristics, but slightly attenuated, and already noted particular for the Orthodox churches. The other countries present relatively flat RT spectra with a weak reduction on high and low frequency bands.

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