Acoustics as a cultural heritage: the case of Orthodox churches and of the "Russian church" in Bari

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Abstract

Architecture of Orthodox churches changed very little in its history as a consequence of the strict adherence of liturgy and its related aspects, to the original canons. This has important implications on the acoustics that characterizes such places which is therefore very specific. The paper starts by considering the case of the Orthodox church of San Nicola (also known as "Russian church") in Bari where an acoustic survey was carried out. Innovative measurement tools like microphone arrays were used, allowing the identification of direction of arrival of sound reflections and, consequently, the architectural elements that play a major role on the acoustics. Then, the results of a detailed literature research are used to put the specific case study into a broader context including a large number of Orthodox churches. Results point out the existence of a very specific relationship between acoustics and architecture, supporting the idea that the first must be considered as a cultural heritage as important as the latter.

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Keywords

Acoustics; Orthodox churches; Architecture; Liturgy; Reverberation time.

Research aims

The paper analyzes the case of the Orthodox Church of San Nicola in Bari, outlining its acoustic characteristics and their relationship with architecture. Use of innovative visualization tools allowed the identification of architectural elements, like the apse, that play an important role on the acoustics. Finally, the comparison with literature data of a large sample of Orthodox churches allowed to put the church in a broader context. In particular, the analysis pointed out a marked relationship between acoustics and architectural features (geometry and materials) that stems from the changelessness of Orthodox liturgy and its related aspects. This supports the idea that acoustics must be considered a cultural heritage (although "intangible"), strictly related to the building itself. In Catholic churches a greater variation appears as a consequence of a richer variety in architectural styles and of an evolving liturgy. However, this should be a stimulus to safeguard the acoustic specificity of each place from gross attempts to adapt to new acoustic requirements.

1. Introduction

Acoustics is an important feature of several cultural heritage buildings. For theatres, in particular, the idea that the acoustics is by itself a “cultural heritage” began to spread at the end of the last century, when two important opera houses in Italy were destroyed by fire [1]. Since then the idea has gained considerable attention from the scientific community leading to the definition of guidelines to correctly measure the acoustical properties of such spaces [2]. In addition, the same concept was extended to other buildings, like worship places [3], in which sound propagation represents one of the most important aspects. Catholic churches, in particular, have experienced significant changes in acoustical needs during their history, in relation to variations in liturgy [4]. In particular, as a consequence of the use of local language accepted by the Second Vatican Council, speech intelligibility received an unprecedented attention that, in many cases, is determining the introduction of, sometimes too invasive, electro acoustics support systems or, in other cases, attempts to adapt the acoustics. Conversely, Orthodox churches experienced almost no change in their liturgy and limited variations in their layout, suggesting an even more important relationship between the building (the “tangible” cultural heritage) and its acoustics (meant as “intangible” cultural heritage [5-7]). As a further element supporting this strong relationship, the Divine Liturgy is almost entirely sung either by the clergy, or by the choir and by the congregation, usually in a responsorial form. The repertoire is made of traditional Byzantine Chants sung without instruments and the lectures are given using cantillation or using “ecclesiastical speech”, and all of them show very specific acoustic features [8]. In addition sound sources occupy fixed positions during the celebration. In fact, the clergy moves from the sanctuary to the nave, which are separated by the iconostasis (a dividing element usually made of painted wood), and vice versa and the doors are open or closed depending on the part of the celebration.

From the architectural point of view, Orthodox churches are usually based on a central plan typology, enriched by spaces specifically functional to liturgy (named *prothesis* and *diakonikon*) and located at the side of the altar. The central plan is fitted to the liturgical needs, as it preserves the central role of the altar while ensuring enough space for the religious celebrations taking place around it. From a symbolic point of view, the most representative and widespread plan shape was the Greek cross, with a dome over the crossing supported by four large pillars and the braces covered with barrel vaults. However, the *quincuncial* plan variation, in which the cross is in a square, and defines four additional sub-volumes located at the corners (usually covered with domes), can also be found frequently. When Christian Orthodox religion spread in Russia such models were originally used. However, after the fall of Constantinople, Moscow became the most powerful and wealthy Orthodox city in the world and architecture had to show this supremacy. Churches became bigger and bigger and new architectural models, often contrasting with the tradition, were experimented. The so called "tent-shaped" churches built in the 17^{th} century were among these experiments that, being clearly in contrast with the byzantine canons, were rapidly dismissed.

In acoustic terms, the above considerations about the similarity of church shapes suggest that significant correlations between reverberation and room volume may be expected for Orthodox churches. Similarly, the limited variations occurred in the Byzantine Chants are likely bound to specific acoustic features. In order to test such hypotheses the paper takes advantage of acoustic measurements recently carried out in the Orthodox church of "San Nicola" (also known as "Russian church") in Bari and, after a detailed bibliographical research, compares them with results already published in the literature.

2. Methods

2.1 Church description

The Orthodox church of San Nicola in Bari is part of a larger building designed by the Russian architect A. V. Ščusev in order to offer hospitality to pilgrims visiting the city to worship the relics of San Nicola. The church was built between 1913 and 1915 according to the 12^{th} century Novgorod-Pskovian style, and is actually made of two superimposed churches. The lower (mostly used in winter)

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was dedicated to St. Spyridon and the upper was dedicated to St. Nicholas. The upper church, that was taken into account in this study, has a quincuncial plan (Fig. 1), inscribed in a 12 m square. An iconostasis made of wood and having three openings divides the interior space into the sanctuary, exclusively used by the clergy, covering an area of about 50 m^2, and the area for the congregation (about 100 m^2). The sanctuary terminates with an apse facing east and includes two of the four angular sub-volumes that are used as the prothesis and the diakonikon. Two pillars and two columns support the dome that reaches the maximum height of 19.3 m. Barrel vaults cover the four braces of the cross, while the four angular bays are covered by lower cross vaults. Walls and vaults are finished in plaster (Fig. 2), while the floor is made of smooth limestone but about one third of its surface (most of the sanctuary area) is covered by carpets. Several windows, having relatively small dimensions, are distributed along the walls, while several pieces of wooden furniture can be found in the church. The total volume of the church is slightly less than 1500 m^3.

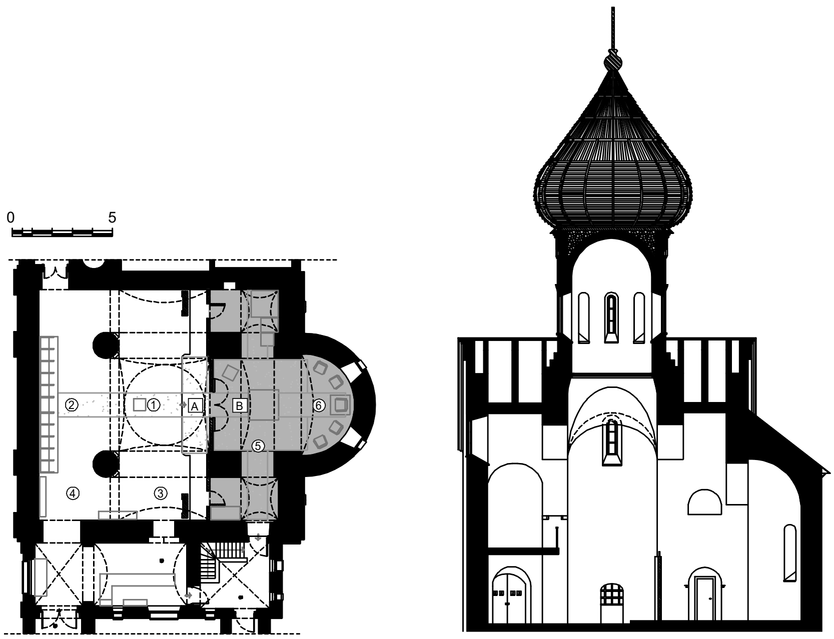

Figure 1a – Plan and cross section of the church with indication of source (A and B) and receiver (1-6) placement.

Figure 2 – Panoramic view of the interior of the church (from receiver 3)

2.2 Measurement method

Acoustic measurements were carried out according to ISO 3382-1 standard [9] together with the guidelines defined for churches [10]. A dodecahedron sound source (Lookline D-301) with a frequency response from 100 Hz to 10 kHz was fed by a 9 s logarithmic sine sweep. The sound was recorded using an Eigenmike 32 (EM32) microphone array with 32 electret microphones controlled through the software Zynewave Podium. The tool also hosts a VST plugin to perform beamforming using one of the available "virtual" microphones, including omni-directional and first-order dipole (so allowing Ambisonic B-format decomposition). The 32 channel response was first processed in Matlab to get the impulse responses (IRs), and then the resulting signals were processed again using the VST plugin to get the desired 3D decomposition (in this case the four B-format components).

Considering the directivity limits pointed out for dodecahedron sound sources [11] and considering the reduced source receiver distance which may emphasize the role of direct sound and early reflections, three different IRs were measured at each receiver after rotating the source so that angles of 0°, 30° and 60° were formed. Consequently, ISO 3382 acoustic parameters for each position were calculated by averaging the values resulting from the three rotations. Sound source was located in front and behind the iconostasis, to represent the usual positions of the priest during the celebration. Finally, six receivers were distributed in the congregation area.

3. Results

3.1 Analysis of measured acoustical parameters

The analysis of reverberation time (T30) measurements (Fig. 3) showed an average value at medium frequencies (500 Hz and 1 kHz) of 2.85 s with almost similar values in the lower frequencies, while a decrease appeared as the frequency grew, in consequence of air absorption. The presence of several wooden elements was likely to explain the low frequency behavior. This was confirmed also by early decay time (EDT) which was very similar to T30 except in the lowest octave bands where much lower values appeared. In fact, most of the low frequency absorbers are located close to receivers, thus determining a higher absorption of the low frequencies.

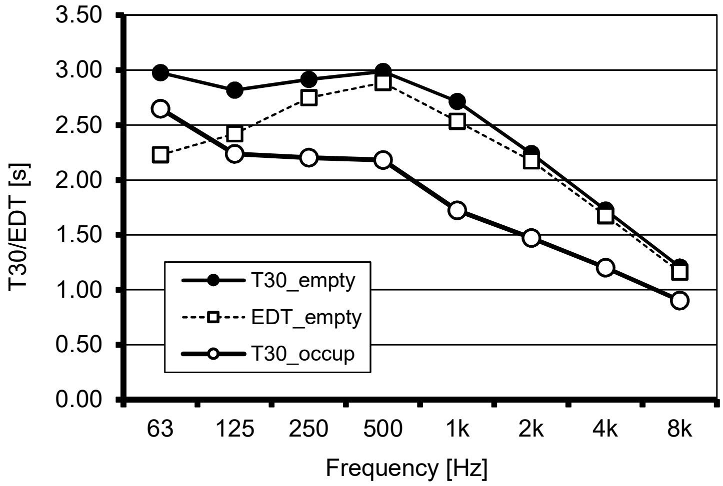

Figure 3 – Plot of measured reverberation time (T30) and early decay time (EDT) as a function of frequency under unoccupied conditions, together with calculated values of T30 under occupied conditions.

Taking advantage of the mixing geometry and even distribution of sound absorbing materials Sabine’s formula was applied to predict the effect of occupancy. During ordinary celebrations about fifty persons (including both clergy and congregation) occupy the church. Taking advantage of the values given in [12] the absorption coefficients for a standing audience with an occupation density of

0.9 person/m^2 and wearing medium clothes (considering the strict dress code applied in Orthodox churches) were determined. The resulting T30 values lowered (at mid-frequencies the average was about 2.0 s), while keeping the same trend as a function of frequency. It is interesting to observe that in occupied conditions the so called reverberant radius (or critical distance) was about 1.5 m, meaning that according to the Articulation Loss criterion (AL_{cons}) intelligibility should be acceptable within a distance from the source of about 3.3 times the critical distance, corresponding to 5 m.

Analysis of other acoustic parameters (Fig. 4) gave more detailed information about this. Clarity for speech (C50) and music (C80) showed the usual decreasing trend as a function of distance, but three outliers appeared, corresponding to combinations A-05, B-03, and B-04, where the iconostasis prevented direct sound to get to the microphone. Difference was up to 6 dB for C50 at points close to the source. A similar behavior appeared for C80, but was less evident as the contribution from other reflections masked the lack of direct sound, particularly at further distances. These results were particularly interesting as they suggested what happens when the clergy is in the sanctuary and the doors are closed, yielding acoustic conditions characterized by significantly lower clarity, particularly for speech. Centre time (Ts) showed, as expected, an increasing trend as a function of distance converging (with the exception of the same outliers found before) towards the theoretical value for a diffuse sound field (equal to T30/13.8). The fact that the difference between outliers and the other points was not negligible (and that the value was larger than the theoretical one), suggested that the missing contribution was due to direct sound and also to early reflections. By means of the theoretical value it was possible to estimate the variation in Ts values under occupied conditions. Results showed that, excluding the outliers, values never exceed 150 ms, thus suggesting that when the church is occupied good intelligibility could be achieved without any electro-acoustic support.

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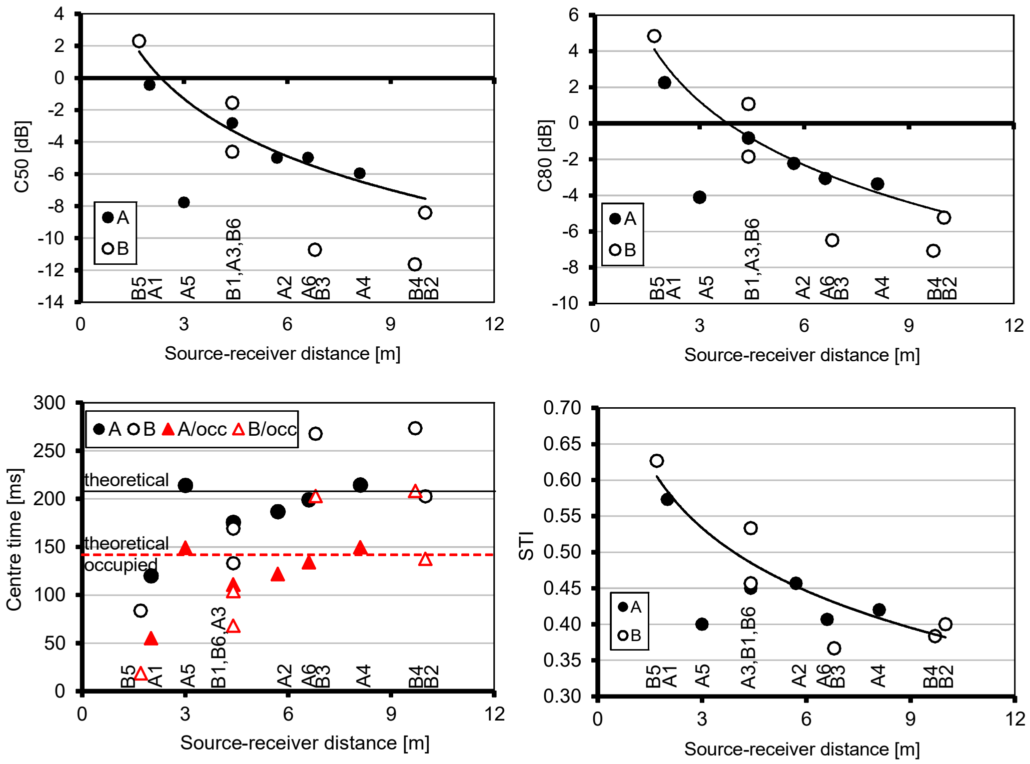

Figure 4 – a) Plot of measured clarity for music (C80) and speech (C50) as a function of source receiver distance under unoccupied conditions, with regression curves calculated excluding outliers. b) Plot of centre time (Ts) as a function of source receiver distance measured under unoccupied conditions and predicted in occupied conditions. Lines correspond to theoretical values the parameter should assume under diffuse field conditions.

3.2 Spatial distribution of sound reflections

By taking advantage of the EM32 potential, three-dimensional sound maps were obtained for each source receiver combination. Such maps are useful to show the direction of arrival of sound reflection and their relative intensity contributing to understand the specific role of architectural elements interacting with sound. An example of the usefulness of such maps is given in Fig. 5 which shows sound arriving at receiver 01 when source was in B (in the sanctuary). Sound came mostly from the vertical plane containing both source and receiver with an interesting contribution coming from the apse and its dome. In fact, with the iconostasis door closed the latter was likely to became the most important contribution arriving to

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the listeners in the nave, thus causing an upwards shifting of the acoustic image, with an undoubtedly evocative effect.

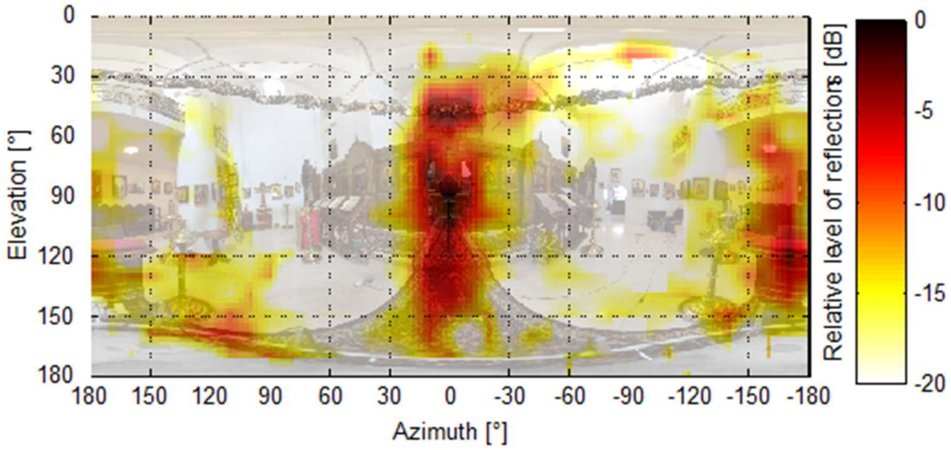

Figure 5 – Directional reflection map for combination B-01 at 1 kHz with reference to the time interval from 5ms to 80 ms.

4. Discussion

In order to discuss and put in the correct context the results observed in the church in Bari a detailed bibliographical survey was carried out [13-22], collecting a sufficiently large sample of acoustic data referred to Orthodox churches located in Greece, Serbia, and Russia. A summary of the main data was given in Table 1 for Greek and Russian churches. Detailed data for Serbian churches were not available but it was possible to retrieve volume and reverberation time at 500 Hz. Most of the churches had a small volume (the median was 1300 m^3) and only eight churches out of 80 had a volume larger than 10000 m^3 (and most of them were the most recent churches built in Russia). Reverberation time was considered for comparisons as it was the only acoustic parameter measured in all the churches. When architectural and geometrical details were not given in the papers they were found elsewhere.

Table 1 – Summary of the main characteristics of the churches analyzed in Refs. [13-21].

Church name	*Age*	*Location*	*V (mc)*	S_{floor} *(mq)*	H_{max} *(m)*	T_{mid} *(s)*
Transfiguration of Saviour	XIV	Thessaloniki, GR	230	41.9	9	1.17
St. Nicholas Orphanos	XIV	Thessaloniki, GR	520	91.6	7	1.39
Katholikon of the Vlatades	XIV	Thessaloniki, GR	835	141.1	9.6	1.5
Annunciation of the Holy Virgin	XV	Moskow, RU	1010	89.8	23.2	2.09
Intercession (lower winter church)	XVII	Fili, RU	1100	213.0	5.4	1.28
St. Catherine	XIII	Thessaloniki, GR	1230	168.9	14	1.76
Panagia Chalkeon	XI	Thessaloniki, GR	1290	119.7	15.1	2.02
St. Panteleimon	XIII	Thessaloniki, GR	1425	140.3	17.4	2.51
Holy Apostles	XIV	Thessaloniki, GR	1575	187.2	16	1.71
St. Basil	XVI	Moskow, RU	1670	93.2	46.6	4.1
Ascension	XVI	Kolomenskoe, RU	1700	110.4	48.4	6.2
Prophet Elias	XIV	Thessaloniki, GR	2250	230.0	17.2	1.76
Intercession (upper summer church)	XVII	Fili, RU	2260	213.0	21.3	1.65
Trinity	XVII	Kostroma, RU	3250	313.7	25.3	3.8
Archangel Michael	XVI	Moskow, RU	6600	339.1	28.3	4.31
Dormition	XV	Moskow, RU	11500	520.0	27.7	4.42
Rotunda of St. George	IV	Thessaloniki, GR	15000	832.9	27.5	4.65
Our Lady of Kazan	XIX	St. Petersburg, RU	40000	1999.7	41	5.5
Holy Trinity of Izmailovsky	XIX	St. Petersburg, RU	52000	1933.8	52	5.45
St. Isaac	XIX	St. Petersburg, RU	75400	3081.3	61.8	7.65
Christ the Saviour	XX	Moskow, RU	88400	3425.5	63.6	8.5

First of all the correlation between T30 and volume was investigated. As shown in Fig. 6, if the churches listed in Table 1 were considered, excluding “tent-shaped” churches which markedly had longer T30 for the given volume, the correlation was good and statistically significant (R^2 = 0.884). The regression curve followed almost perfectly the theory, according to which T30 should be proportional to $V^{1/3}$. If the Serbian sample was also included [22], the regression equation changed a little, becoming statistically less significant (R^2 = 0.693) and moving to the left in consequence of the significant amount of churches with smaller volume and slightly longer reverberation time. Unfortunately, few details were given about the composition of this sample so it was very difficult to explain the more reverberant behavior of the outliers. However, the sample included several modern churches

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that likely lacked the typical furniture of older churches, thus explaining the longer reverberation. Conversely, for churches in Table 1 it was possible to explain how shape and materials influenced the position in the plot so that more convolved shapes were less reverberant than more compact and simple shapes. However, the variations were relatively small so this in-depth analysis was avoided. The church of San Nicola fits very well with the regression line, showing a slightly longer T30 compared to volume which may be explained as a consequence of the widespread use of plaster on the wall surfaces.

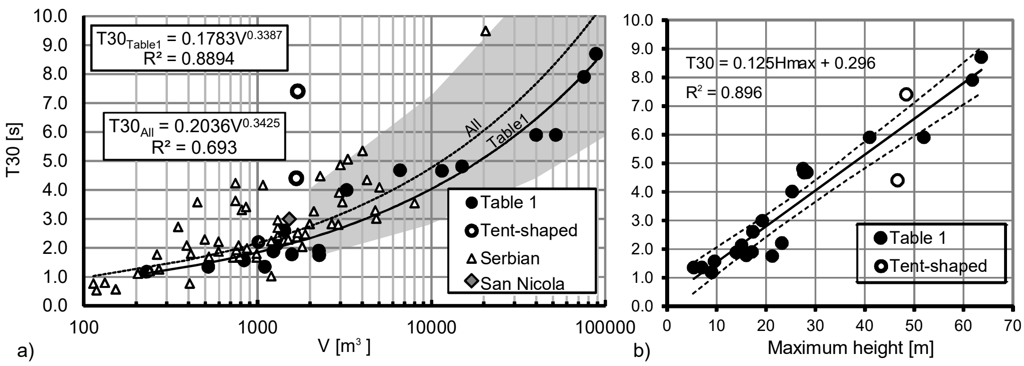

Figure 6 – Reverberation time at 500 Hz as a function of: a) room volume for different sub sets of data (grey area correspond to the area occupied by Catholic churches surveyed in Ref. [4]); b) maximum church height (dashed curves correspond to confidence interval of the regression line).

Another correlation which was worth being considered was that between T30 and the maximum height. In fact, this combination usually shows scarcely correlated results, but in this case the statistical significance was high (R^2=0.895) and the regression equation yielded T30 = 0.117 H_{max} + 0.306. No outliers appeared in this case as the two tent-shaped churches and even the larger and most recent churches, fitted particularly well to the model. This was coherent with the fact that tent-shaped churches have very disproportionate geometry in which diffuse field conditions (on which Sabine's formula relies) are not met because the mean free path is much more influenced by the longest dimension (i.e. the height).

Finally, in order to point out the characteristic nature of Orthodox churches compared to Catholic churches, the grey area in Fig. 6 shows the area in which most of the churches surveyed in [4] fall. This set of data was characterized by larger volumes and more scattered T30, as an obvious consequence of the variations due to different architectural styles and much bigger dimensions. Conversely, the stricter set of rules that regulated the building of any new Orthodox church (with the only exception of the most recent cases), and the dimension more suited to smaller congregations, clearly represent the "trademark" of this group of buildings. Similar considerations could be made with reference to the relationship between some specific acoustics features of Orthodox churches, like the emphasis in the low frequency range and its relation with Byzantine Chants [8], but for sake of brevity they were not discussed here.

5. Conclusions

The paper started by considering the very specific case of the Orthodox Church of San Nicola in Bari, outlining its acoustic characteristics and their relationship with architecture. Use of acoustic maps allowed the identification of architectural elements, like the apse, also playing an important role on the acoustics. Finally, the comparison with literature data of a large sample of Orthodox churches from Serbia, Greece and Russia allowed to understand that the church in Bari, although its more recent origin, is in very good agreement with the dimensional and acoustic characteristics of most of the other examples taken into account. More interestingly, this analysis pointed out a marked relationship between acoustics and architectural features (geometry and materials) that stems from the changelessness of Orthodox liturgy and its related aspects. This clearly supports the idea that acoustics must be considered a cultural heritage (although "intangible") strictly related to the building itself. The fact that diversity in style and larger dimensions seem to prevent any simple correlation between acoustics and architecture in Catholic churches does not diminishes the importance of the topic, as a more detailed analysis is required in that case to take into account evolution in liturgy. In fact, historical Catholic churches are, usually, acoustically fitted to the liturgy of time in which they were built (or completed). So, from this point of view, care should be taken to protect this specificity from gross attempts to adapt to new acoustic requirements asking for the highest intelligibility.

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