

Cathedral Acoustics: Bristol Cathedral as a Case Study

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ABSTRACT

The acoustic environment of a cathedral is essential to its character, and part of its intangible cultural heritage, and therefore must be studied, preserved, and disseminated. This paper presents the acoustic study of Bristol cathedral, serving as a case study to detail the procedure followed to analyse the acoustic field of English cathedrals as part of the EC-funded Marie-Sklodowska-Curie Fellowship ‘Cathedral Acoustics’. The acoustic characterisation includes an in-depth analysis of the different sound sources involved in both present and past uses of the cathedral, as well as the review of the acoustically significant architectural changes throughout history. Acoustic measurements were used to capture the Room Impulse Responses (RIR) of the space at several source-receiver combinations. The measured RIR have been used to describe the current acoustic behaviour of this highly reverberant space and to create auralisations based on specific speech and singing extracts which form part of liturgical practices and cultural celebrations held in the cathedral. The sound extracts used for the auralisations were previously recorded in an anechoic environment.

Keywords: Cathedral acoustics, Room impulse responses, Auralisation

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1. INTRODUCTION

Cathedrals are an essential part of Europe's cultural, architectural and artistic heritage, and their acoustics is key to their character. The European Commission recognises the preservation of Cultural Heritage as a priority, considering activities focused on heritage science or cultural heritage research to have a strong social, cultural, and economic impact [1]. Cathedrals are the group of sacred sites visited by the largest and most diverse group of people in Europe, attracting over 8.2 million visitors per year [2]. For this reason, the last decades have seen an increase in interest in the study and preservation of the acoustics of churches and cathedrals [3-6]. In this context, the project *Cathedral Acoustics*, funded through the European Commission's Marie Skłodowska-Curie Actions, aims to study the acoustics of English cathedrals.

Cathedral Acoustics focuses on the study, preservation and dissemination of the acoustical heritage of four English cathedrals: Bristol, Ely, Ripon and York. The proposed acoustic study involves two distinct parts. The first is the acoustic characterisation of the space as it is nowadays by capturing the Room Impulse Responses (RIR), which describe the acoustic field. The second is the estimation of the RIR associated to hypothetical scenarios or to different historical periods by using simulation techniques. Both parts require a complete historical analysis of the cathedral under study, in order to document the architectural changes, as well as the liturgical or cultural events that take or have taken place, which may involve changes in the decoration or ephemeral assemblies, different types and/or locations of sound sources, and variations in the location and/or density of listeners. This methodology which combines measurement and simulation techniques has been previously applied to similar buildings [7-10] yielding valuable results.

This paper presents the characterisation of the current acoustics of Bristol Cathedral through on-site measurements. We will describe the technique utilised as well as introduce the most salient aspects of the cathedral's history, focusing on those architectural changes that are likely to have had an acoustical impact. We will then present the results of the measurements as well as an overview of the acoustics of the different parts of the cathedral.

2. ACOUSTIC CHARACTERISATION METHODOLOGY

The acoustic characterisation of the cathedral is based on the analysis of the measured RIR. Experimental measurements were carried out by using as reference the procedure established in the ISO3382 [11] and following the specific guidelines developed for similar buildings [12, 13]. The geometric complexity of cathedrals coupled with their dimensions require a fragmented study by zones. Therefore, several sound source positions are set in order to assess the acoustics of the different parts of the cathedral, and also to reflect different uses of the space. An omnidirectional sound source (NTi DS3 dodecahedral loudspeaker together with a NTi PA3 power amplifier) is used to emit the excitation signal. Receiver/listener points are distributed throughout the congregation/audience area. At each source-receiver combination, both monaural and binaural RIR are registered by using a B-format microphone (Soundfield ST450) and a dummy head (Neumann KU 100) respectively. The omnidirectional component of the B-format RIR (W) is used to calculate monaural acoustic parameters, and the additional directional signals (X, Y, Z) are used to evaluate spatial characteristics, together with the binaural RIR captured with the dummy head.

A sine-sweep is used as excitation signal. Its frequency range, level, and duration is adjusted to each space so that the frequency range covers the octave bands from 125 to 16000 Hz if possible, and the impulse to noise ratio (INR) is as high as possible at each octave band. The sweeps used in Bristol cathedral had a duration of 22 seconds and covered the frequency range from 50 Hz - 16 kHz. They were emitted at a level of 80 dBA in the nave and the choir and with a level of 76 dBA in the chapels, as measured at one metre from the sound source using pink noise. Such levels were the maximum levels we could set avoiding microphone clipping.

Although the measurements at Bristol cathedral were taken when the space was unoccupied and overnight, the background noise was considerably high. The noise from building services equipment and nearby traffic were the main contributors to the general background noise level.

The playback and recording process are achieved using the digital audio workstation Pro Tools 12 and the signals captured are processed in MATLAB in order to obtain the RIR. Commercial software (MATLAB, EASERA and Dirac 6) have been used to analyse the RIR and calculate the acoustic parameters.

3. BRISTOL CATHEDRAL AS A CASE STUDY

Bristol Cathedral has more than nine centuries of history, it is one of the finest examples of a medieval “hall church”, with the vaulted ceilings in the nave, choir, and aisles all at the same height. Furthermore, Bristol cathedral is a hub of activity offering a minimum of three services each day and being a focus of a great variety of cultural events. An acoustical study of the space needs to take into account the building’s construction process and architecture, as well as its past and current uses.

3.1 Construction Process and Description of the Space

The construction process that shaped the acoustics of Bristol cathedral can be divided into two phases: (1) its time as an Abbey, from its foundation in 1142 to its dissolution in 1539, and (2) its time as a cathedral, spanning from 1542 to the present day.

We can trace the origins of the cathedral to the St Augustine's Abbey founded in 1140 by Robert Fitzhardinge. The original abbey was dissolved by Henry VIII in 1539, and the nave, which was being constructed at the time, was never completed [15]. In 1542, the church was proclaimed cathedral by Henry VIII, thus becoming one of the thirteen cathedrals of the New Foundation [16]. The Diocese of Bristol was created, establishing its See in the former Abbey.

Not too much remains visible today of the Norman church, except certain parts of the walls of the transepts and the bottom part of the pillars of the tower. The Chapter House, whose construction ended in 1165, is the most important relic of the Normandy Abbey [17]. The first incorporation made to the Norman church was the Elder Lady Chapel, dated from the early 13th century (1220). It was built in the Early English Gothic style, located in the northern transept of the cathedral, adjacent to the northern part of the choir. (Figure 1, left) [18]. Between 1298 and 1332 the eastern part of the Norman church is reconstructed in Decorated Gothic style [19], including the vaults of the central nave and the aisles, the choir, the Eastern Lady Chapel, the Berkeley Chapel and the Sacristy. The work is done giving the same height to the central nave, to the sides and to the choir. This type of construction, named as “hall church”, became a reference design in European architecture, especially in German Gothic architecture.

The reconstruction works stopped for a century, until the Central Tower and Transepts were erected in Perpendicular Gothic style in the late 15th or early 16th centuries [20]. In



Figure 1. Interior views of Bristol cathedral: Elder Lady Chapel (left) and view of the choir, rood screen and hall nave (right).

1536 the reconstruction of the central nave was paralyzed remaining incomplete until the end of the 19th century. The new nave of Bristol cathedral was added in 1887 by the architect George Edmund Street, who designed a Neogothic hall nave in harmony with the rest of the building and with similar dimensions to those provided by Abbot Newland in the late 15th century.

In 1888, the works of the west facade concluded with two twin towers located at the feet of the nave. The redistribution of the interior was completed at the beginning of the 20th century, including the stone choir screen (Figure 1, right) that separates the nave and the choir, the reredos behind the High altar and the pulpit [21].

Due to this long construction process, characteristics linked to two of the most important styles of British architecture can be appreciated in the building: Norman and Gothic (including all its phases: Early English, Decorated and Perpendicular Gothic).

Undoubtedly, the dimensions of the cathedral play a decisive role in its acoustics, having an approximate interior volume of $31,556 \text{ m}^3$. Table 1 summarises its main geometrical dimensions and Figure 1 shows the floor plan of Bristol cathedral.

The material found in a major proportion in the cathedral is the stone, which is found in all the supporting structure of the building (arches, pillars and the perimeter walls). The cathedral also has stone vaults, except in the transept, the choir and the Lady chapel, which have wooden vaults. The cathedral has marble and limestone floors, covered by carpet in certain areas such as the altars. Beautiful stained glass windows surrounded the entire building. Furnishing basically consist of numerous chairs covering the nave and the High altar, and wooden pews in the elder Lady chapel, without forgetting the decorated wooden stalls of the choir.

Table 1. Geometrical data of Bristol cathedral

Main dimensions of the space (Length, Wide, Height) [m]					Approximate floor surface (S) [m ²]				
L _{Max}	L _{Nave}	L _{Choir}	W _{Max}	H _{Max}	S _{Total}	S _{Nave}	S _{Choir}	S _{Elder}	S _{Lady}
90	37	15	22	15.8	1910	772	146	95	163

3.2 Acoustic survey

Due to the dimensions of the cathedral and its multifunctional character, 5 sound source positions were set in order to analyse its current acoustic behaviour. The first position was in the Nave's Altar (SN), where mayor liturgical celebrations and instrumental and choral concerts are held on a regular basis. The second was in the medieval Elder Lady Chapel (SE), a semi-independent space used for prayer. The third was positioned in the choir (SC) and the fourth in the High Altar (SA). The third and fourth positions were considered as focal points in the medieval 'hall' church, where spoken and sung services take place daily, such as the Choral Evensong. The fifth source was in the Eastern Lady Chapel (SL), which is currently used for services, as well as small concerts and lectures. A total of 32 receiver points were distributed throughout the audience/congregation area. The RIR were registered in those source-receiver combinations associated with each use and/or area of the cathedral. Table 2 summarises the combinations of sources and receivers that have been analysed and Figure 2 shows the floor plan of Bristol cathedral with source (S) and receiver (R) locations.

Table 1. Summary of the source-receiver analysed combinations

Source position ID	SN	SE	SL	SA	SC
Source location	Nave	Elder Lady chapel	Lady chapel	High Altar	Choir
Num. Rec. points	12	4	4	8	10
Receiver points ID	R1 – R12	R27 – R30	R23 – R26	R14 – R17 R19 – R21 R32	R13, R32 R15 – R22

Regrettably, two iconic spaces in Bristol cathedral could not be studied: the small Berkeley Chapel, where nowadays the Morning Prayer is celebrated; and the Norman Chapter House, where some community events and talks are held. In addition to this, due to access limitations it was not possible to include in this study the pulpit in the nave or the organ. These configurations will be assessed through acoustic simulation.

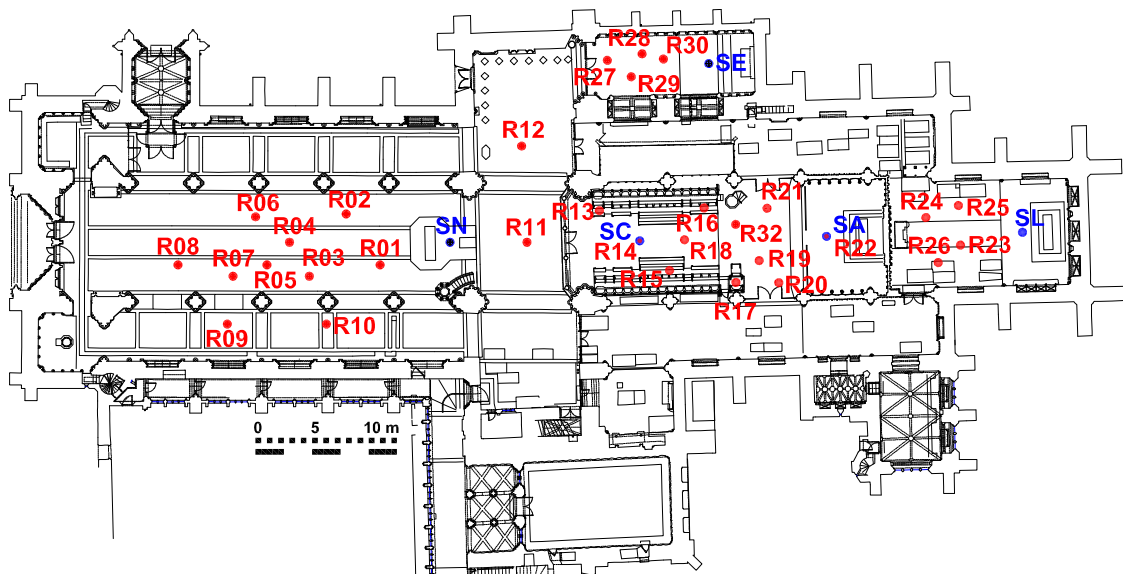


Figure 2. Floor plan of Bristol cathedral with source (S) and receiver (R) positions.

3.3 Results and discussion

The acoustic parameters calculated from the measured RIR are used to assess four aspects of the acoustics of Bristol cathedral: its reverberant environment, its effect on speech, its effect on music, and the perceived spaciousness.

The reverberation time, T_{30} , is the most relevant parameter when characterising the acoustic behaviour of a space as it provides an insight into the listening experience within the building. The volume of the building and the fact that its finishing materials consist predominantly of highly sound-reflecting surfaces such as stone and marble, result in a highly reverberant acoustic environment, with an average reverberation time of 4.5 seconds at mid frequencies.

Figure 3 shows the spatially averaged values of the reverberation time (T_{30}) in seconds (s) measured in the cathedral at each octave band, considering each source position independently. As expected, the variation of the reverberation time with the sound source position considered is negligible within the main space of the cathedral (nave and choir). Nevertheless, when the sound source is located in the chapels lower values of T_{30} are found. The reverberation time in the Eastern Lady Chapel (SL) is about 0.4 seconds lower for all frequency bands, possibly due to its location in the cathedral, having the reredos of the High altar "closing" the space. But it is in the Elder Lady chapel (SE) where T_{30} is remarkable shorter for all frequency bands. Such difference between the chapel's reverberation time in comparison to the rest of the building is due to the fact that it works as a semi-independent space, whose volume is much smaller (approximate volume of 756 m³), and in which textiles and wood are more prominent (Figure 1, left). However, the chapel has large open areas connecting it to the rest of the cathedral. When analysing the Schroeder decay curve derived from the RIR registered in the chapel multiple slopes are found. Figure 4 shows some examples (decay curves measured in receiver positions R28 and R30 for 500 Hz and 2 kHz) in which the initial decay (the first slope) corresponding to the chapel, and the late decay (the second slope) representing the influence of the rest of the cathedral, can be easily distinguished. This confirms that the chapel and the cathedral behave as a coupled-volume system. The Bayesian analysis of this decay curves has been performed with the tool designed by Martellotta [22].

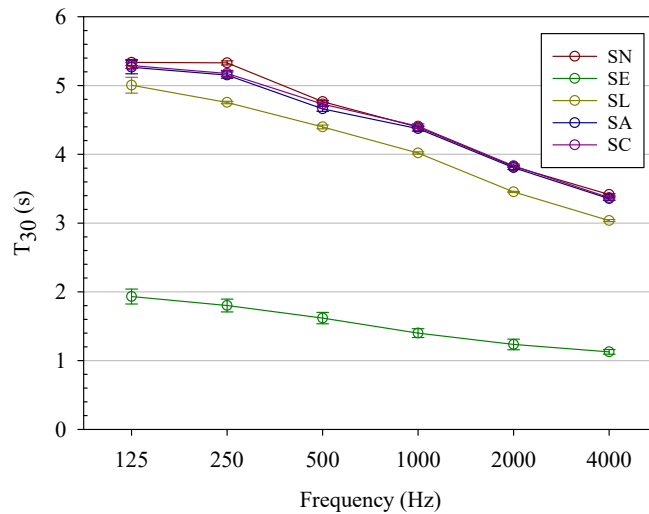


Figure 3. Spectral behaviour of the reverberation time (T_{30}) measured for each position of the source. The bars represent the deviation from the mean value in terms of the standard error. For SE, T_{10} values are represented.

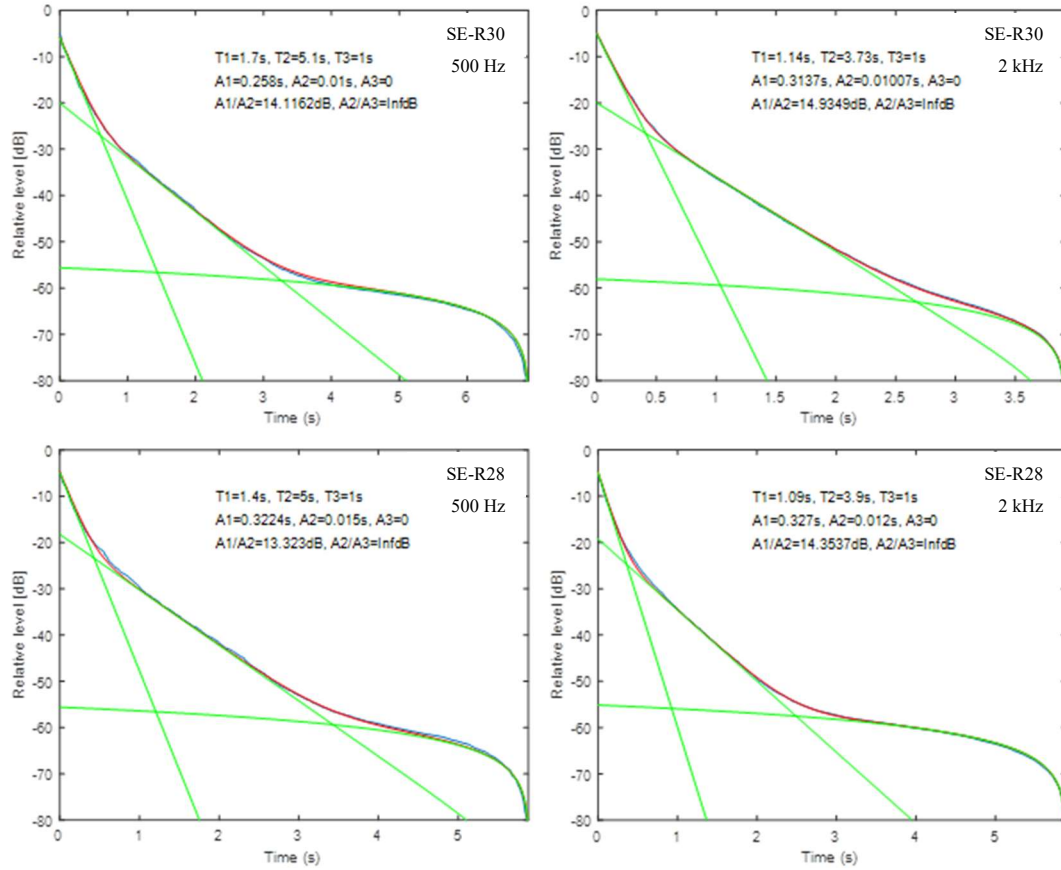


Figure 4. Bayesian analysis of the decay curves calculated from the RIR measured in R28 and R30 at 500 Hz and 2 kHz when the source is located in the Elder Lady Chapel (SE).

Due to the characteristics of the Schroeder decay curves obtained in the Elder Lady Chapel, the reverberation time of this space was assessed with T_{10} in order to avoid the effect of the second slope in the results.

In addition to the reverberation time, there are a number of parameters that have been used to assess the acoustic behaviour of the building. The subjective appreciation of the reverberant environment of the cathedral can be assessed through the EDT parameter. Perceived clarity of sound is assessed by using several parameters that depend on the balance between early-arriving and late-arriving energy. While C_{80} is typically employed to evaluate the musical clarity within a room, a wide variety of parameters (T_s , D_{50}) are used in conjunction with the speech transmission index (STI) in order to provide a comprehensive assessment of speech clarity and intelligibility. Furthermore, the apparent source width (ASW) is considered one of the major aspects of the spatial characteristics of rooms. This attribute is related to the amount of early-arriving lateral reflections and can be measured in terms of $IACC_E$ (or $1-IACC_E$).

In order to compare the acoustic field of the cathedral in regard to the 5 source locations and its areas of influence, Table 3 summarises the spatially and spectrally averaged values estimated for several monaural and binaural parameters. The acceptable values of each parameter considered for the discussion presented in this paper are also included in the table. Those values are based on previous subjective studies performed in similar buildings [24–28]. This summary is provided in order to examine how the different acoustical characteristics have an impact on the sonic events that take and have taken place in the past in Bristol cathedral.

Table 3. Acoustic parameters, spatially and spectrally averaged^a, measured for each source location

Source ID	T_{30m} (s)	EDT_m (s)	T_{Sm} (ms)	C_{80m} (dB)	D_{50m} (-)	STI ^b (-)	1-IACC _{Em} (-)
SN	4.58	4.36	316.62	-6.22	0.15	0.33	0.55
SE	1.51	1.40	97.94	1.30	0.44	0.53	0.83
SL	4.21	3.28	205.73	-2.02	0.32	0.41	0.74
SA	4.52	3.80	232.44	-2.48	0.29	0.40	0.59
SC	4.57	3.18	174.67	0.42	0.46	0.49	0.66
Acceptable values ^c	3-5	3-5	<300	> 0	> 0.3	>0.45	-

^a Arithmetically averaged for the octave bands established in the ISO 3382-1 [11]. The IACC mid values are averaged according to Okano et al [23].

^c These parameters are not listed in [11]. The STI was calculated from the impulse response, without considering the background noise

^b Acceptable values (for reverberation parameters vary depending on the use) considered for the discussion presented in this paper, based on previous subjective studies performed in similar buildings [24-28]

The EDT value shows that the perceived reverberation is greater in the nave than in the choir and the Eastern Lady chapel. Such results for the nave area might be due to the lower presence of early reflections in this part of the cathedral, where also the distance between the source-receiver positions is considerably larger than in the rest of the configurations. Furthermore, EDT_m values both in the choir and in the Eastern Lady chapel are considerably lower than T_{30m} values, which indicates a significant contribution of strong early reflections at some receiver points. This might be caused by the proximity of their position to the sound source or/and by the nearby hard reflecting surfaces that surround them.

The average values of T_S , D_{50} and STI show that it is in the nave where the congregation/audience experiences the most unfavorable acoustic characteristics in relation to speech perception. Contrastingly, in the Elder Lady chapel (SE), the acoustic conditions are more favourable for speech transmission than for any other zone in the cathedral and this is likely to be the reason way the chapel is currently used for spoken celebrations with no need of electroacoustic support. According to the mean values presented here, it is in the choir space, with the sound source located in the choir, where music is best experienced by listeners, since acceptable values of the clarity parameters are reached. The spatial impression is greater in the chapels, where highest values of the IACC_{Em} parameter are encountered.

This averaged values are useful to give a general idea of the acoustics in the different parts of the cathedral, but in order to evaluate these results in more detail, a point-by-point analysis is required.

Figure 5 shows the spectrally averaged values measured at each source-receiver combination, which vary significantly with distance. It is found that EDT_m values are significantly lower than T_{30m} values when the source-receiver distance is less than 15 m, except in the Elder Lady chapel. This suggests that early reflections have no significant influence in receiver positions located further than such distances from the source location, which implies, in general, poor transmission of the speech (T_{Sm} values higher than 300 ms, D_{50m} values below 0.2 and STI values rated as Poor/Bad) and poor music clarity (C_{80m} values under -6 dB) at those receiver points, which are mostly located on the hall nave. The values of these acoustic parameters calculated for those receiver points located closer than 10 m from the source,

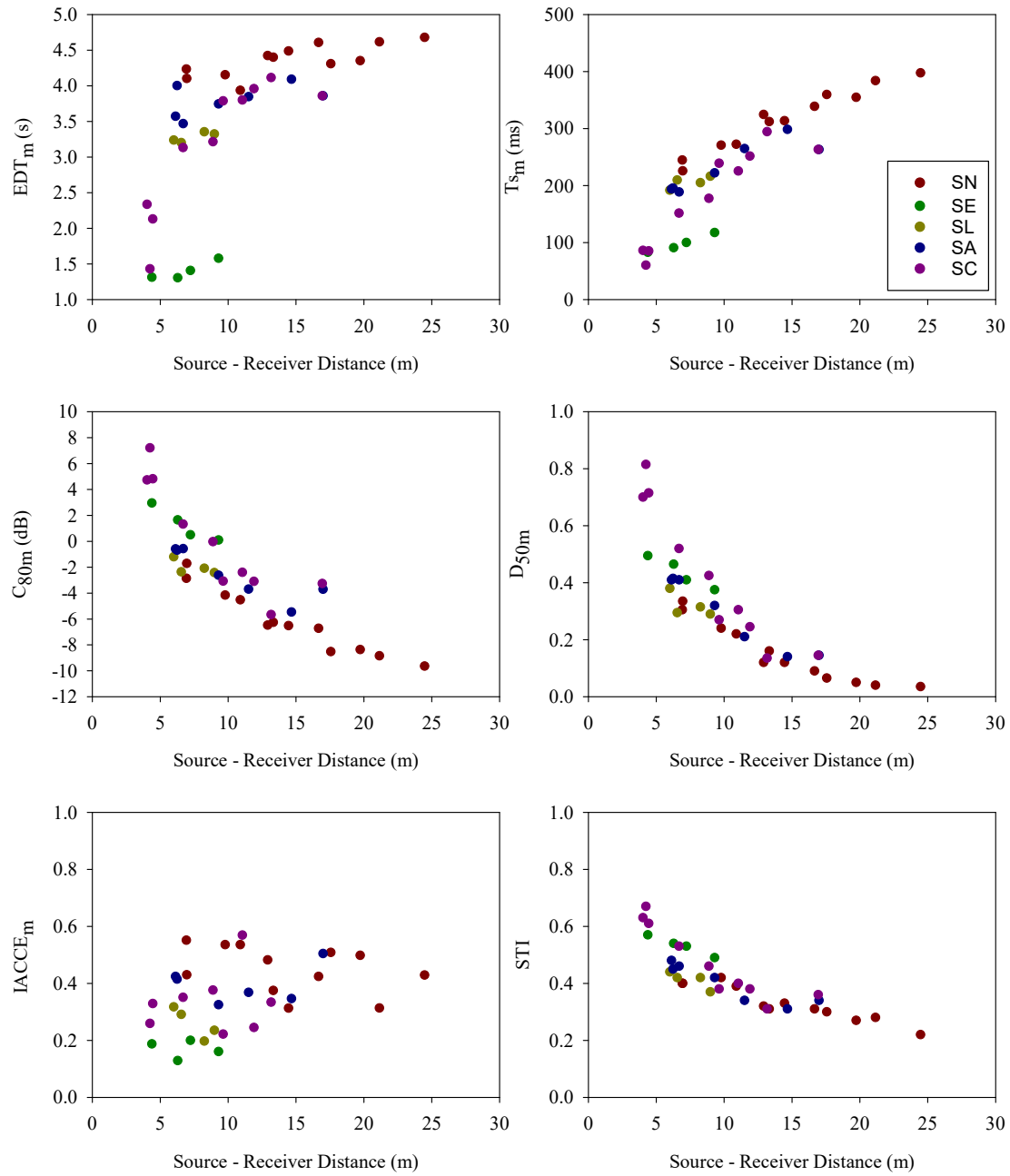


Figure 5. Acoustic parameter values, spectrally averaged, measured at each receiver point for each source-receiver combination in Bristol cathedral, as a function of source-receiver distance.

indicate more favourable acoustic characteristics both for music and speech, especially in the Lady chapel and the choir.

The spatial impression assessed with the values of the IACC_{Em} parameter doesn't show such a clear dependence with the S-R distance. According to the graph, it is in the chapels where the feeling of spaciousness and envelopment is greater. Nevertheless, IACC_{Em} values in the entire cathedral are of the order of those obtained in the best subjectively valued concert halls [29].

4. CONCLUSIONS

In this paper, the acoustic study of Bristol cathedral based on experimental acoustic measurements is presented. The study emphasizes the fact that the building offers different spaces, which, despite being part of a whole, offer different possibilities to experiencing the sound inside the cathedral.

Although the cathedral has a reverberation time of about 4.5 seconds at mid frequencies, which is high value that in general terms leads to a poor speech and music transmission within the space. It is worth noting that listeners' expectations in this kind of buildings are difficult to evaluate, since it is common to "hear" that the reverberant environment inside cathedrals helps visitors feel connected with the building [30]. The early decay time is strongly correlated with the subjective sense of reverberation and the lowest values of this parameter are found in the choir and the Lady chapel (around 3 seconds at mid frequencies) meaning that in these parts of the cathedral listeners experience a reverberation level lower than in the nave. This fact benefits the acoustic conditions for speech transmission in these areas, which is corroborated with the values obtained for the parameters related to speech transmission quality.

The acoustic characteristics of Bristol cathedral in terms of music perception are also important, since liturgical music, both vocal and instrumental, is an essential part of celebrations, and concerts are frequently held. In this respect, the low C_{80m} values (below -6 dB in nave) denote poor musical clarity when bearing in mind choral, chamber, and classical symphonic music. Nevertheless, several authors studied preferred T_{30m} values for organ music in churches [27,28], and suggested preferred values from 4 to 5 s. Furthermore, the characteristics of plainchant are well suited for the acoustics of the cathedral in terms of its more reverberant spaces, since plainchant is characterised by being monophonic and having slow melodic lines, and therefore, plainchant is often found more impactful when performed in spaces with long reverberation times [31]. In other words, the long reverberation time in spaces such as Bristol Cathedral gives the plainchant items sang a harmonic element that isn't present in the composition, because the notes from a plainchant are sang at the same time than the decay of the previous notes is still lingering in the space [32].

The Elder Lady Chapel is a singular space, working as a coupled-volume with the rest of the cathedral, which presents a much less reverberant environment, ideal for spoken celebrations.

The RIR measured in Bristol cathedral will be used for auralisation purposes in combination with a set of anechoic recording including a selection of extracts of speech and music pieces that represent the cultural and liturgical use of the cathedral over the centuries. Additionally, the data presented here will be used for adjusting a computer model of the building which will be used to simulate hypothetical scenarios based on research findings such as the presence of a large audience and/or relevant architectural changes in order to recreate the acoustics of the building through history.

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6. REFERENCES

1. A. Conticello, "Joint Programming Initiative: Cultural Heritage and Global Change: a new challenge for Europe", Crossroads of Europe, Pavia, (2012).
2. Ecorys. "*The economic and social impacts of England's cathedrals. A report to the Association of English Cathedrals*", (2014).
3. S. Girón, L. Álvarez-Morales and T. Zamarreño, "*Church acoustics: A state-of-the-art review after several decades of research*", Journal of Sound and Vibration, 411, 378-408, (2017).
4. P. Małecki, J. Wiciak and D. Nowak, "*Acoustics of Orthodox Churches in Poland*", Archives of Acoustics, 42(4), 579-590, (2017).
5. R. Suárez, A. Alonso and J. J. Sendra, "*Virtual acoustic environment reconstruction of the hypostyle mosque of Cordoba*", Applied Acoustics, 140, 214-224, (2018).
6. M. Sender, A. Planells, R. Perelló, J. Segura, and A. Giménez, A. "*Virtual acoustic reconstruction of a lost church: application to an Order of Saint Jerome monastery in Alzira, Spain*", Journal of Building Performance Simulation, 11(3), 369-390, (2018).
7. A. Alonso, R. Suárez, and J.J. Sendra, "*On the assessment of the multiplicity of spaces in the acoustic environment of cathedrals: The case of the cathedral of Seville*". Applied Acoustics, 141, 54-63, (2018).
8. A. Pedrero, R. Ruiz, A. Díaz-Chyla and C. Díaz, C. (2014). "*Acoustical study of Toledo Cathedral according to its liturgical uses*". Applied Acoustics, 85, 23-33.
9. B. N. Postma and B. F. Katz, "*Acoustics of Notre-Dame Cathedral de Paris*", In Proceedings of the International Congress on Acoustics, 11-13, (2016).
10. L. Álvarez-Morales, A. Alonso, S. Girón, T. Zamarreño and F. Martellotta, "*Virtual acoustics of the cathedral of Murcia considering occupancy and different source locations*", In Proceedings of Euronoise, 1949-1956 (2018).
11. ISO 3382-1, "*Acoustics-Measurement of room acoustic parameters, part 1: Performance rooms*", International Organisation for Standardisation, Geneva, Switzerland (2009).
12. F. Martellotta, E. Cirillo, A. Carbonari and P. Ricciardi, "*Guidelines for acoustical measurements in churches*", Applied Acoustics, 70, 378-388, (2009).
13. L. Álvarez-Morales, T. Zamarreño, S. Girón and M. Galindo, "*A methodology for the study of the acoustic environment of Catholic cathedrals: application to the Cathedral of Malaga*", Building and Environment, 72, 102-115, (2014).
14. D.T. Murphy, "*Archaeological acoustic space measurement for convolution reverberation and auralization applications*". In Proceedings of the 9th International Conference on Digital Audio Effects (DAFx), 221-226. (2006).
15. H. J. L. J. Massé, "*The cathedral church of Bristol: a description of its fabric and a brief history of the episcopal see*", G. Bell & sons, (1901).
16. F. Bond, "*The Cathedrals of England and Wales*", Jeremy Mills Publishing, (2007).
17. M. Fitzgerald, "*The story of Bristol cathedral*", Raphael Tuck & Sons Ltd., London, (1936).

18. J. Ross, "*The cathedral church of Bristol: historical and descriptive handbook*", The British Publishing Company Limited, (1949).
19. J. Harvey, "*Cathedrals of England and Wales*", Batsford. New Ed, (1974).
20. J. Cannon and B. Williamson, "*The Medieval Art, Architecture and History of Bristol Cathedral: An Enigma Explored*", The Boydell Press, Woodbridge, (2011).
21. <https://bristol-cathedral.co.uk/the-cathedral/brief-history/> (Last accessed on 28th February 2019)
22. F. Martellotta, L. Álvarez-Morales, S. Girón and T. Zamarreño, "*An investigation of multi-rate sound decay under strongly non-diffuse conditions: The crypt of the cathedral of Cadiz*", Journal of Sound and Vibration, 421, 261-274, (2018).
23. T. Okano, L. L. Beranek and T. Hidaka, "*Relations among interaural cross-correlation coefficient (IACCE), lateral fraction (LFE), and apparent source width (ASW) in concert halls*", Journal of the Acoustical Society of America, 104, 255-265, (1998).
24. A. Carvalho, A. Morgado and L. Henrique, "*Relationships between subjective and objective acoustical measures in churches*", Building Acoustics, 4, 1-20, (1997).
25. D. Sumarac-Pavlovic and M. Mijic, "*Preferred reverberation time of Serbian Orthodox churches*", Proceedings of 17th ICA, Rome, Italy, (2001).
26. Y. Ando, "*Subjective preference in relation to objective parameters of music sound fields with a single echo*", Journal of the Acoustical Society of America, 62, 1436-1441, (1977).
27. V. Desarnaulds, "*De l'acoustique des églises en Suisse – Une approche pluridisciplinaire*", Doctoral thesis, École Polytechnique Fédérale de Lausanne, Switzerland, (2002).
28. F. Martellotta, "*Subjective study of preferred listening conditions in Italian Catholic churches*", Journal of Sound and Vibration, 317, 378-399, (2008).
29. S. Cerdá, A. Giménez, R. M. Cibrián, S. Girón and T. Zamarreño, "*Subjective ranking of concert halls substantiated through orthogonal objective parameters*", Journal of the Acoustical Society of America, 137, 580-584, (2015).
30. <https://ecologyofthecathedral.com> (Last accessed on 28th February 2019)
31. L. Beranek, "*Acoustics and musical qualities*", Journal of the Acoustical Society of America, 99 (5), 2647-2652, (1996).
32. M. Forsyth, "*Buildings for Music: The Architect, the Musician, the Listener from the Seventeenth Century to the Present Day*". CUP Archive, (1985).