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# Mapping the acoustics of Ripon cathedral

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## ABSTRACT

Cathedrals are amongst the most significant buildings of European cultural heritage and are of great significance for the study of intangible heritage. This paper presents a detailed acoustic study of Ripon Cathedral, an English medieval cathedral whose history goes back to the 7th Century. Experimental and simulation techniques have been applied in order to develop a better understanding and preservation of the acoustic environment of Ripon cathedral. This research addresses the acoustical conflict inherent to this kind of spaces: its extreme reverberation builds a unique environment for vocal and instrumental music, specially organ music, but at the same time those same characteristics are a challenge for the intelligibility of the spoken word, which is crucial to the delivery of sermons. Acoustic maps have been created based on the diverse uses of the space, the history of the building, and its architectural features. Such maps have been used to analyse the acoustic characteristics throughout the cathedral's interior space. This work is part of the EC-funded Marie-Sklodowska- Curie Fellowship 'Cathedral Acoustics'.

Keywords: Church acoustics, Room impulse responses, Acoustic simulation

## 1. INTRODUCTION

*Cathedral Acoustics* is a project which aims to study the acoustics of a diverse sample of English cathedrals by focusing on four examples: Bristol, Ely, Ripon and York, which were chosen in relation to their historical classification, their ground plan typology as well as architectural style. The aim of the project is to study the current acoustic characteristics of the buildings through Room Impulse Response measurements (RIR) as well as work with computer simulations to study how structural, ornamental and usage changes would have affected the acoustics of the space throughout history.

Research on the acoustics of heritage sites is of the utmost importance for two main reasons. Firstly, it allows us to preserve the acoustics of the spaces which may be threatened by restoration work and allows us to store that information to help us preserve the intangible heritage of these buildings for posterity and to aid refurbishing work. Secondly, understanding how the acoustic conditions changed over time allows us to study what this might have meant for our ancestors, including how this may have affected changes in the use and experience of the space.

The present paper focuses on an initial study of Ripon Cathedral, which is conducted both through acoustic measurements as well as a computer simulation of the space. This preliminary study includes an overview of the methodology utilised, including the historical data that informed the measurement and simulation decisions and an analysis of the results based on reverberation time ($T_{30}$, EDT), musical clarity ($C_{80}$) and speech intelligibility (STI) parameters.

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## 2. RIPON CATHEDRAL

### 2.1 An overview of the construction process

The history of Ripon Cathedral dates back to the 7th century. The present building is raised over the oldest Saxon crypt in England (1), which was part of the original church of St. Wilfrid, which was erected on the site of the monastery of Ripon, founded by Scottish monks in the 660s.

Successive reconstructions and extensions have resulted in different architectural styles coexisting in the building. The construction of the present cathedral began in 1154 incorporating part of the oldest structure in Early English Gothic style. Subsequently, Archbishop Walter de Gray (1216-1255) continued the works by constructing the current west façade and the two towers that flank it, as well as the tall wooden spires and lead covers that once topped the towers. At the end of the 13th century, the eastern part of the choir was reconstructed in Decorated English style. The most important modification in the 14th century was the construction of the Lady Chapel over the Chapter House (2), which has now become the Cathedral Library. In the 16th century, the aisles were erected in Perpendicular style.

### 2.2 Description of the interior

As many other English cathedrals, Ripon cathedral has a Latin Cross shape, although in this particular case the single transept is only slightly longer than the nave width, as can be seen in Figure 1. The nave (41.7 meters long from the west doors to the transept) has two almost alike lateral aisles demarcated by Perpendicular-style gritstone pillars and a stone ribbed vault on top (3). From those pillars, the arches that hold the oaken vault that covers the central nave (at a height of 24.9 m) emerge. The nave, surrounded by stained glasses, is austere in decoration.

Notable is the "art nouveau" pulpit dated from 1913, which stands on marble pillars and has silver and bronze ornamentation. From the pew area of the nave it is possible to view the colourful stone carved Rood screen and the organ (Figure 2, left). Such a wide and closed screen serves as a sound and visual barrier, being originally raised to separate clergy from seculars (2). Beyond the screen is the choir, where many architectural styles meet: Norman–Gothic Transitional, Perpendicular, and Decorated. The carved oak choir stalls are surmounted by lofty canopies. The chancel area is 30.4 m long, from the screen door to the east window presiding the Main altar (Figure 2, right). The presbytery is separated from the lateral aisles by light wooden screens, except in the south part of the altar, where a stone sedilia is found.

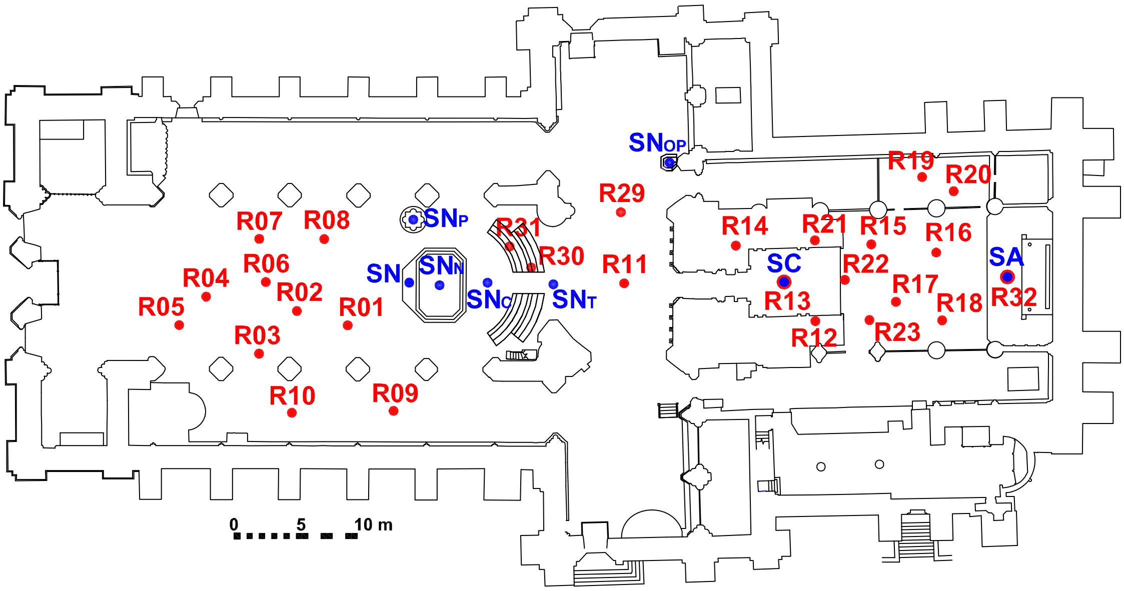


Figure 1 – Floor plan of Ripon cathedral with the source (S) and receiver (R) positions set for the acoustic measurements and the acoustic simulations.

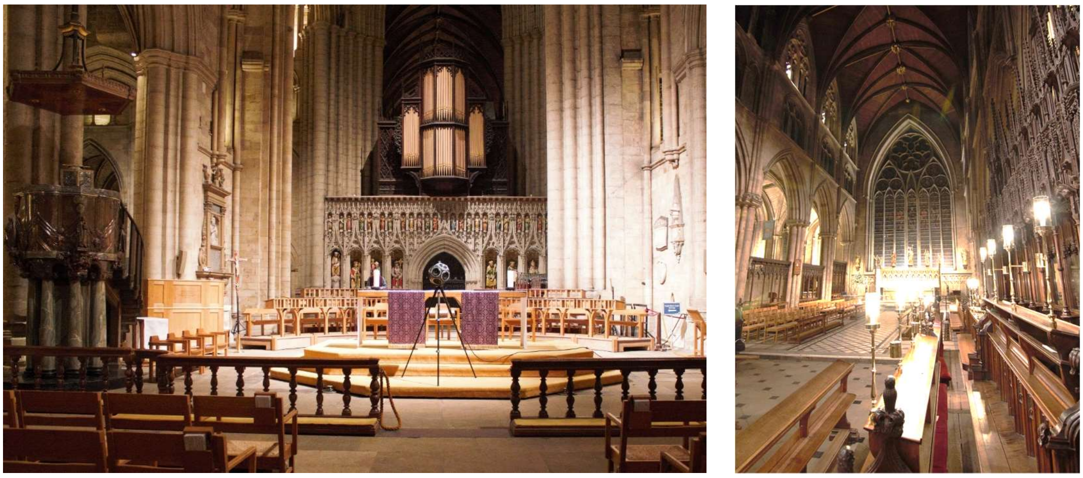

Figure 2 – Interior views of Ripon cathedral: View of the roodscreen from the main nave (left) and view of the east end wall from the choir stalls (right).

## 3. METHODOLOGY OF ANALYSIS

The acoustic study of Ripon cathedral presented in this paper is based on the analysis of the room impulse responses registered on site. Furthermore, simulation techniques are used to complete the analysis and create the acoustic mappings of the nave space.

### 3.1 Acoustic measurements

The acoustic measurements follow ISO3382-1 (4) as well as considering the specific guidelines developed for similar buildings (5,6). Sine-sweeps of a duration of 13 seconds covering a frequency range from 50 Hz to 16 kHz were emitted through a dodecahedral loudspeaker (NTi DS3 loudspeaker together with a NTi PA3 power amplifier) placed in multiple positions. Up to 31 receiver positions were chosen throughout the congregation area. For each source-receiver combination a set of RIR (Room Impulse Responses) were captured by using a B-format microphone (Soundfield ST450) and an artificial head (Neumann KU 100). The digital audio workstation Pro Tools 12 and MATLAB software were used to capture and process the signals respectively. EASERA software was used for the acoustic analysis and the calculation of the acoustic parameters. All the instrumentation and data analysis methods are ISO3382-1 compliant.

Source and receiver positions were selected based on the diverse uses of the space, the history of the building, and its architectural features. Ripon cathedral's interior is physically divided by the roodscreen, and therefore, the nave, the transepts and the chancel were characterised independently. Binaural and B-format RIR were measured at receiver positions from R01 to R11 and R29 to R31 with the sound source placed in the Nave's Altar (SN), where mayor liturgical celebrations and instrumental and choral concerts are held on a regular basis. In the chancel, receiver positions 12 and 10 were characterised with the source located in the choir (SC) and at the presbytery (SA), respectively. Figure 1 shows the floor plan of Ripon cathedral with source (S) and receiver (R) locations set during the measurement session. Although it would have been of interest to study the effect of sources located at the pulpit and at the lateral chapels, this was not possible due to access and time restrictions.

### 3.2 Acoustic Simulation

The acoustic simulation of Ripon cathedral was completed using the software CATT-Acoustic™ v9.1b powered by TUCT™ v2.0a (7). Simulations were run with TUCT *Algorithm 1: Short calculation, basic auralization* using *transition order 1*, with 300,000 rays. Source and receiver positions were simulated corresponding to the ones set during the measurements.

Due to the physical division of the space and for the purpose of this paper, the acoustic model has been simulated in two parts: on the one hand, the space formed by the nave and the transept, and on the other, the chancel. The openings that actually communicate both spaces, which cover a total area of 108 $m^2$ (green surface in the model, Figure 3), have been considered as an "open" surface with an absorption coefficient close to one at all frequency bands, i.e. almost total acoustic absorption. This decision was made to simplify the model and reduce the calculation time, having note that the number of rays that returned from the choir space to the nave during some preliminary tests was despicable in the sense that results of the acoustic parameter values at the S-R combinations analysed in the nave were not significantly affected by this simplification. Figure 3 shows the simplified acoustic model of the cathedral nave, which also includes the transept, used to carry out the acoustic simulation presented in this paper. The model has 2,836 planes and an approximate volume of 31,000 $m^3$.

The acoustic properties of each finishing material (represented by the different colours in the model) are given by the corresponding absorption and scattering coefficients (see Table 1). The initial absorption coefficients were obtained from the literature (8,9). The scattering coefficients were assigned depending on the complexity and the degree of decoration of each surface. For those surface materials whose absorption and scattering coefficients were more complex to determine, the research team worked on a careful tuning process that compared measured and simulated room impulse responses and acoustic parameter values in order to determine the most appropriate values. The porosity of the gritstone and the degree of decoration of some of the surfaces with this material, have required an increase in the values initially assigned according to bibliography (8). This uncertainty in the construction/finishing materials is inherent to these heritage spaces, and comparable results has already been obtained in similar buildings (10). Other finishing materials, such as the wooden vault, has also required a moderate adjustment at certain octave bands (See Table 1).

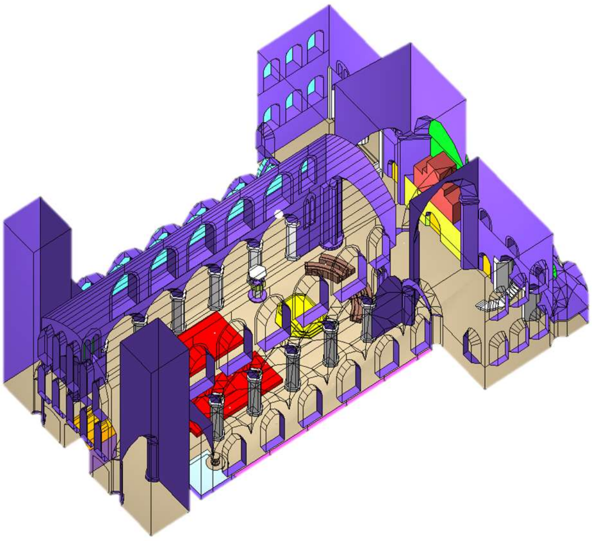

Figure 3 – Acoustic model of the nave of Ripon cathedral

Table 1 – Acoustic property of materials used in the acoustic model

| Material Name | Colour | Area (%) | Absorption/Scattering coefficients 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2kHz | 4 kHz |
|---|---|---|---|---|---|---|---|---|
| Gritstone walls | | 61.2 | 0.08/0.12 | 0.08/0.13 | 0.09/0.14 | 0.09/0.15 | 0.09/0.16 | 0.09/0.17 |
| Rough ceramic floor | | 10.8 | 0.02/0.10 | 0.02/0.10 | 0.02/0.10 | 0.02/0.10 | 0.02/0.10 | 0.02/0.10 |
| Wooden vault | | 5.1 | 0.17/0.10 | 0.17/0.10 | 0.10/0.15 | 0.10/0.15 | 0.10/0.20 | 0.08/0.20 |
| Stone ribbed vaults | | 4.5 | 0.08/0.20 | 0.08/0.25 | 0.09/0.30 | 0.09/0.35 | 0.09/0.40 | 0.09/0.45 |
| Gritstone pillars | | 4.3 | 0.08/0.20 | 0.08/0.20 | 0.09/0.30 | 0.09/0.30 | 0.09/0.40 | 0.09/0.40 |
| Stained glasses | | 4.3 | 0.18/0.10 | 0.06/0.10 | 0.04/0.15 | 0.03/0.15 | 0.02/0.20 | 0.02/0.20 |
| Wooden chairs | | 1.5 | 0.05/0.20 | 0.08/0.24 | 0.10/0.28 | 0.12/0.32 | 0.12/0.36 | 0.12/0.40 |
| Openings | | 0.9 | 0.97/0.10 | 0.97/0.10 | 0.98/0.10 | 0.98/0.10 | 0.99/0.10 | 0.99/0.10 |
| Wooden stalls | | 0.8 | 0.15/0.20 | 0.15/0.24 | 0.18/0.28 | 0.20/0.32 | 0.20/0.36 | 0.20/0.40 |
| Organ | | 0.7 | 0.14/0.20 | 0.14/0.25 | 0.14/0.30 | 0.14/0.35 | 0.16/0.40 | 0.16/0.45 |
| Limestone Roodscreen | | 0.4 | 0.04/0.30 | 0.04/0.35 | 0.05/0.40 | 0.05/0.45 | 0.06/0.50 | 0.06/0.60 |

The initial adjustment of the model is based on the $T_{30}$ values, following an iterative process so that the absorption coefficients of selected materials (mainly gritstone in this model) is carefully changed until measured and simulated spatially averaged values of reverberation time differs by no more than 5%, which is the minimum noticeable difference (JND) associated to this parameter (4). Once this first requirement is matched, other acoustic parameters are used for a "point to point" and "frequency band by frequency band" comparison of measured and simulated values, both in absolute values and in terms of their corresponding JND. In this case, EDT, $C_{50}$, $C_{80}$, $D_{50}$, and $T_S$ results have been included in the comparison. The model of Ripon cathedral's nave is considered adjusted with 76.7% of the measured and simulated results (considering all frequency bands) obtained for each source-receiver combination differing by no more than 2 JND, as generally recommended in room acoustic simulation (8), and with 91.2% of values differing by no more than 3 JND, which can be considered acceptable for these kind of buildings (6).

## 4. RESULTS AND DISCUSSION

Acoustic parameter values derived from the impulse responses registered on site evidence the differences between the acoustic environments of the nave and choir. Such difference is evidenced in the results for the reverberation time parameters.

The spectral behaviour of the reverberation time is shown in Figure 4. It can be seen that the $T_{30}$ in the cathedral nave is higher than in the chancel at all frequencies bands. The $T_{30m}$ ($T_{30}$ mid-frequency averaged) obtained in the nave (SN) is 4.3 seconds, which is above typical recommended values for a clear speech transmission, being nevertheless within the limits of the preferred values suggested by several authors for organ music and Gregorian chant (11,12). The 2.7 s measured in the chancel, both when the source is placed in the choir and at the presbytery, presumably denote a more suitable acoustic environment for the variety of the requirements of the space in terms of sound. However, caution needs to be exercised when referring to recommended values in relation to cathedrals as the perception of reverberation is strongly influenced by psychoacoustic and cultural factors, and the objective values recommended for the perception of speech and music can be at odds with visitors' expectations. For example, Carvalho (13) published a comparison between two identical chapels but with different acoustic treatments, and that paper pointed out that users preferred the more reverberant chapel, objectively less suitable for the transmission of the word, because they were used to the traditional reverberant acoustic environment of Portuguese churches.

The perceived reverberation is better assessed with the Early Decay Time parameter. $EDT_m$ measured values, when frequency averaged, reveal that the perceived reverberation does not significantly vary with the relative position of the listener, neither in the nave nor in the chancel. The exceptions are those receivers located in the choir stalls when the sound source is placed in the choir (SC), whose EDT values are lower than in the rest of the choir, mainly due to their closeness to the sound source (S-R distances lower than 5 m). Results also pointed out that, when the source is placed in the nave (SN), the perceived reverberation in the transept is higher than in the nave (in Figure 4, see the two points at about 17.6 m from the sound source, corresponding to R11 and R29 in Figure 1, showing a $EDT_{mid}$ of almost 5 s). Obtaining EDT values higher than those obtained for $T_{30}$ in receiver positions at that distance from the source is unusual, and may be due to some strong early reflections presumably coming from the roodscreen.

In terms of sound clarity, in this particular paper we have focused on assessing music through $C_{80}$, and speech intelligibility through the Speech Transmission Index, STI. Further analysis in relation to other parameters will be conducted in future studies. Figure 4 shows $C_{80}$ values, spectrally average, and STI measured at each source-receiver combination. If the attention is focused on the values obtained from the impulse responses measured in the chancel, both with the source located in the choir (SC) and in the presbytery (SA), it can be seen that measured values denote acceptable/good acoustic conditions both for music ($C_{80m}$ > -5dB) and for speech transmission (STI > 0.45 except for those positions located furthest from the sound source, with a S-R distance > 15 m). Similar results are obtained in the nave regarding clarity of music, although, in general, low values of $C_{80}$ parameter are registered when the S-R distance is greater than 15 m. However, STI values rated as *poor* are measured in all those receiver positions located more than 8.5 m apart from the sound source (SN), which means a poor quality of the transmission of the word in large part of the audience area when no PA system is used.

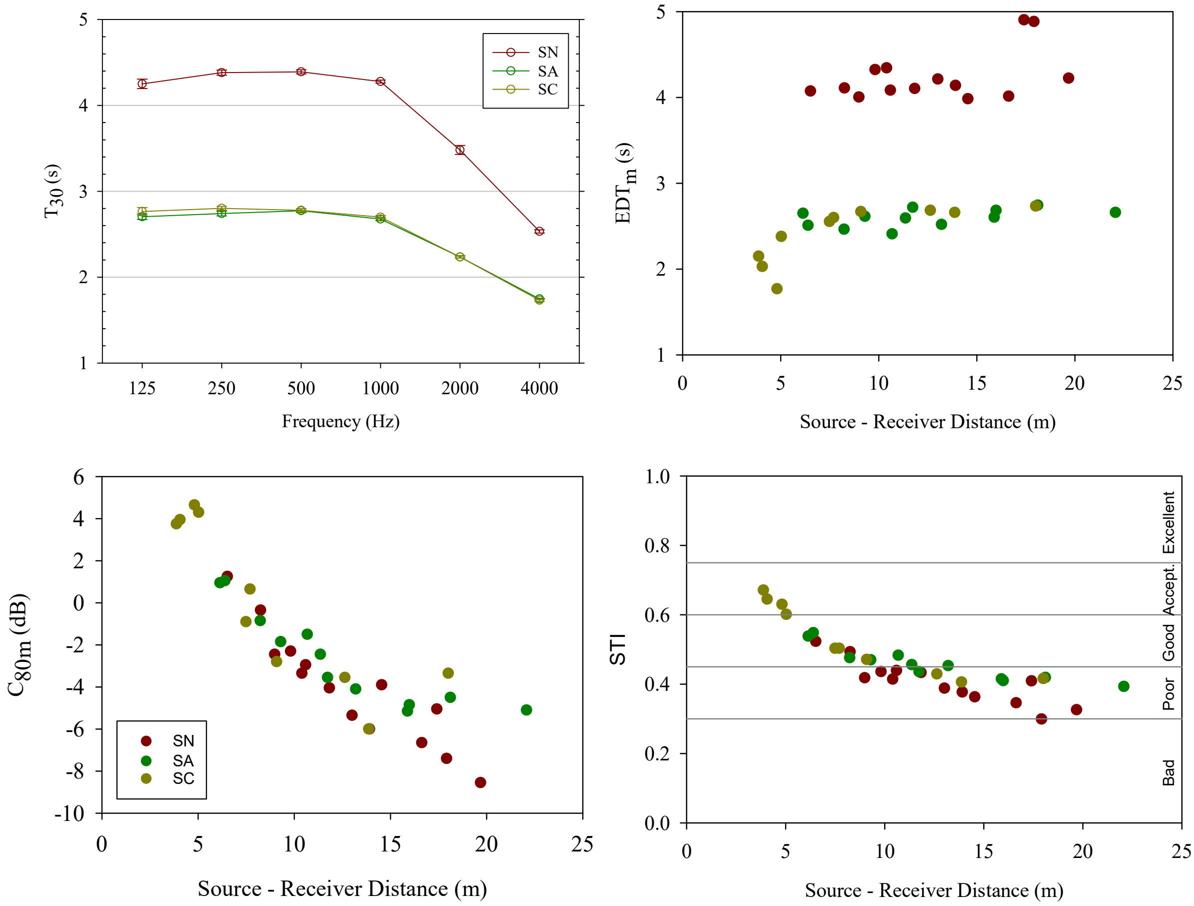


Figure 4 – Reverberation time measured values, spatially averaged, for each frequency octave band (upper row, left); EDT values, spectrally averaged, (upper row, right), measured at each source-receiver combination; $C_{80}$ values, spectrally averaged (lower row, left) measured for each source-receiver combination; and STI (lower row, right) measured for each source-receiver combination.

## 4.1 Acoustic mapping of the nave

In addition to the initial acoustic analysis reported above, further analysis of the acoustics of the nave of Ripon cathedral was conducted using acoustic simulation techniques. The use of the simulation models allows a greater level of detail by extending the acoustic analysis through the whole audience area (previously limited to the receiver points set during the measurements) and including more source receiver positions which were not included in the measurements mainly due to access or time limitations.

The cathedral nave is where major celebrations and cultural events are normally held. There are 4 positions where the sound source is commonly placed for those events (See Figure 1). Speech-based events use the pulpit ($SN_P$) and the nave altar ($SN_N$) as part of the daily service, nowadays, using an electroacoustic support system to be able to reach the audience seated in the chairs furthest from the altar. Behind the altar there are choir stalls ($SN_C$) in which the choir members are located when accompanying the service and the musicians are placed during the concerts held in the nave. Moreover, the transept ($SN_T$) is time to time used for small meetings and talks. All the furniture (with the exception of the pulpit) is removable to be able to adapt the configuration of the altar space to the different activities held in this part of the cathedral. In addition, the 15th century stone pulpit located in the south transept, next to the rood screen, has been included as another sound source position ($SN_{OP}$) since apparently has been exceptionally used for sermons.

Mappings were generated by using TUCT, with the suggested number of rays (99000 rays) and suggested echogram length based on T30 values. Map step was set as default (1 m) and the map height was set to get 1.20 m from the floor. Figure 5 shows the acoustic maps of $C_{80}$ parameter at 1 kHz,

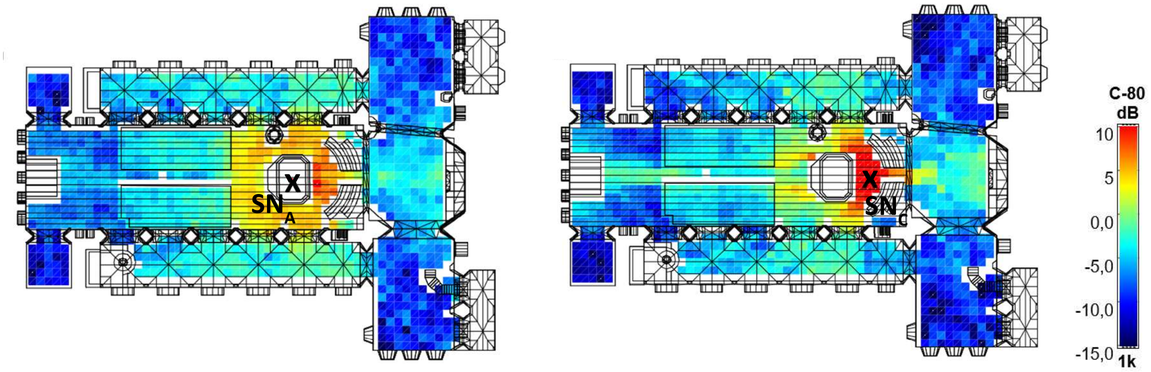


Figure 5– $C_{80,1kHz}$ acoustic maps of Ripon cathedral nave with the sound source located in the altar nave, $SN_A$ (left) and in the choir stalls, $SN_C$ (rigth).

obtained from the acoustic simulation. $SN_A$ and $SN_C$ have been considered in this case, as representative sound source positions from where the music involved in liturgical and/or cultural activities held in the nave is mainly performed. It can be seen how acceptable values of $C_{80}$ are reached in the areas of the central nave and in the lateral aisles where audience/congregation is commonly located during major celebrations and concerts.

Figure 7 shows the acoustic mappings of the STI generated to assess the perception of speech in this part of the cathedral. Same conditions were used for all the STI estimations: Background noise NCB28, emission level of the sound source 94 dB SPL 1 KHz. Regarding the nave, it can be seen that only in the altar space and in the closer positions in the chairs of the central nave, both for $SN_P$ and $SN_A$, values of STI rated as *fair/good* are reached. These results support the need to use an electroacoustic support system to achieve a clear transmission of the speech even in the positions furthest from the source, and especially if the background noise is higher. The use of electroacoustic support is less critical when the activity takes place on the transept, as long as the audience/congregation is not placed too far from the sound source position, limiting the audience area to the central part of the transept for $SN_T$, and avoiding the south transept when $SN_{OP}$ is used.

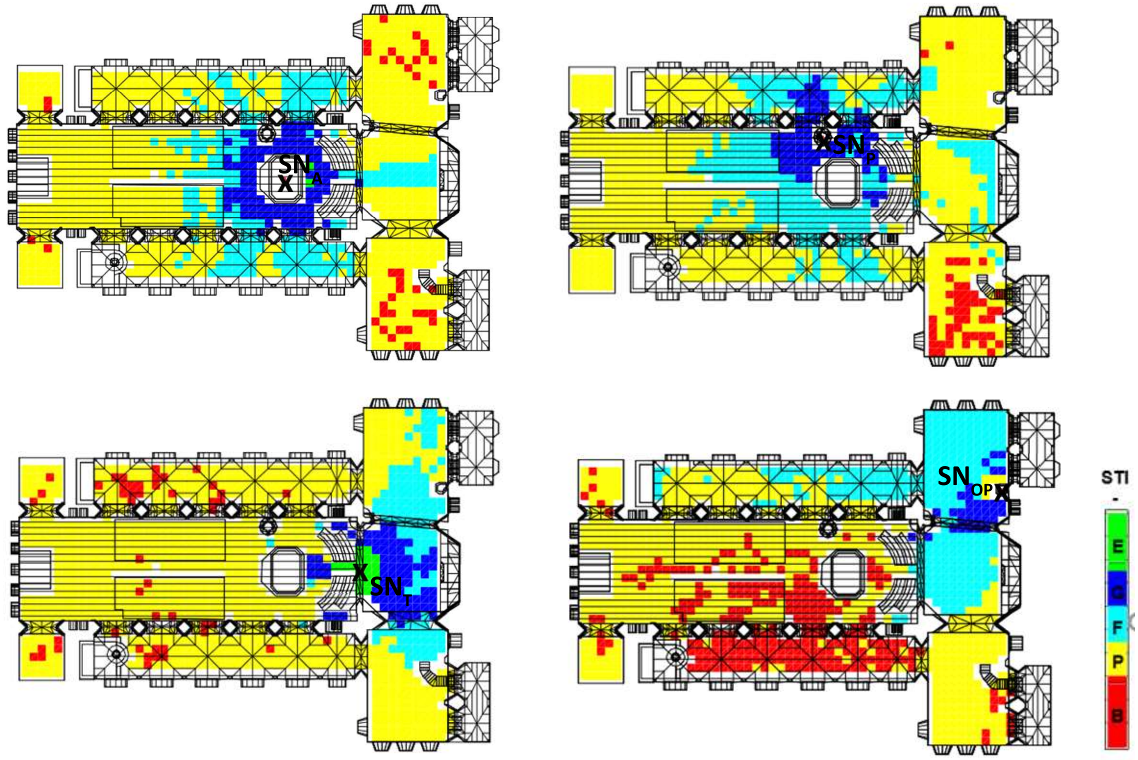


Figure 7 – STI acoustic maps of Ripon cathedral's nave and transept with the sound source located in the nave altar, $SN_A$ (upper row, left); in the pulpit, $SN_P$ (upper row, right); behind the choir stalls of the nave, $SN_T$ (lower row, left), and in the old pulpit, $SN_{OP}$ (lower row, right).

## 5. CONCLUSIONS

This paper summarised an initial acoustic analysis of Ripon cathedral performed as part of the Marie Skłodowska-Curie project *Cathedral Acoustics*. The aim of this work was to analyse the acoustic field of the space, evaluating it in terms of the perceived clarity of sound, both for music and speech transmission, attending to the great variety of uses and spatial configurations that this complex building allows.

It is not the purpose of the paper to judge how users experience the acoustic environment of the cathedral, but the influence the building has on the quality of sound depending on the use and the configuration of the space. The first peculiarity of this cathedral, is that the physical separation between the nave and the chancel, makes them behave like two acoustically semi-independent spaces, with different reverberation times (4.3 and 2.7 respectively). In view of the results of the measurements and the simulations, the nave is a magnificent place for music performances, although apparently it is too reverberant for a good transmission of speech without the use of any electroacoustic support (STI rated as poor for the majority of the audience area).

A less reverberant acoustic environment, more suitable for speech transmission and non-ecclesiastical music performances, is apparently experienced in the chancel, where acceptable values of $C_{80}$ and STI are reached in the majority receivers included in the study.

A more in-depth acoustical analysis through the acoustic measurements and also through the acoustic simulation will be conducted.

## ACKNOWLEDGEMENTS

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