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Acoustic characterization of Cathedral of Santiago de Compostela

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ABSTRACT

The Cathedral of Santiago de Compostela is one of the most important buildings of Romanesque art in Spain and is also the end of the pilgrimage of the Camino de Santiago, religious and cultural tradition that dates back to the 9th century. The cathedrals of pilgrims (Santiago, Vatican and Jerusalem) have special characteristics due to the continuous walking of the pilgrims in the churches. The Cathedral of Santiago has currently had different architectural performances to ten centuries and along with its initial Romanesque structure (basilical Latin cross plan with three naves and an apse chapels) have appeared elements basically Baroque (dome, altar, baldachin, chapels). Measurement and characterization of the Cathedral of Santiago had not been addressed previously and at the same time this work has been the collaboration of three research teams from 4 universities (Polythecnic University of Madrid, Uniersity of A Coruña, University of Seville, Polythecnic University of Bari). This work is going to expose the results of acoustic parameters for the characterization of the Cathedral from the measurement of impulse response in different configurations of source-receptor, obtained by GAMMA (UPM-UDC) research team. The results of temporary parameters, energy parameters, spatial parameters and parameters of intelligibility will be presented. The different parameters obtained have been divided into four zones with well differentiated acoustic characteristics and also related to the different liturgical uses that takes place in the Cathedral. Acoustic parameters have been analyzed both according to the frequency and the distance from the source. The results obtained by the GAMMA team will be subsequently compared with the other teams and will serve as a basic element for the calibration of virtual models of the Cathedral.

Keywords: Acoustics, Parameters, Cathedral
I-INCE Classification of Subject Number: 25

1. INTRODUCTION

This work contains some of the measures that were carried out in the Cathedral of Santiago de Compostela during the month of June 2018. This work was done by three research groups from four different universities (Polythecnic University of Madrid (UPM), University of A Coruña (UDC), University of Seville (US) and Polythecnic University of Bari (PB)). The idea of the three groups was to obtain acoustic measurements of the Cathedral of Santiago, and this measurement and different equipment, different systems were used in order to carry out comparative studies of the results in the future.The purpose of these instructions is to ensure the uniformity of the publication.

The part of the work that will be exposed in this paper corresponds to the measures carried out by the Group GAMMA (UPM-UDC) and further treatment and extraction of acoustic parameters of the Cathedral.

Previously we have to explain the situation in which measures were conducted in May 2018 (the administration of the Cathedral of Santiago allowed our access from 21:00 hours on 21 may at 0700 hours on 22 May). The Cathedral was in the process of reforms and several areas were affected. It was restoring upper zone of the main altar and the dome. These two areas were covered by scaffolding and protective fabrics. The final stages of the restoration of the painting of the sculptural group of the Pórtico de la Gloria were also performed. In this case, there was a physical separation of the last area of arches of the nave by a screen of vinyl, which closed the final part of the Cathedral

(including the Portico) and means a reduction of the total volume of the Cathedral. This initial explanation is interesting to take it into account for future work that was carried out in the Cathedral in the final months of 2018.

2. THE CATHEDRAL OF SANTIAGO DE COMPOSTELA: HISTORICAL AND ARCHITECTURAL DESCRIPTION

The Cathedral of Santiago de Compostela is home in his crypt, beneath the main altar, the urn that holds the relics of Santiago the greater, whose discovery, towards the year 820-830, in that same space, gave rise to one of the three great centres of pilgrimage Christian history, with Jerusalem and Rome.

We have one of the best known and admired in the world, both for its architectural and artistic heritage - an effective combination of Romanesque and Baroque styles, among others - as for its history, being the end of the Camino de Santiago, the more spiritual path long-lasting and living in the West, originated in the 10th century.

This unique building is successor of others earlier that served to House and to dignify the remains of the Apostle discovered in "Compostela" (“campo de estelas”) at the beginning of the 9th century, as the churches which at different times was sent to build the Kings Alfonso II, Alfonso III and Bermudo II. Numerous archaeological remains have been found of this pre-Romanesque church and detail the construction of a basilica with three naves and a great header.

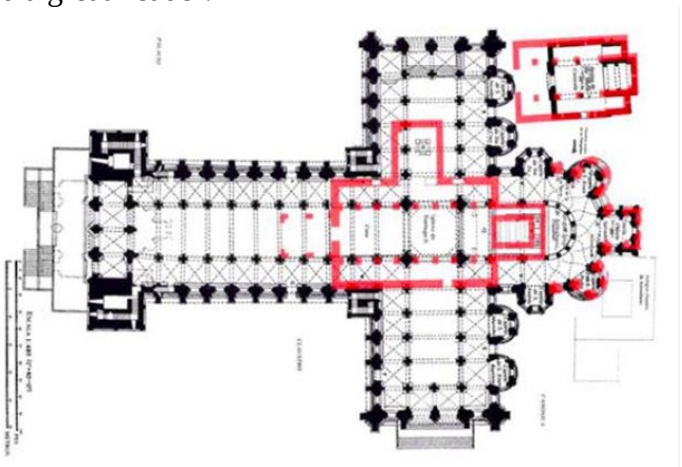


Figure 1. Original Basilica (in red) over the actual plan of the Cathedral[1]

The construction of the great Cathedral of Santiago de Compostela should begin around the year 1075 during the reign of Alfonso VI, Bishop Diego Peláez-sponsored and directed by the master Bernardo el Viejo and master Esteban these early stages were developed between the years 1075 and 1100. From the year 1100, under the mandate of Archbishop Gelmírez, continues the works by the master Bernardo, the younger (master of Platerías) will move throughout the 12th century. We can say that most of the Cathedral was finished in 1122. In 1168 the master Mateo, completed the cathedral, including the West facde, the Pórtico de la Gloria, the crypt under the Western façade and the construction of the choir in the main nave, so that in 1211 was celebrated the consecration of the Basilica with the presence of king Alfonso IX.[2]

Also during the 13th century the Romanesque towers of the Obradoiro on both sides of the western façade, was built the medieval ciborium disappeared or the Romanesque choir, and completed the sculptures of Platerías and Azabachería and is continued work in the upper part of the main façade.

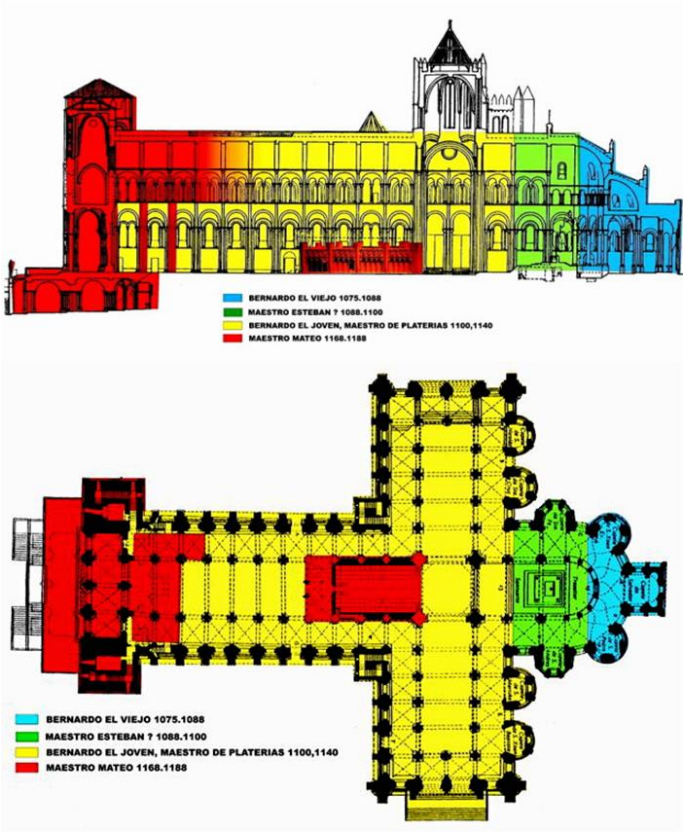


Figure 2. Evolution of the construction of the Romanesque cathedral during 13th and 14th centuries

During the 14th century the dome will be rebuilt and some defensive towers will rise. In the 15th century are important actions on the façade of Obradoiro with the replacement of Romanesque rosette window by a large stained glass window rosette also builds the first cloister in Gothic style. In the 16th century modifications are performed in the cloister and is rushing the construction of various Episcopal buildings. In the 17th century works of the construction of the monumental stairway that we know today and the brackets against the Bells Tower (South). Also built the Clock Tower in order to stop the inclination that this tower to cause of being greater than the North and less consolidated. In the interior of the Cathedral is designed the baldachin that was created to enhance the high altar, framework of veneration of the apostle. In the 18th century is the construction of the new facade of Obradoiro[3].

At the level of interior architecture, we can highlight that the Cathedral is set in the form of basilical Latin cross, with three naves and a wide transept also divided in three naves, with four apses. The head of large size, with ambulatory and five apses. The most original element in this Basilica area, and it extends by the Cruiser, is the existence of a clerestory or second floor, running through the aisles of the Basilica space, continuing the aisles in the transept and the own ambulatory, until goes across the cathedral. All these chapels, united to the triforium, allowed a wide range of spaces and made possible the simultaneous worship celebration, as it was suitable for a pilgrimage church. Also originally had eight towers: west-facing façade, the transept and Confluence space Basilica-transept facades. The dimensions of the Cathedral are 100 meters the length of the basilica, 70 meters in length of the transept, 8.3 meters in width in the nave and transept, 4.3 meters width in the aisles, 22 meters high central nave and 32 meters high on the cruise.

Figure 3. Flat side of the Romanesque cathedral and the present Cathedral[3]

3. ACOUTICAL MEASUREMENTS

The previous work of the three research groups was carried out according to the proposals made by Martellotta[4]. Based on the recommendations contained in that publication, it was decided to develop the following method to the analysis of the Cathedral which can be broken down into the following phases, which have taken place chronologically in the following order:

- Taking of general and planimetric data.
- Decide positions for sources (3) and receivers (25) in the Cathedral.
- Realization of acoustic measurements in situ, processed and acoustic assessment.

For the realization of the measures has been followed the standard ISO 3382[5] and have been taken into account the choice of the positions of the source, the choice of positions of the receiver and the equipment to be used.

3.1 Source positions

Analysing the formation of the Cathedral, it was decided to locate sound sources in the following positions: (S1) Main altar, pulpit (S2) and modern altar (S3). In the two first positions the sound source should be placed in the axis of symmetry. In the pulpit, the source should be placed as close as possible to the balustrade to simulate the natural position of the priest. A source of Omni-directional type will be used in all cases.

3.2 Receiverpositions

A general rule to be followed is that recipients are preferably located in the main listening area (MLA), although for churches this area is much less than in areas of interpretation defined. In fact, in many churches (especially the very large) the area occupied by banks or seats may vary depending on the period of the year with the largest area observed during the major holy days. In addition, should also be considered that the people standing are not unusual in churches. Consequently, for the purpose of acoustic measurements, the MLA must be defined as the combination of the largest area covered by banks and the area that is most likely to be occupied by standing. However, the definition of the optimal location of receivers (able to guarantee a precise description of the variations of acoustic parameters) cannot be solely based on practical considerations; they must take into account the actual distribution the sound in the space. To scientifically define such rules, were statistically analysed the results of acoustic measurements in several churches[6].

3.3 Source-receiver configurations

Following is the configuration of sources and receptors on the plan of the Church. The sources were 1.7 m height and the receivers were 1.2 m height. 3 positions of source - in green-(new altar, ancient altar and right pulpit) and 23 positions of receiver –

in red-(12 in the main nave, 5 in the transept, 4 in the area of the altar-choir and 2 in the ambulatory). Of the 23 positions, only recorded data 18 of them due to problems of time, only could get to having to use the same sound source to the three teams.

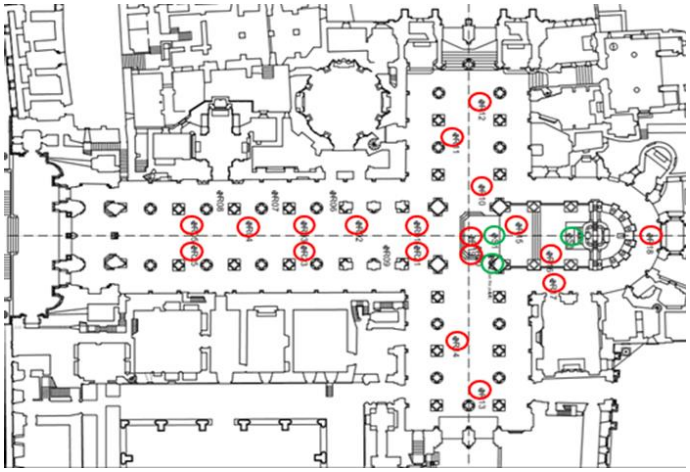


Figure 4. Source and receptor positions

The measures that will be exposed below are those obtained by the GAMMA Group (UPM-UDC). In this case was used as a sound source a dodecahedron AV-12[3], a CROWN 2500 power amplifier, an omni-directional microphone AKG C-92, a figure of eight microphone, AKG C-91 (both mounted on a double support), a MOTU UltraLite-mk4 soundcard and an acquisition measure system DIRAC v6.0. We also used a sound level meter for measurements of ambient noise and a meteorological station for the determination of the environmental values (temperature, pressure and relative humidity). The measures were developed between 00 hours and 07 hours of May 22, 2018. Measures of groups of Bari and Seville, as well as comparisons of values obtained by the three teams are expected to present them in the near future.

Acoustic parameters have been obtained from the measurement of impulse response for each source-receptor combination. The encoding that has been used for each combination has been e.g. S01R01 (source 1-receptor 1). The signal of excitation of the dodecahedron was exponential sweep of pure tones from 20 Hz to 20 kHz with duration of 21.3s[7]. The amplification of the sound card and amplifier of power set has remained constant throughout the process of measurement, checking previously adequate signal-to-noise ratio and not producing saturation in any combinations of source-receptor.

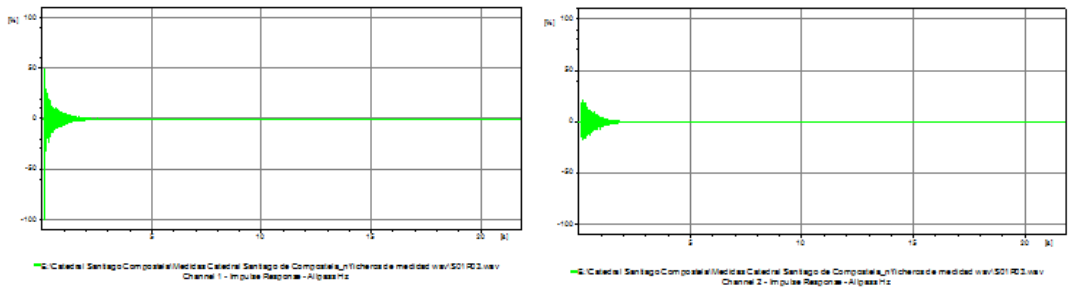
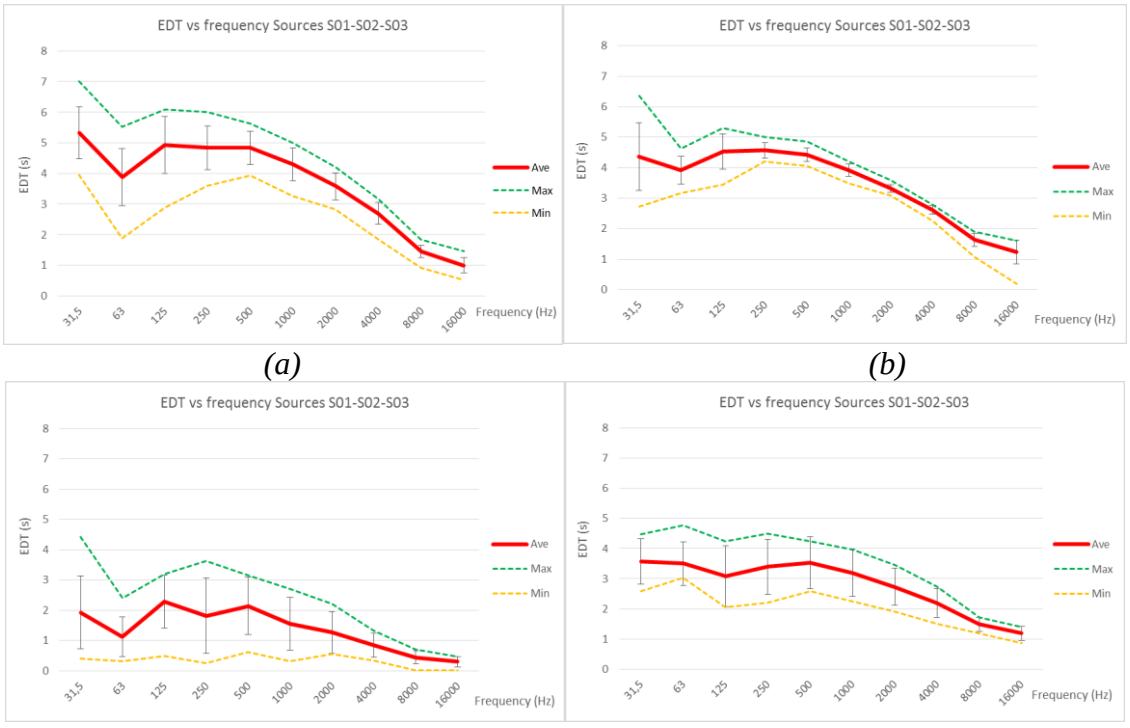


Figure 5. Impulse response of both mocrophones

It will present the results of three temporary parameters (EDT, T20, T30), four energy parameters (D50, C50, C80, Ts), a parameter space (LF) and two parameters of intelligibility (AlCons, STI). The parameters were calculated in bands of 1 octave and 1/3 octave bands. The results presented correspond to values in 1 octave bands between 31.5 Hz to 16 kHz.

When we started to process data, it was found that there were significant differences between the positions occupied by the receivers in the Cathedral and it was decided to carry out a study to separate areas of the Church according to the liturgical use of the same. Thus it was decided to divide the Cathedral in 4 zones: that we have referred to as *main nave* (R01, R02, R03, R04, R05, R21, R23, R25 receiver positions); *transept* (R10, R11, R12, R13, R14 receiver positions); *altar-choir* (R19, R20, R15, R16 receiver positions); *ambulatory* (R17, R18 receiver positions). For each of the above areas, it has conducted a study separately with each source (S01, S02, S03) and the average of the three sources. There has also been a comprehensive study of all the sources and all the receivers.

Below are some of the results of some of the parameters listed above.

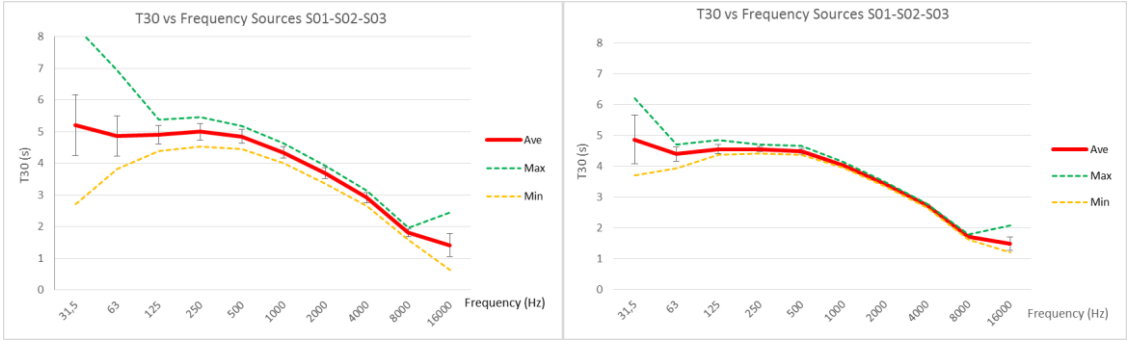


(a) *(b)*

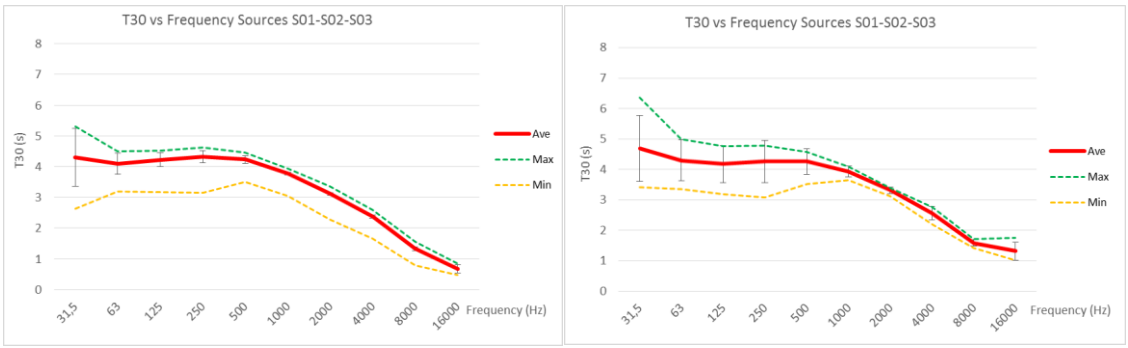
(c) *(d)*

Figure 6. EDT (a) main nave; (b) transept; (c) altar-choir; (d) ambulatory

It could be seen that the values of EDT in the main nave and transept are quite similar and decrease in the ambulatory and especially in the altar-choir. This decrease in the area of the altar-choir is due to the special configuration of the area with a baldachin of less height than in the rest of the Church and the presence of windows that separate this area from the ambulatory virtually in its entirety. Also the presence the scaffolding and protective fabrics in this area affect the perception of the early reverberation.

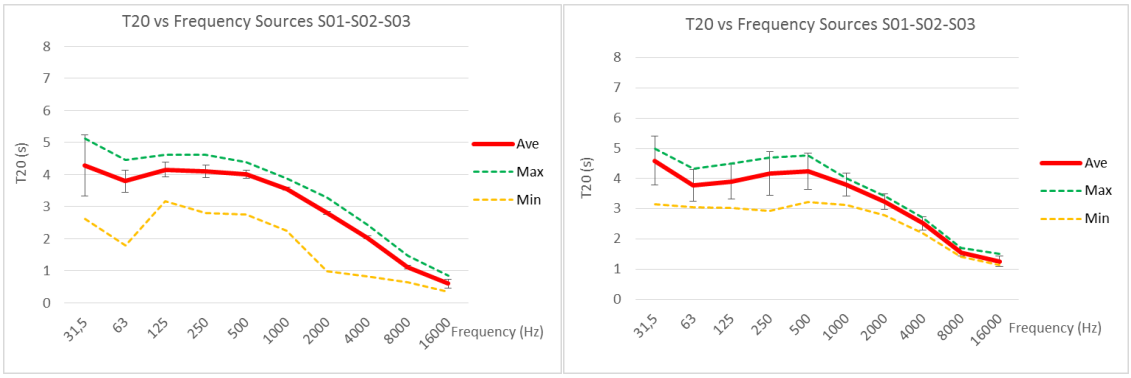


(a) *(b)*



(c) *(d)*

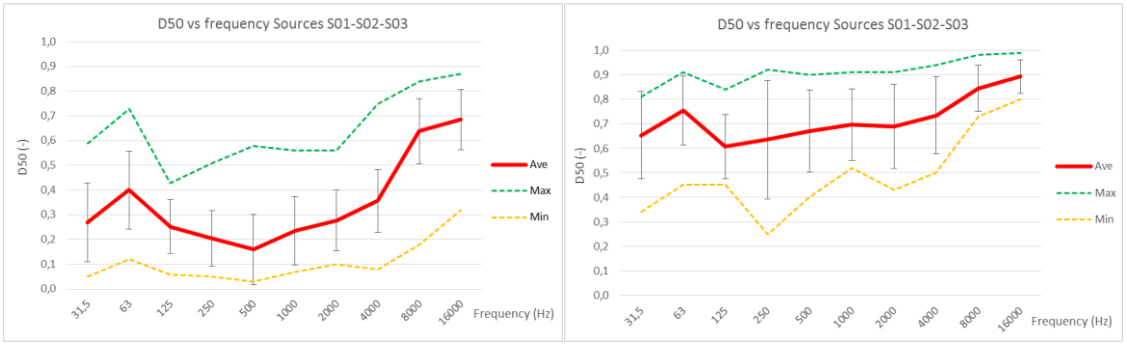
Figure 8. T30 (a) main nave; (b) transept; (c) altar-choir; (d) ambulatory



(a) *(b)*

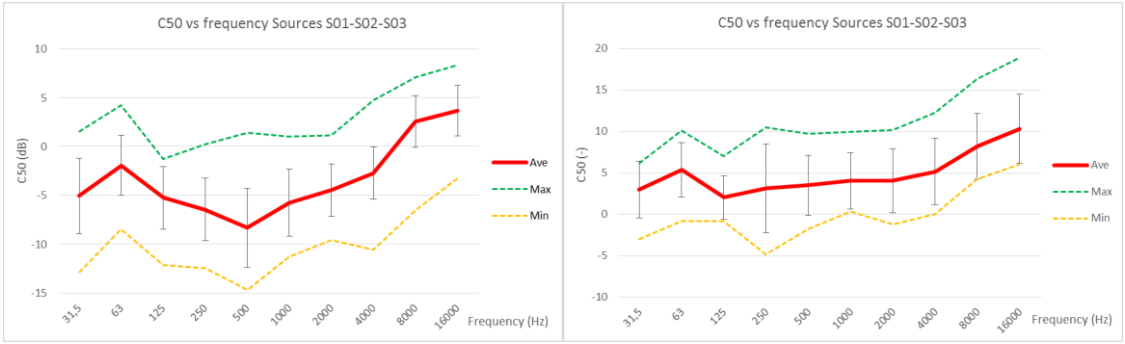
Figure 8. T20 (a) altar-choir; (b) ambulatory

Variations of the T20 and T30 reverberation time are not as accused in the areas of altar-choir and ambulatory to be an estimation of reverberation in one period of a little more than EDT.



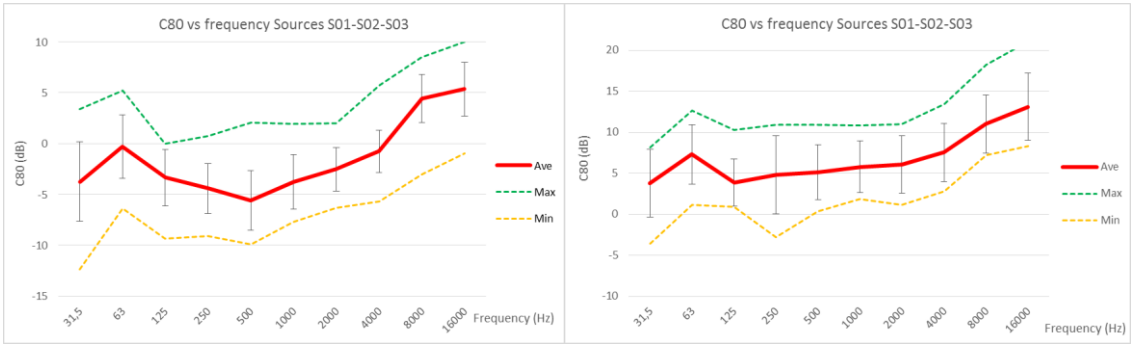
(a) *(b)*

Figure 9. D50 (a) main nave; (b) altar-choir



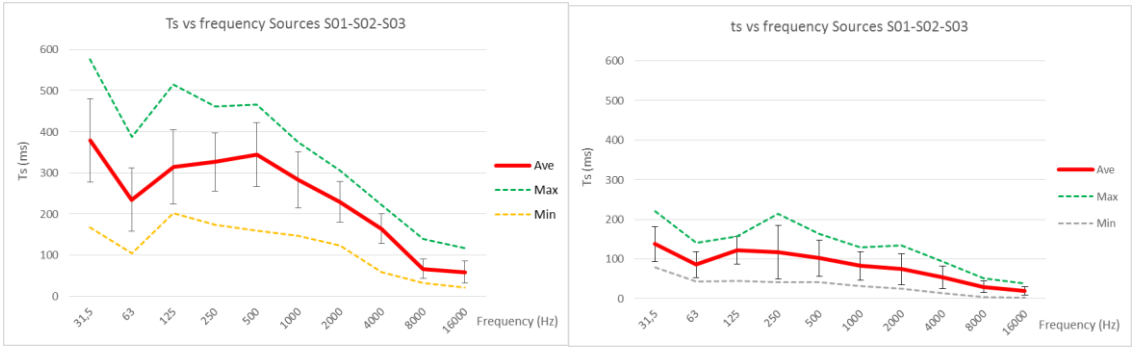
(a) *(b)*

Figure 9. D50 (a) main nave; (b) altar-choir



(a) *(b)*

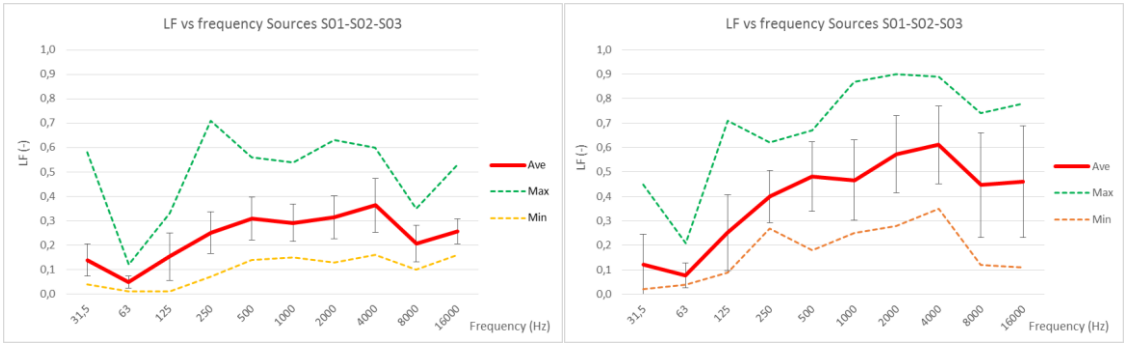
Figure 11. C80 (a) main nave; (b) altar-choir



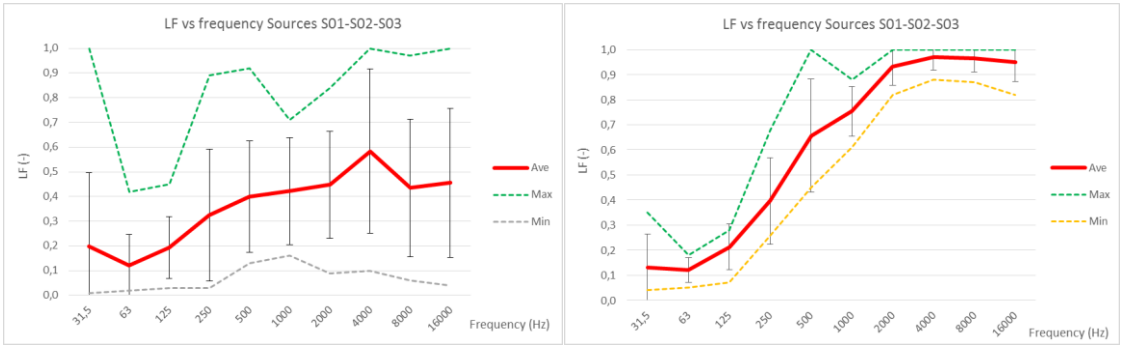
(a) *(b)*

Figure 12. Ts (a) main nave; (b) altar-choir;

With regard to the energy parameters of definition and clarity, very low values can be seen in areas of central nave, transept and ambulatory (without too many differences but with values lower in the ambulatory) and otherwise very good values in the area of altar-choir. This will be decisive in the perception of greater amount of direct field in the area of the altar-choir which will assist the intelligibility in this area against the other three. The same could be seen in the case of the value of central time Ts, with a value low in the zone of altar-choir and very high values in the nave and transept, and intermediate in the area of the ambulatory.



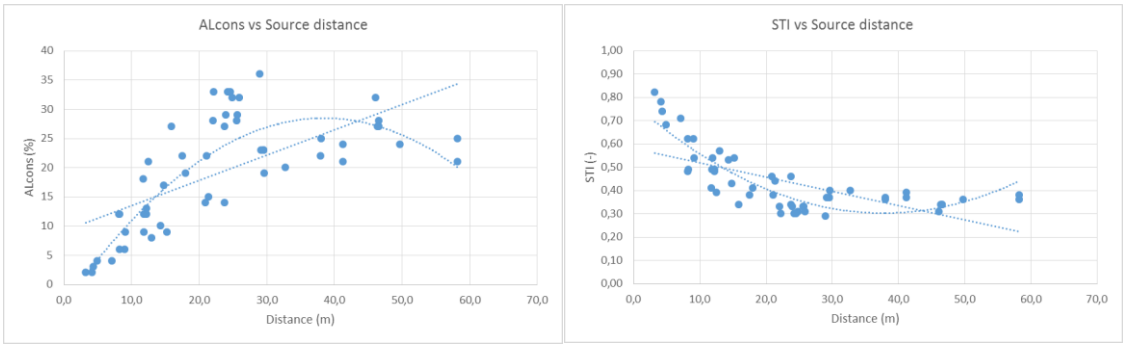
(a) *(b)*



(c) *(d)*

Figure 13. LF (a) main nave; (b) transept; (c) altar-choir; (d) ambulatory

The fraction of energy side LF, is relatively high in all areas, lower in this case in the main nave because of the same length and the low reflection angles occurring in the arcades and aisles, with its position of sound sources LF is increased in the area of the transept due reflection angles greater than in the central nave. In the area of the altar-choir increases a little less, but also high due to the multitude of reflection both in the altar, baldachin and the side windows. The values are very high in the area of the ambulatory the practical absence of direct field at reception points.



(a) *(b)*

Figure 14. All receivers (a) ALcons; (b) STI

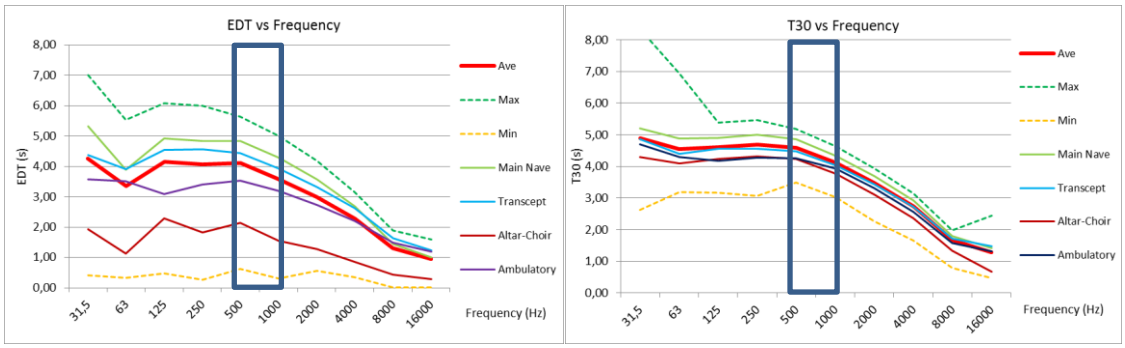
Parameters related to the intelligibility are really bad except in the area of altar-choir.

Also, the average values of the above parameters in the bands of midrange (mid) for all source-receiver configurations have been calculated in order to have comparable values with others obtained in the literature[8,9].

Table 1. Average mid values with all sourece receivers configutations

	EDT_{mid} (s)	$T20_{mid}$ (s)	$T30_{mid}$ (s)	$D50_{mid}$ (-)	$C50_{mid}$(dB)	$C80_{mid}$(dB)	Ts_{mid} (ms)	LF_{mid} (-)
Oct Band	500-1k	500-1k	500-1k	500-2k	500-2k	500-2k	500-1k	500-2k
JND	5%	5%	5%	5%	1 dB	1 dB	20 ms	0.05
Mean	3.84	4.48	4.358	0.29	-5.32	-2.86	266	0.44
std	1.27	0.43	0.31	0.24	6.07	5.16	113	0.23
N JND	6.7	2	1.5	4	6	5	5.5	4.5

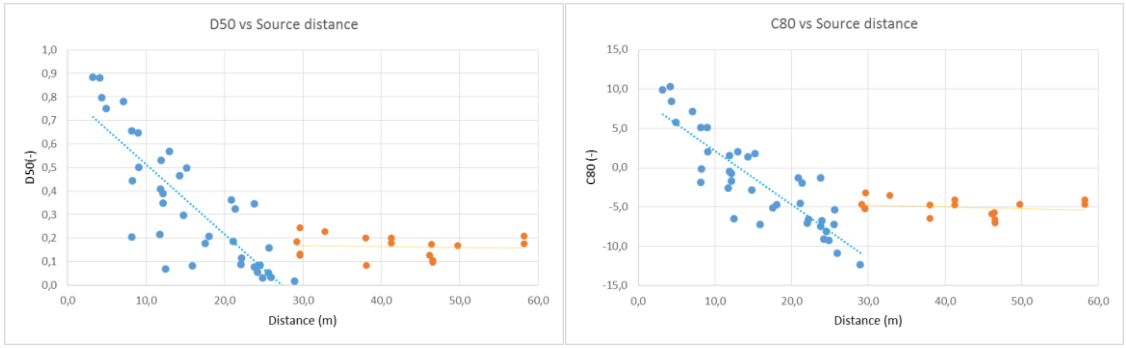
The high value of the standard deviation of some parameters (EDT, energy) compared with the corresponding JND is because I believe that a calculation of the average among all source-receiver settings is not suitable to be the values of the altar-choir area and very different from the other two zones ambulatory. If only the nave and transept areas configurations, are averaged you same parameters have values of standard deviation of 2 JND. Conversely the T20 and T30 temporary parameters present a suitable standard deviation between 1 and 2 JND to be parameters with much lower dispersion between the four zones.



(a) *(b)*

Figure 14. Average and separated zones (a) EDT; (b) T30

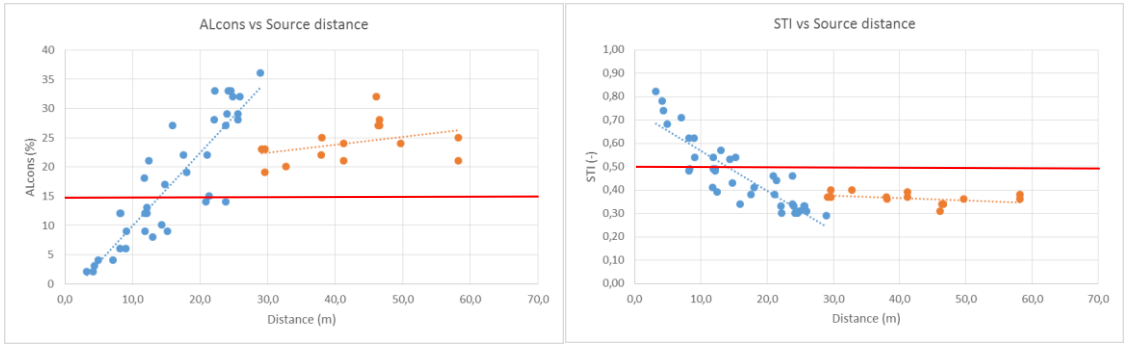
We can also make a study of the dependence of the energetic parameters (mid value) with the distance from the source and as can be seen from figure graphics xx, there is a decreasing linear dependency with the distance for separation up to 29 m of the sources and for greater distances these parameters of maintains approximately constant.



(a) *(b)*

Figure 14. All receivers (a) D50; (b) C80

Similar behavior can be observed in the parameters of intelligibility, where only for distances less than 12 m intelligibility can be considered acceptable.



(a) *(b)*

Figure 14. All receivers (a) ALcons; (b) STI

4. CONCLUSIONS

The values obtained in the result of the measurements of the Group GAMMA-UPM-UDC that are presented in this work, will allow starting the first acoustic study on-site Cathedral, as so far only work of simulated models had been made without to calibrate them from actual measurements.

For us has been a very positive experience to join efforts of several research teams from different universities for the analysis of the features of the Cathedral of Santiago acoustic. Also in future work we hope to be able to compare the results of the measurements of the other teams, as well as geometric models of the Cathedral using different tools of simulation by work teams.

In terms of values, we should remember how said at the beginning of the work, the situation of restoration which took place during the implementation of the measures, which may alter the actual values of the acoustic parameters obtained.

It could be said that the Cathedral reverberation time is not excessively high (4.3-4.4 s), while both energy parameters and intelligibility are quite poor, with the exception of the area of altar-choir, which by its special configuration and status rehabilitation is quite acceptable values.

It has been decided to divide the study of the Cathedral into four distinct areas (central nave, transept, altar-choir and ambulatory), given that the results of the parameters obtained are very different between them.

As future lines of work have the comparison of measures between the different teams and tell them and validation of geometric models with different simulation tools. Also the realization of a second measurement campaign in the Cathedral when the restoration works end.

5. ACKNOWLEDGEMENTS

We want to express our appreciation to the members of the team of Seville Lidia Alvarez, Miguel Galindo and Alfonso Álvarez. Also Foundation A Casa da Pedra of the Cathedral of Santiago de Compostela for the facilities that we have provided in the implementation of these measures. In addition to Luisa Segade. from the University of A Coruña.

6. REFERENCES

1. Keneth J. Conant, "Arquitectura Románica da catedral de Santiago de Compostela", Colegio Oficial de Arquitectos de Galicia, Santiago (1983).

2. "Liber Sancti Iacobi - Codex Calixtinus", translation, A. Moralejo, C.Torres, J Feo, ed. X. Carro Otero, Pontevedra (1992).

3. "La transformación de la catedral a través de los tiempos". Xunta de Galicia (1995).

4. Francesco Martellotta, "Guidelines for acoustical measurements in churches", Applied Acoustics Vol 70, pp. 376-389 (2009).

5. UNE-EN ISO 3382-1 "Acústica. Medición de parámetros acústicos en recintos", Asociación Española de Normalización y Certificación AENOR (2010, 2012).

6. Krzysztof Kosała, Zbigniew W. Engel, "Assessing the acoustic properties of Roman Catholic churches: A new approach", Applied Acoustics Vol.74, pp.1144–1152 (2013).

7. ISO 18233, Acoustics-applications of new measurement methods in building and room acoustics, Geneva, (2006).

8. Lidia Álvarez-Morales, et al, "A methodology for the study of the acoustic environment of Catholic cathedrals: Application to the Cathedral of Malaga", Building and Environment Vol.72, pp. 102-115 (2014).

9. Antonio Pedrero, et al, "Acoustical study of Toledo Cathedral according to its liturgical uses", Applied Acoustics Vol.85, pp. 23–33(2014).