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Characteristic Function in a Room: Definition, Properties and use as analysis tool

Cerdá-Jordá, Salvador[1]; Giménez-Pérez, Alicia[2]
Applied Physics Dept., *Universitat Politècnica de València*

Cibrián, Rosa[3]
Physiology Dept., *Universitat de València*

Segura-García, Jaume[4]
Computer Science Dept., *Universitat de València*

Girón, Sara[5]
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, *Universidad de Sevilla*

ABSTRACT

The impulse response (IR) of a room, recorded by an omnidirectional microphone, is the starting point for basic room acoustics. The square of the IR is considered to represent the distribution of how energy arrives from the source to the microphone, and the most commonly used acoustic parameters are obtained from it, using specific IR software. The method for obtaining these parameters depends in part on the software used and the parameters calculated on acoustic frequency bands. In this work, we present a new tool for analyzing the impulse response (IR) of a room: the characteristic function, an approach for globally characterizing rooms directly using the IR signal measured. Using this method greater or lesser variability of IR, measured at different points of a room, can be shown. In general, a linear dependence of distance between characteristic functions at different points from the source is found.

Keywords: Impulse response, Transfer function
I-INCE Classification of Subject Number: 76

http://www.upv.es/contenidos/ACUSVIRT/

[1] Salvasdor.Cerda@uv.es
[2] agimenez@fis.upv.es
[3] Rosa.M.Cibrian@uv.es
[4] Jaume.Segura@uv.es
[5] sgiron@us.es

1. INTRODUCTION

Impulse response (IR) is the starting point for studying a complex system. In room acoustics, IRs have been used since Sabine [1] began to analyze rooms, using a source of a given frequency. Although, in the beginning, Sabine only determined the amplitude decay curve, nowadays well-established procedures exist to measure IRs in a wide frequency spectrum. The impulse responses of rooms present a similar pattern, although, at first sight, differences can clearly be observed between two IRs determined in two places in the same room or in different rooms. Except in rooms with very particular geometries, it is known that the reverberation time (RT) for the different frequency bands does not usually show large variations (normally below 3%). This allows RT to be used as the main characterizing parameter of a room. However, despite being a very important global parameter, it is necessary to use other parameters to determine the acoustic qualities of a room, e.g. to evaluate the acoustic conditions for speech: Ts, C50, RASTI; for music: C80, G, ITDG [2]. In fact, it has long been known that IR measured with a standard omnidirectional source and an omnidirectional microphone does not allow some very important spatial features in hearing measured by spatial parameters to be determined, such as the LF or the IACC [3].

The objective of this work is to compare, holistically, i.e. taking all IRs into account, IRs measured at different points of a room in an elementary graphical way. To do this, a polynomial is associated with each IR whose coefficients are the elements of the IR squared. This polynomial is named the *characteristic function of the IR* (CF). To compare IRs, the polynomial is evaluated and plotted in the interval (0,1]. With this simple idea we hope to obtain a representation enabling us to compare the IRs. An additional aim is to establish conclusions, when comparing the graphs obtained from the graphic, on applying that technique to a theoretical impulse response corresponding to an exponential pure decay. The results show that CFs vary with distance to the source in a linear way. This implies that the exponential pure decay model is insufficient to explain the variations observed experimentally.

2. THE CHARACTERISTIC FUNCTION OF AN IMPULSE RESPONSE

Consider that we have measured the IR, h(i) at a point in a room using standard procedure From it, we define the following function [4]:

$$f(x) = \sum_{i=1}^{N} h^2(i) x^i \qquad \text{Equation1}$$

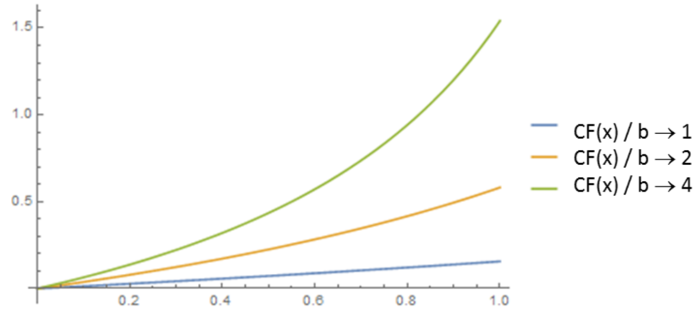
Where x is a variable in the interval [0,1]

With this definition, we have f (0) = 0 and f (1) = E^2, that is, the energy of the IR. If we consider a model $h(i) = e^{-\frac{i}{b}}$ and take N as infinity, we obtain, as a sum of the series (1), the function:

$$f(x) = \frac{x}{e^{\frac{2}{b}} - x} \qquad \text{Equation 2}$$

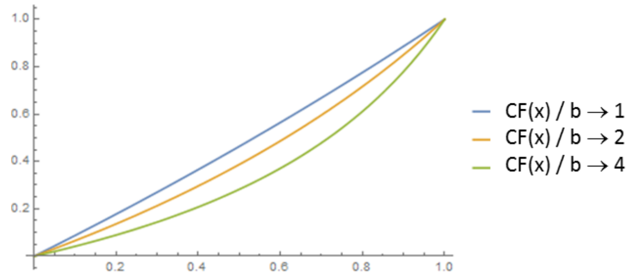
The following graph presents the functions obtained for different values of parameter b.

Figure 1. *CF(x) for several pure exponential decay IRs*



As we see with the theoretical IR, there is a great variation according to the value of b (related to RT). This is due in part to the fact that the energy of the IRs is quite different (CF (1)). To avoid this energy factor, and as what we intend with this technique is to appreciate differences between two IRs not attributable to an energy factor, we define the characteristic function using the normalized IR. In this case, the graphs obtained are as follows:

Figure 1. *CF(x) for several normalized pure decay IRs*



With the normalized IRs we have CF (0) = 0 and that CF (1) = 1. As CF (1) also admits an energy interpretation and we want to compare IRs from the same room that have very similar RT values, we change the definition using the decimal logarithm. Thus we can consider that the characteristic function of an IR of a room is provided by the expression:

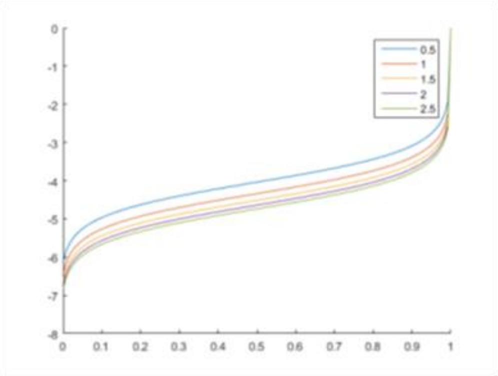
$$CF(x) = 10log\left(\sum_{i=1}^{N} h_{norm}^{2}(i)x^{i}\right) \qquad \text{Equation 3}$$

By using logarithms we can interpret the units of the CF as dB. However, with this definition, the CF is only defined in (0,1) If we consider the RT as a parameter and a pure decay model, we arrive at a normalized IR of:

$$h(t) = \sqrt{\frac{\mathrm{RT}}{\mathrm{Ln}(10^{6})}}\, e^{-\ln(1000)t/\mathrm{RT}} \qquad \text{Equation 4}$$

The graphs for different RTs are presented in Figure 3

Figure 2. *Graph of the logarithmic definition of CF for several RTs*



Note that we have considered a variation of RT between 0.5 s and 2.5 s (> 3%) using normalized exponential decay IRs (4) and that the CF is evaluated in the semi-open interval (0.1] for N = 128 evenly-spaced samples.

3. CHARACTERISTIC FUNCTIONS FOR DIFFERENT ROOMS

To show the usefulness of the CF introduced, we have calculated and represented it for different rooms. We have selected 12 different rooms divided into four groups according to their main use:

1. Conference rooms: Auditorium of the Universitat Politècnica de València (UPV) (RT_{mid} = 1.3 s), Auditorium 6G of the UPV (RT_{mid} = 1.5 s) and Auditorium of the ETSII of the UPV (RT_{mid} = 0.68 s).

2. Concert halls: Auditori of Torrent (RT_{mid} = 1.9 s), Auditorio of Ribarroja (RT_{mid} = 1.8 s) and Palau de la Música of the City of Valencia (RT_{mid} = 2.4 s).

3. Theaters: Teatro Serrano of Gandía (RT_{mid} = 1.4 s), Teatro Principal of Valencia (RT_{mid} = 1.5 s) and Teatro Antonio Ferrandis of Paterna (RT_{mid} = 1.6 s).

4. Churches: Basilica of Santa María of Elche (RT_{mid} = 6.3 s), Basilica of Sant Jaume of Algemesí (RT_{mid} = 5.1 s) and Cathedral of Valencia (RT_{mid} = 4.7 s).

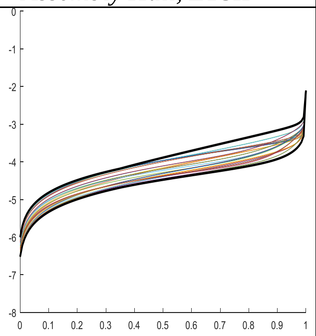
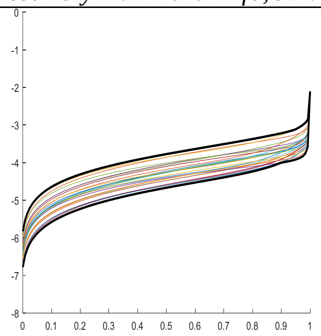
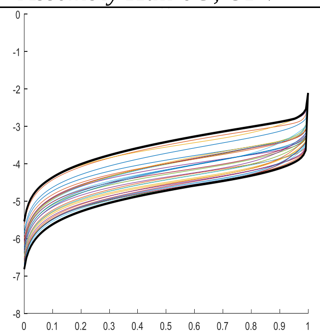
In all the rooms studied it was observed that the representation obtained from the IRs measured presents considerable visual variation. This means that although the RT in the rooms varies little (around 3%), the CF can be considered as a tool that allows the differences that the IRs have at different points of the same room to be seen. Let us now see this in the rooms studied. To do so, the upper and lower envelope of the graphics have been determined and represented in thicker black lines for each room.

Figures 4,5,6,7 show the CF obtained in each room for the different points measured.

3.1 Conference rooms

In these three rooms, the corresponding volumes are V_{ETSII} = 424 m³, $V_{Paraninfo}$ = 2,700 m³ and V_{6G} = 3,266 m³. For these rooms, the area between the envelopes of the CF does not seem to be directly related to the volume of the room.

Figure 4. *CF in dB in Conference Rooms*

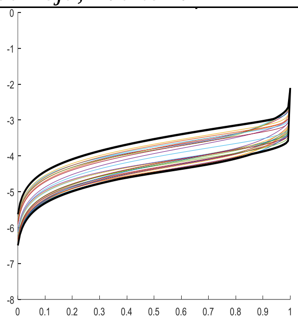
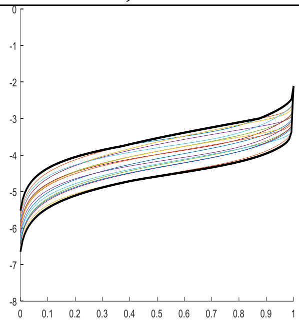
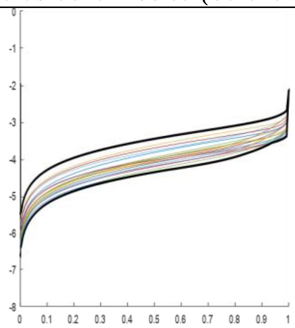
Assembly Hall, ETSII	*Assembly Hall Paraninfo,UPV*	*Assembly Hall 6G, UPV*
		
RT_{mid}=0.68 s	RT_{mid}=1.3 s	RT_{mid}=1.5 s

It can be observed in the three images how the halls have CFs showing the peculiarities of each room. First, note that differences are observed visually both between the three rooms, and within the same room. This is a remarkable result since the CFs capture the complete IRs at each point, normalize them and build a polynomial, the graph of which shows differences between one IR and another, even though the RT does not change much in the same room. If we observe how the FCs change, we see that approximately up to x = 0.5, the graphs look like vertical translations of the envelope. From x = 0.5 some curves intersect, but in the case of room 6G, these intersections are not as clear as in the other two rooms. On the other hand, the area that the graphs cover in each room seems directly related to their size. This will be confirmed in the next section in which we examine the variation between the FCs of two IRs with the distance to the source [5].

3.2 Concert halls

In these three rooms the corresponding volumes are $V_{ribarroja}$ = 7,830 m³, $V_{torrent}$ = 6,430 m³ and V_{palau} = 14,700 m³. For these rooms the area between the envelopes of the CF does not seem to be directly related to the volume of the room.

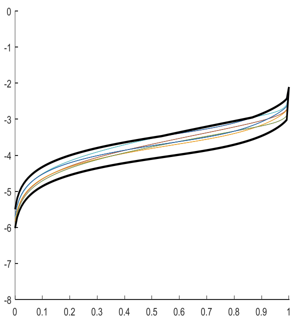
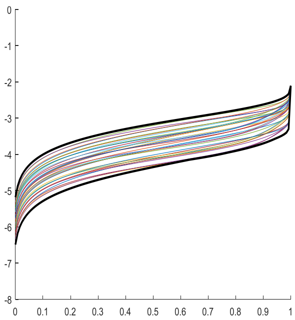
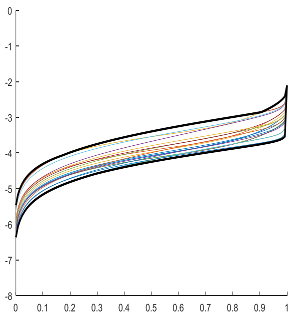
Figure 5. *CF in dB for the Concert Halls*

Ribarroja, Auditorium	*Torrent , Auditorium*	*Palau de la Música (Valencia)*
		
RT_{mid} = 1.8 s	RT_{mid} =1.9 s	RT_{mid} =2.4 s

3.3 Theaters

These three theaters have quite different geometric characteristics. Serrano theater has a fan-shaped floor plan, an amphitheater and a volume of 5,064 m^3. In the study, few IRs were calculated given their size. The volume of the Teatro Principal of Valencia is 6,986 m^3. It has horseshoe-shaped floor and boxes at various heights. Finally, the Paterna's theater has a rectangular floor plan and is the smallest of the three with a volume of 2,700 m^3. The comparison of the CF indicates that the greater homogeneity of the IR is presented by the Teatro Principal of Valencia, while the other two theaters show CFs that intersect for small values of x.

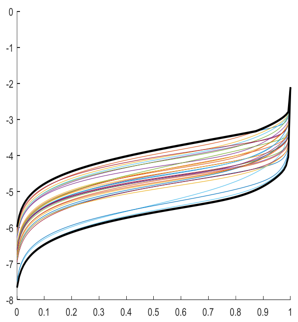
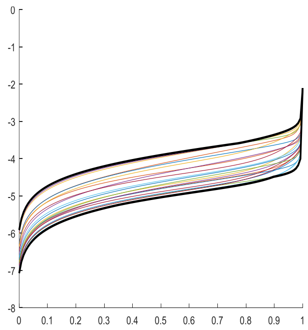
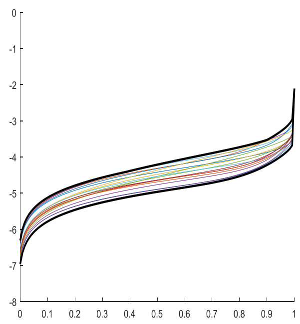
Figure 6. *CF in dB for the Theaters*

Gandía, Serrano Theater	*Valencia, Principal Theater*	*Paterna, Ant. Ferrandis Theater*
		
RT_{mid} = 1.4 s	RT_{mid} =1.5 s	RT_{mid} =1.6 s

3.4 Churches

It can be seen in the three images that the behavior in each of the churches studied is different. The surface area covered by the CFs seems to be clearly related to the size of the churches. However, the graphs intersect so it is expected that the acoustic behavior will be different at different points of the rooms.

Figure 7. *CF in dB for the Churches*

Valencia, Cathedral	Algemesí, S. Jaime Ap. Basílica	Elche, Santa María Basílica
		
RT_{mid} = 4.7 s	RT_{mid} =5.1 s	RT_{mid} =6.3 s

4. CF DEPENDENCE ON DISTANCE

In all the rooms studied, we determined the upper and lower envelopes of the CF obtained from the IRs measured. Although all of them satisfy CF (1) = 0, it can be observed that the lower envelope is like a vertical translation of the upper envelope. In addition, the CF, for values of x <0.5, show a similar behavior. To quantify this possible vertical translation, the upper envelope has been considered as reference (Eu) and the following parameter has been defined for a CF:

$$MDcf = \frac{1}{N}\sum_{i=1}^{N}|CF(i) - Eu(i)| \qquad \text{Equation 5}$$

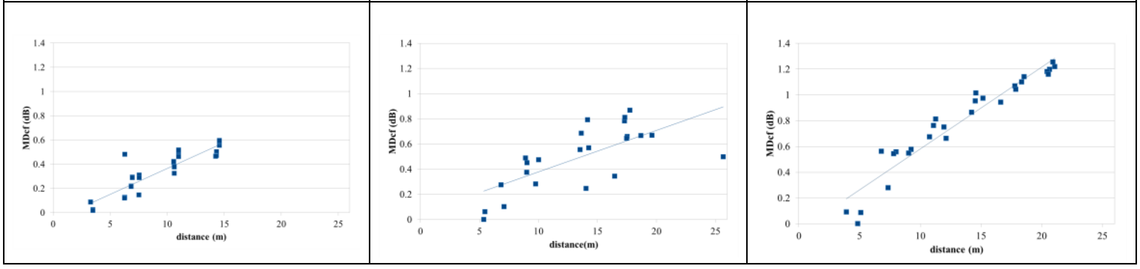
This allows us to quantify the distance of a CF to its upper envelope and study the relationship between that measure and the distance of the corresponding IR to the source. The following figures (figures 8,9,10,11) show the results obtained.

4.1 Conference rooms

In the three conference rooms studied, it can be observed that the difference between CFs depends on the distance from the point of measurement to the source. This dependence is notable in the Assembly Hall ETSII and the 6G conference room of the UPV. In the case of the Paraninfo, although the ratio can be explained statistically with a 49% validity, this ratio is the poorest of those obtained for the three rooms. If we look at the range of distances, we see that the two larger rooms have a similar, so it is clear that the IRs present different behavior in each room. In the case of the Paraninfo, the data series could almost be divided into two groups of different linear tendencies.

Figure 8. *MDcf versus distance from source for Conference Rooms*

Assembly Hall, ETSII y = 0.043x - 0.065 R^2 = 0.803	Assembly Hall Paraninfo,UPV y = 0.033x + 0.049 R^2 = 0.489	Assembly Hall 6G, UPV y = 0.064x - 0.053 R^2 = 0.920

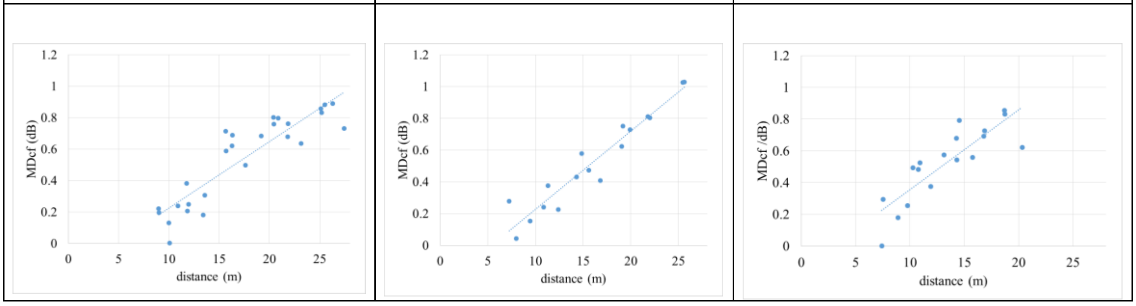


4.2 Concert halls

In these three examples there are high R^2 values, especially in the Torrent Auditorium. In addition, we observe that the slope of the regression line in the three cases is quite similar, m ≈ 0.047.

Figure 9. *MDcf versus distance from source for Concert Halls*

Ribarroja, Auditorium y = 0.042x - 0.197 R^2 = 0.814	Torrent, Auditorium y = 0.049x - 0.266 R^2 = 0.923	Palau de la Música (Valencia) y = 0.050x - 0.144 R^2 = 0.722

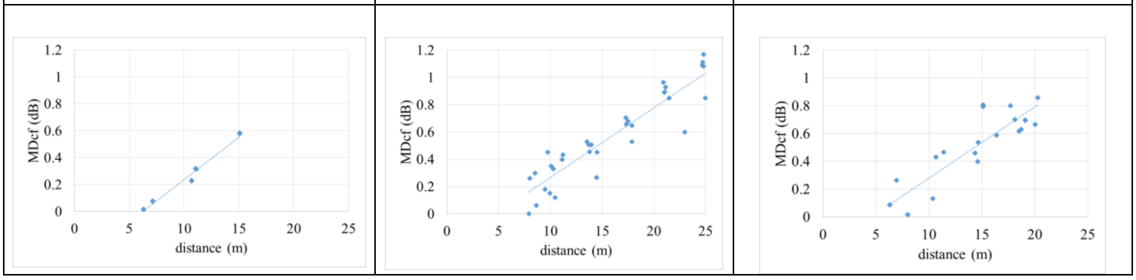


4.3 Theaters

For the theaters studied, we observed high values of R^2. The slopes, in the case of the Teatro Principal of Valencia and the Teatro Antonio Ferrandis of Paterna, are almost the same 0.05, being slightly higher in the case of the Teatro Serrano of Gandía.

Figure 10. *MDcf versus distance from source for Theaters*

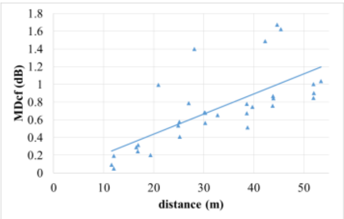
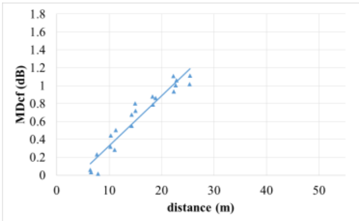
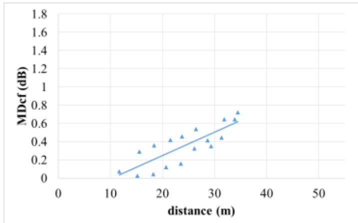
Gandía, Serrano Theater y = 0.063x - 0.392 R^2 = 0.974	Valencia, Principal Theater y = 0.051x - 0.242 R^2 = 0.861	Paterna, Ant. Ferrandis Theater y = 0.051x - 0.232 R^2 = 0.767



4.4 Churches

In this case we found a quite different behavior. On the one hand, the Basilica of Sant Jaume of Algemesí shows a very good linear dependence with a slope of 0.056, similar to those obtained in other types of rooms. However, both for the Cathedral of Valencia and for the Basilica of Santa María of Elche, the linear dependence is poorer and the slopes are very low, in the order of 0.02. However, as in the case of the Paraninfo, it seems that the data series could be separated into two groups with different linear tendencies. This behavior that we have observed in these Churches is enough to merit another study that we shall present to this Congress.

Figure 11. *MDcf versus distance from source for Churches*

Valencia, Cathedral $y = 0.023x - 0.013$ $R^2 = 0.490$	Algemesí, S. Jaime Ap. Basilica $y = 0.056x - 0.233$ $R^2 = 0.923$	Elche, Santa María Basilica $y = 0.026x - 0.265$ $R^2 = 0.674$
		

5. CONCLUSIONS

In this work we have defined the characteristic function of an impulse response. To undertake a global comparison of the IRs, we have used normalized IRs and logarithms to interpret CF measurements in dB. The CF can be calculated for a theoretical IR of pure exponential decay with a fixed RT. For this model, CF is independent of the position. However, in a room it is known that the RT varies around 3%, so it can be expected that, when determining the CF of several IRs in the same room, there will be differences between them.

From the analysis of the 12 rooms studied in this paper, it can be deduced that the CF varies more than expected according to the elementary model of pure exponential decay. This shows that the CF can be used as an analysis tool capable of showing the variations that IRs present in a room in a global way, without the need for calculating acoustic parameters. From a visual analysis of the CF, the complexity of the variation in the IR can be deduced, as intersections in the CF graphs can be observed in some rooms. However, some parts of the graphs remain parallel. This fact led us to quantify the difference between the IRs by measuring the distance points between their CF and the upper envelope Eu of all the FCs in the same room. Having done so, we found that the difference between CFs presents a linear dependence on the distance from the IR to the sound source, with a very good correlation in most of the rooms studied.

6. ACKNOWLEDGEMENTS

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