Estimation of Some Physical Room Acoustical Measures from Convolving HRTF’s with the Room Impulse Response

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Abstract
A study is made on some room acoustical parameters in view of establishing a possible relationship between them. The investigation is theoretical and concerns the Inter-Aural Cross-Correlation Coefficient, IACC, the Early Lateral Energy Fraction ELEF, or a related measure, the spaciousness S, and finally the Initial Time Delay Gap, ITDG. To this end the impulse response (IR) for a symmetrical rectangular room with two side balconies is calculated by means of the image source method. Furthermore, and for a more realistic determination of the parameters in question, especially the IACC, diffraction around the head is taken into account in evaluating the IR of the room through convolving it with the Head Related Transfer Function (HRTF) for both ears as measured on a dummy head (KEMAR) in an anechoic environment. Three-dimensional mappings for the values of the parameters from filtered IRs are processed where the directional characteristics of the different components of the IR are accounted for in the IACC, but to a different degree in the ELEF, whereas the ITDG is not affected by diffraction around the head. An attempt is made in view of determining some correlation between these parameters, and it is found that simple relations may in fact be established between them. A further practical implication of this work in room acoustical applications is to estimate one of the concerned parameters, when inaccessible, from the knowledge of the value of any of the other ones.

1. Introduction
In room acoustics there is often a need of well-defined objective descriptors to quantify specific subjective impressions on the acoustics of a performance space. Several such parameters may be found listed in textbooks [1-4] or in review articles [5]. Depending on the purpose of use of the enclosure, different parameters may be of interest, and the Reverberation Time is a classical example of controversy in use of acoustical parameters. The urge of elaborating more acoustical parameters instigated an almost four decade long research activity in several parts of the world starting from the early fifties. This resulted in the definition of several objective measures, and some of which have found useful applications due to their positive correlation with the human acoustical subjective impressions. One can name for instance the Early Lateral Energy Fraction, ELEF, first proposed by Barron and Marshall [6], and which is defined as the proportion of lateral sound energy reaching a listener in the early total sound energy. This parameter has been found to correlate strongly with the impression of spaciousness or apparent source width: the larger is the value of this parameter, and the stronger is the impression of spaciousness in the enclosure. This gave some explanation to the praise won by the old narrow rectangular halls in which the sound signal reaching a member of the sitting audience is strongly reinforced by early reflections occurring on the lateral walls. Another parameter for estimating the degree of sound diffuseness is the Inter-Aural Cross-Correlation, IACC, the definition of which was the subject of long discussion between several authors. IACC is calculated through a simple cross-correlation of the impulse responses at the entrance of both ears of the listener. These parameters will be defined later on and will be studied in subjective acoustical contexts.

2. Impulse response of a rectangular room with simple building details on the walls
The impulse response of a room for a pair of well defined positions of the sound source and the observer is defined as the signal received by a sensor at the observer position when a short and intense signal is emitted by the source. On a time scaled axis the impulse response is then be represented by the series of impulses starting by the direct one, and then followed by its successive reflections on the various walls of the room. The impulse response has beyond doubt an importance position in room acoustical studies as it is a powerful means for describing the transmission path between the source position and the receiver position [7]. In the limit of high frequencies, the study of sound wave propagation within a closed space often makes appeal to one of two sorts of algorithms: the image sources method, and the particle ray tracing method. The merits of each of the two methods are mainly judged in terms of computing time and memory storage [8]. In the special case of rectangular enclosures the image sources method is by far easier and better implemented in computer programs than the ray tracing method [8-10]. The details of the enclosure considered in this study are shown in Fig. 1, which may be considered as medium sized performance hall. All walls and ceiling of the room are taken as perfectly hard whereas the floor is
taken as perfectly absorbing. In addition to visibility tests, the inclusion of diffracting elements with simple geometry on the walls of the room necessitates considering the diffraction of sound waves by straight edges. This phenomenon can be treated efficiently by the theory of Biot and Tolstoy [11], particularly suitable for problems formulated in the time domain. Diffraction of sound waves around the head is non-negligible and should be taken into account too when evaluating parameters based on binaural measurements. To this end the response for an impulse recorded at the ear entrance, the so-called Head Related Transfer Function, HRTF, was also included in the impulse response calculations [12].

The early part of a typical such impulse response as predicted from the room defined previously is plotted in Fig. 2.

![Figure 1](image1.png)

**Figure 1:** Sketch of the rectangular room with the hard diffracting elements on two lateral walls.

![Figure 2](image2.png)

**Figure 2:** Early portion of the IR of the room in Fig. 1 as predicted by the image sources method.

In the calculation procedure used in this last figure, and which is also taken in what follows, the sound source is at some position typical to that of a performer in the room and the receiver is at a height position corresponding to the ear of a seated listener.

3. The Inter-aural cross correlation, IACC

The IACC has been given several definitions, but the most widely accepted of these definitions is the maximum value of the temporal quantity \( \kappa(\tau) \) within \( |\tau| < 1 \text{ms} \), \( \kappa(\tau) \) being expressed as:

\[
\kappa(\tau) = \frac{\int_0^{100\text{ms}} p_l(t) p_r(t+\tau)dt}{\sqrt{\int_0^{100\text{ms}} p_l^2(t)dt \int_0^{100\text{ms}} p_r^2(t)dt}}
\]

where \( p_l \) and \( p_r \) are the sound pressures measured respectively at the left, and the right ears of a dummy head [1]. The IACC is a measure of the diffuseness of the sound field, and the lower its value and the lesser correlation between the sound signals at the ears and the wider the sound source appears to be. A surface plot on the variation of the IACC in the study case room is presented in Fig. 3.

![Figure 3](image3.png)

**Figure 3:** Plot of IACC coefficient within the room.

In this last figure the IACC is evaluated from the IR after a low pass filtering with a cut-off frequency of 800 Hz and including diffraction effects around the head.

4. The Early Lateral Energy Fraction, ELEF, and Spaciousness, S

The perception of auditory information has a directional dimension, which is made possible to the brain through the simultaneous processing of the signals arriving at both ears. When the signals reaching the ear are large in number, their analysis is made in a global manner rather than analysing each signal separately. The effect of sound reflections incoming from different directions on the sensation of spatial impression is often given different nominations such as “spatial responsiveness”, “ambiance”, “apparent source width”, “räumlichkeit”,...
“spaciousness” or “subjective diffuseness”. Research has proved that spatial impression may be brought about with just a few reflections provided specific conditions on mutual coherence, intensities, arrival times and directions are met for the separate reflections [2,6]. Hence spatial impression, is directly related to the ratio of lateral energy to the total energy during the first 80 ms of the impulse response, or formally the ELEF is given by:

\[ \text{ELEF} = \frac{\int_{t_0}^{t_2} p^L(t)dt}{\int_{t_0}^{t_2} p^C(t)dt} \]  

(2)

where \( p^L(t) = p^C(t) \cos \theta \), \( \theta \) being the angle of lateral incidence, and \( p \) the sound pressure. Calculations made on the variation of the ELEF in the room are shown in Fig. 4, where only the plain impulse response is required for the calculations without the need of including the effects of diffraction around the head.

5. The Initial Time Delay Gap, ITDG

The ITDG is defined as the time in ms measured between the arrival of the direct sound and that of the first reflection reaching the listener’s ear [13]. In auditorium acoustical contexts, the ITDG was merely intended to be a measure of perceived acoustic intimacy, a subjective property of concert halls strongly related to proximity to performers. The ITDG has however been the subject of some criticisms [4], with perhaps the most obvious of these being that the earliest reflection reaching the ear after the direct signal is not obligatorily a lateral one (cf. ELEF above).

A mapping of the values of the ITDG within the room of interest is shown in the plot of Fig. 5. As expected, the largest values of the ITDG are to be found around the sound source where the first reflections, in this case from the lateral walls, take the longest delay following the direct signal from the sound source. Unlike the IACC and the ELEF, the ITDG does not depend on frequency.

6. IACC vs Spaciousness and ELEF

On a coordinate system with axes representing the values of the IACC and the ELEF, or S, each of the receiver positions within the room is represented by a dot having for coordinates the corresponding parameter values. The dot constellation in the graph of Fig. 6 is a plot of IACC vs. S.

\[ \text{IACC} = \frac{1}{1 + S/200} \times 100\% \]  

(4)
This curve is to be compared to the lower hypothetical one [2]. At using Eq. 3 a relationship may be established between IACC and ELEF which reads:

\[
IACC \approx \left(1 - \frac{ELEF}{200 - ELEF}\right) \times 100\% \quad (5)
\]

but a simpler correlation may be elaborated namely:

\[
IACC = 100 - \frac{ELEF}{1.5} \quad (6)
\]

The relative difference between these last two expressions is less than 5% for not too large values of ELEF.

**7. IACC vs ITDG**

A plot of IACC vs. ITDG is presented in Fig. 7. The equation of the line resulting from a curve fitting has for expression:

\[
IACC = 10 \cdot ITDG + 6 \quad (7)
\]

with the IACC as earlier being given in %, and the ITDG in ms.

![Figure 7: IACC vs. ITDG.](image)

Using Eq. 6 would result in a relationship between the ELEF and the ITDG expressed as:

\[
ELEF = 140 - 15 \cdot ITDG \quad (8)
\]

As the ITDG is independent of frequency, different equations than Eqs. (7, 8) are to be expected for relating this parameter to the IACC or the ELEF for other frequency filtering of the impulse response.

**8. Conclusions**

In this paper, a theoretical study was made on the relationship between some room acoustical descriptors. These descriptors are the IACC, the ELEF (alternatively the spaciousness) and the ITDG, often used as physical measures of subjective listening preferences in performance halls. The room used for the calculations was taken as rectangular with perfectly hard walls and ceiling and having two simple lateral protuberant elements representing balconies, while the floor was taken as perfectly absorbing. As the evaluation of these parameters necessitates knowledge of the impulse response, this latter was calculated using the image sources method. Only the plain impulse response at the listener position is needed for calculating the ELEF and the ITDG, whereas the IACC requires knowledge of the impulse response at both ears of the listener. This was accomplished through incorporating in the calculation program the HRTF’s as measured on a dummy head. The important result drawn from this study is that there is possibility for establishing simple relationships between the subjective acoustical parameters IACC, ELEF and ITDG, and these are given by Eqs. (4-8). Although the ITDG does not depend on frequency the effects of frequency are important, and other filtering than that considered in this study may lead to other relationships.

**9. References**


