



PREDICTIONS vs MEASUREMENTS IN ROOM ACOUSTICS: A DIFFICULT ADJUSTMENT

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ABSTRACT

Virtual acoustics deals with the simulation of acoustic fields experienced by a listener within a natural environment. The measurement of impulse responses along the room for specific source positions arrangement is usually needed. Measurements of room acoustic parameters are standardized. Nevertheless, some dispersion-uncertainty arises both from the device's characteristics and from experimental set up even though meeting the standard requirements. The influence of the source directivity patterns and the position of the receiver are here analyzed. Results of the most 'sensitive' parameters (C80, IACCE, but also EDT) may be notably influenced. Some results are presented in this paper.

1. INTRODUCTION

Auralization is the technique of creating audible sound files from numerical (simulated, measured or synthesized) data [1]. The auralization must cover all relevant cognitive aspects of the specific case analyzed because perception of sound signals has multiple dimensions. The term was firstly introduced by Kleiner et al. [2]

Virtual acoustics means digitally processing sounds so that they appear to come from particular locations in three-dimensional space, with the goal of simulating the complex acoustic field experienced by a listener within a natural environment. Sometimes Auralization and Virtual Acoustics are used as synonymous.

A virtual audio model can include:

- model-based sound synthesizers,
- geometric room acoustics modeling,
- binaural auralization for headphone and loudspeaker listening,
- high-quality animation,
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As an example, Digital Interactive Virtual Acoustics (DIVA) Project, developed at Helsinki University of Technology [3] has the goal to create a virtual musical event that is as authentic as possible both in terms of audio and visual quality. The DIVA environment is an integrated implementation of a virtual reality system currently aiming at a virtual symphony orchestra performance. Multiple sound sources (physical models of musical instruments) are conducted by a virtual conductor (controlled by a position tracker with 3 transmitters). The real-time calculation of auralization is enhanced by accurate HRTF approximations, a new late reverberation model, and by an efficient image source method.

Either perceptually or physically based modeling techniques can be used to create virtual acoustics [4]. In professional audio-as well as in computer music, perceptually based approaches produces very accurate results by using optimized efficient algorithms. In this writing attention is focused on physically based approach. In principle, a high quality virtual acoustics should be achieved by modeling physical principles of sound propagation, reflections and scattering from boundaries, diffraction on obstacles, etc.

In order to carry out a reliable room acoustic simulation many physical processes and characteristics of the materials and of devices have taken into account. Next section briefly describes the most important.

2. VARIABLES AND PHYSICAL APPROACHES

2.1 Simulation methods

Different ways could be used for room acoustics simulations that are required for physically based virtual acoustics. In theory, wave-based techniques offer the most accurate results. From the element methods, finite element method (FEM), boundary element method (BEM) and finite difference time domain (FDTD) methods had been the most developed. They take into account wavy phenomena, especially important for low frequencies. Nevertheless, time computation required for high size rooms and high frequencies is not practical. More practical techniques are based on geometrical acoustics, such as ray tracing (RT), beam tracing (BT) or image source (IS) methods. In any case, it is of great significance to know how reliable the auralization is, and to what extend the acoustical details are actually simulated [5]. The more is the quality of the room acoustic model used for calculation of the impulse response the more is the quality of the auralization.

2.2 Room model.

All room acoustic software are able to import the geometrical model from architectural design software, typically a CAD model. From an acoustic point of view, precision of such models is more than enough. Even more, it would be better to simplify geometrical models with very high resolution. Details with a precision of 8.5 cm or lesser are only of interest for frequencies above 5 kHz.

2.3 Source modelling

Radiation characteristics of sound sources are dependent on frequency and direction of radiation. That is to say, sound sources are characterized by its spectral sound power and directivity pattern. Minimum requirements for them are specified in standards. For example ISO 140-4 (Field measurements of airborne sound insulation between rooms) requires a maximum standard deviation for the source directivity measured in free field and under pink noise excitation, in third octave bands. ISO 3382-1 [6] requires lesser standard deviation for the source directivity, in octave bands. We will discuss in detail later uncertainties in measurements (and in room simulations) caused by directivity patterns.

2.4 Material absorption

Absorption coefficients used in room simulations and provided by manufacturers. In general absorption coefficients are obtained from measurements in reverberation chambers [7] and, therefore, their figures are realistic for diffuse sound incidence that happens at late response in room simulation software based in geometrical acoustics. But, really, absorption coefficients are angle dependent, what is very important for first reflections. For example, a change of 0.2 in absorption coefficient (0.4 for normal incidence and 0.2 for real angle incidence) implies a difference in 3 dB in energy for the reflected ray. It seems of great importance to introduce correctly the angle dependence in absorption coefficients for beam tracing and image model methods. In the last version of a popular software [8], reflection coefficients of the walls involved in generating the image (secondary sources) can be angle dependent by enabling the option of angular absorption.

2.5 Scattering coefficients

The scattering coefficient is defined as the ratio of the non-specularly reflected sound energy to the totally reflected energy. It does not include any information about the directivity of the scattered energy. If deeper knowledge on the directional pattern of the scattered sound is required, measurements or calculations of the polar response become necessary [9]. It is expected that with the measurements methods in process of standardization [10] more reliable figures for scattering coefficients will be published. Room simulation software should calculate the fraction of energy which is not specular but taken into account scattering coefficients both due to edge diffraction and due to surface roughness.

3. REAL ACOUSTICS. OBJECTIVE MEASUREMENTS

It may seem strange the question: what is real acoustics?. Into a performance in a concert hall, for example, one can answer that real acoustics means the total acoustic impression of a listener in his seat. Nevertheless, such answer is not free of subjectivism. Since that it deals with a physical phenomenon objective parameters can be used-and measured, to quantify such impression. This way ends in to define measurement standard focused to obtain unambiguously results for the acoustic parameters related to acoustic impression. Such is the goal of ISO 3382 [6] for performance spaces. But, how these methods ensure unambiguous figures of the acoustic parameters?. This question must be answered in terms of the just noticeable difference (jnd) of each one of the acoustic parameter. Some acoustic parameters (T30, for example) are little sensitive to variables involved in the experimental arrangement but not other ones (C80, LF, IACCE).

On the other hand, the figure of an acoustic parameter is not one individual characteristic of the room. It is clearly dependent on the position in the room. A requirement for room simulations is that the spatial resolution must represent the natural listening experience related to noticeable differences for all listener positions. In theory (for an ideal diffuse sound field) local variations are related with the correlation function of their corresponding impulse responses [11].

4. SOME RESULTS ABOUT UNCERTAINTIES IN MEASUREMENTS

In this section some results concerning to the influence of some variables of the experimental arrangement are shown. In all measurement results here presented sweeps signals were used to obtain impulse responses since they are relatively tolerant of time variance and totally immune to harmonic distortion [12]. All devices (sound sources, amplifiers, microphones, filters) fulfilled the requirements of ISO 3382-1 standard.

4.1 Directivity patterns of the source

Two dodecahedron loudspeakers with directivity diagrams fulfilling the specifications of ISO 3382-1 were used. Fig 1 shows their directivity characteristics in the equator plane by 'gliging' 30° arc, as well as ISO 3382-1 tolerances.

In order to quantify the uncertainty of the measurement (experimental arrangement) the experimental standard deviation (STD_{exp}) was evaluated by taking 10 measurements without any change of the setup-fixed orientation of loudspeaker [13]. Then this figure quantitatively expresses the repeatability in terms of dispersion characteristics of the results of successive observations carried out under the same measurement conditions. STD_{exp} obtained from all dodecahedron loudspeakers used was similar and always a little fraction of the value of the corresponding jnd [14] of the acoustic parameter measured.

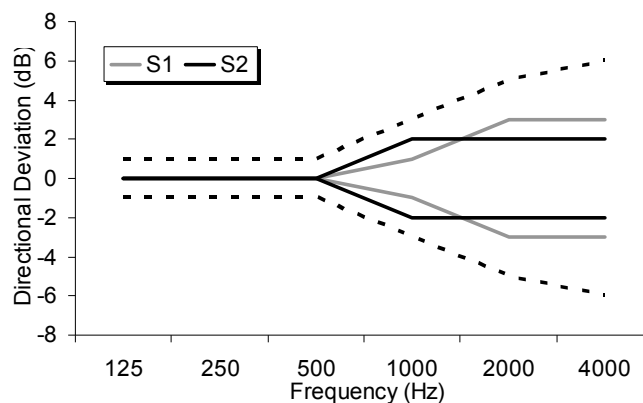


Fig.1 Directivity for two sources: maximum deviation from mean value for 'gliding' 30° arc. Upper and lower curves are the ISO 3382 tolerances.

Since the loudspeakers meet the ISO requirements one can think that the orientation of the source when measuring acoustical parameters in a seat is unconcerned. As a first example, figure 1 shows the results obtained from sources S1 and S2, with random-specific orientation. Four acoustical properties are grouped with their objective parameters.

Table 1. Results from S1 and S2 with random-specific orientation.

	Reverberance		Clarity		Loudness	Apparent Source Width	
	T30 _{mid} (s)	EDT _{mid} (s)	C50 _{mid} (dB)	C80 _{mid} (dB)	G _{mid} (dB)	LF _{E4}	1-IACC _{E3}
S1	2.88	2.73	-4.3	-1.4	2.9	0.12	0.60
S2	2.89	2.75	-5.9	-2.5	3.7	0.12	0.46
STD _{exp}	0.02	0.03	0.1	0.1	0.1	0.01	0.01
jnd	0.14	0.14	1	1	1	0.05	0.08

It's clear that such a deviation produced by the measurement itself is not enough in order to explain the differences found at some parameters as C50_{mid}, C80_{mid}, G_{mid} and IACC_{E3}. Taking into account that only one link of the measurement chain was replaced, a difference larger than jnd for clarity must be considered unacceptable. In addition, remarkable results are also found regarding the IACC_{E3} data. By using Beranek's criteria [15] the 'good' valuation of the spaciousness of the hall obtained with the source S1 –at least at that source-receiver position– will become to solely 'acceptable' in the case of having used the source S2.

In order to study the influence of the source orientation on the results of different acoustic parameters, a total of 24 different source orientations for the same source- receiver position were considered. The receiver position was selected at the central part of the audience – 18.2 m from the source – and was certainly a representative point of the main audience area. Due to the symmetry of the sources, a rotation of 120° was covered in 5° steps, which is thought to be representative of the directivity of the sources. Denoting by STDs the standard deviation of the measurement including the effect of the source orientation, figure 2 shows that, for frequencies above 500 Hz, STDs surpass the limit of a half of jnd (thick line) for both parameters and sources except in the case of C80 at 1 kHz for one of the sources.

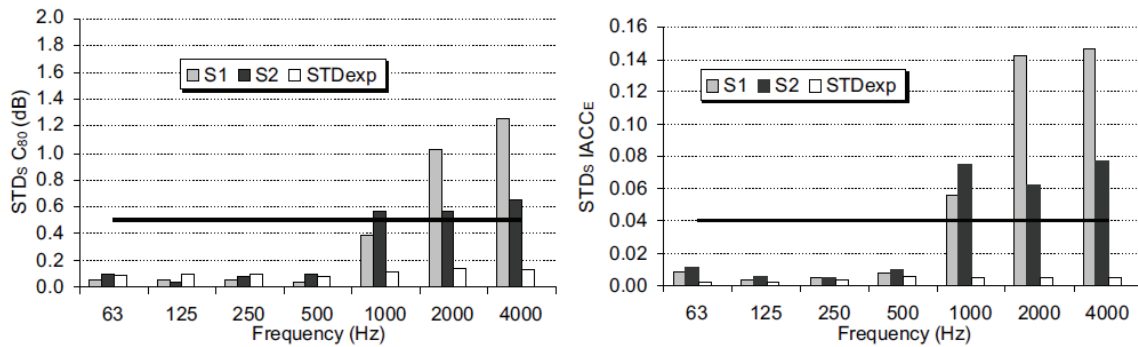


Fig.2 STDs octave band values for C80 and IACCE from sources S1 and S2, 24 orientations. Thick line: stated range of tolerance.

Detailed observation of the impulse responses obtained from different source orientations [16] revealed that the main deviation is introduced at the very start of the impulse response with the arrival of the direct sound. It depends on the lobe's shape of the dodecahedron loudspeaker and whether a maximum or a minimum of the source directivity is facing the receiver. Variations on the measured values depend both on the frequency band and on the way those parameters are derived. The most 'sensitive' parameters are C50, G and IACCE. But, even within the group of reverberation time parameters, EDT is influenced by source orientation due to its integration interval is shorter. In short, for auralization purposes, it is hence of importance to use a suitable source with an omni-directional pattern over a wide frequency range.

4.2 Receiver position

When one thinks of the acoustic evaluation of a specific receiver-position in a room one assumes the seat as a point. Nevertheless, listener position allows some spatial variability, as well as of the two positions of our ears. Several researchers have reported the possibility that values of the most common acoustic parameter show significant variations caused by different source positions or small displacements of the microphone. With regard to receiver's position, both Bradley [17] and Pelorson [18] found that for all measures considered and investigated in all rooms, a displacement of 30 cm leads to significant changes. Nielsen [19], again, found differences between 1.4 and 3.2 dB for values of C80 measuring at eight positions within the same seat. More surprising still are the fluctuations in parameters focused to measure spaciousness obtained by Okano [20] or D. de Vries [21]. Their results confirmed the existence of large variations in the values of both LF and IACC, not only between seats within the same room, but in different positions within the same seat, coming to question the potential of these parameters to describe changes on ASW due to its extreme sensitivity to local interference phenomena.

In order to study influence of the receiver position on the measurement of acoustic parameters, an experimental setting was designed to measure on a seat with greater resolution. By means of a swing-mounted tripod, IRs at 25 positions (central position and 24 positions on two circles of 15 and 25 cm of radius each one, every 30°). Figure 3 shows the results obtained for C80 at 125 Hz, 500 Hz and 2 kHz frequency bands. In spite of such bands are quite above of the Schroeder's frequency, it turns out surprising that figure of the parameter shows a certain sinusoidal characteristic. This implies that local undulatory phenomena arise into the measurement surface and clearly influences the results.

In order to summarize, figure 4 shows the resulting deviations from averaging several positions measured in different rooms. In the left graph, STD_R and STD_{exp} are compared. STD_R (average value from 125 Hz to 4 kHz bands) ranges from four to seven times the STD_{exp}. Right graph shows the effect of distance, 15 or 25 cm from the center. These differences are lower than those found at the literature, especially for parameters related with spaciousness.

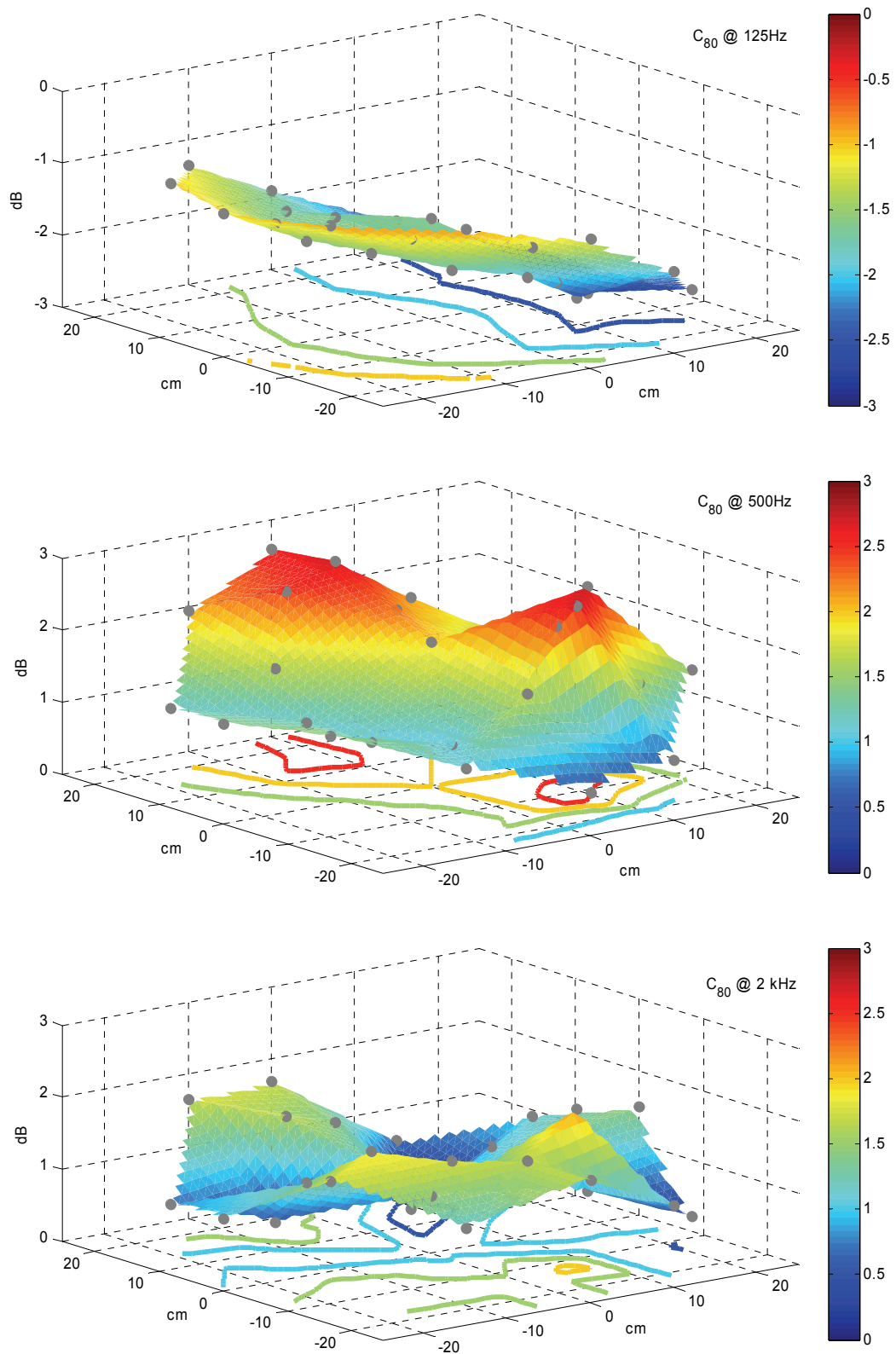


Fig. 3 C_{80} values-receiver position dependent, for 125 Hz (up), 500 Hz (mean) and 2 kHz (low) frequency bands.

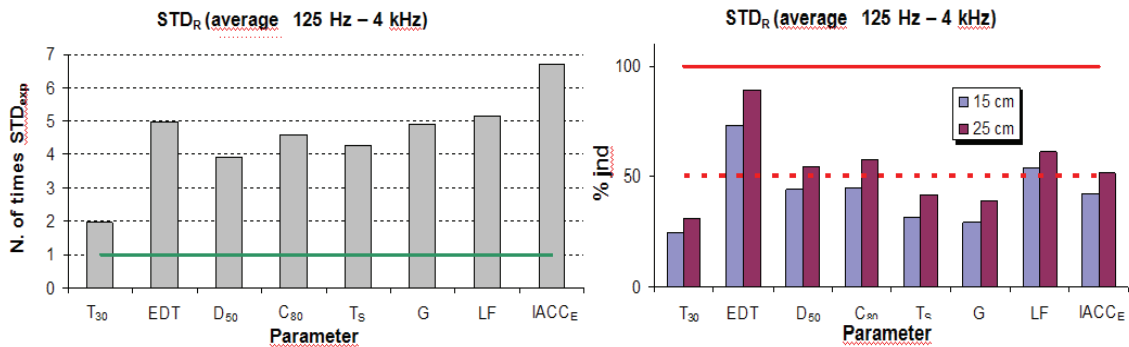


Figure 4 Influence of the position of the receiver. STD_R (averaging 125 Hz – 4 kHz) versus STD_{exp} (left) and jnd (right) of each parameter.

5. ASSESSING MEASUREMENT UNCERTAINTIES THROUGH SIMULATIONS

Enhanced computing power enables the acoustician to test a vast array of variables efficiently, thus making it possible to come up with configurations which would otherwise be unfeasible solely through measurement procedures. The use of simulation software could aid us in diminishing the complex procedures required when spatial distributions within halls are analysed.

Up to now, research on uncertainties due to source orientation has been limited to, as well as by, measurement procedures. The peculiarity of the phenomenon, which appears solely at higher frequencies, seems to suggest that simulation software – whose main limitation is ray-tracing at low frequencies – is not a limiting tool. It may enable us to test the ‘source orientation’ variable spatially in a time-saving way, in sharp contrast to the use of measurements. In addition, present display facilities implemented by developers of the programs are a great aid for interpreting results.

In this example [22], the directivity of four different acoustic sources was measured and the influence of its accurate orientation spatially quantified in five enclosures for speech and music. In order to determine the effect of the source orientation on the results of various acoustic parameters, 72 simulations were carried out with each source. A full 360° rotation was covered in 5° steps. For the spatial analysis, a grid of receivers – one receiver per m^2 – was placed all over the audience zone excluding balconies. Over three thousand receivers, each one ‘measuring’ 7 parameters – T_{30} , EDT, C_{50} , C_{80} , T_s , G and LF – at 8 frequency bands for each simulation and source, were finally utilised. Over 50 million data had to be carefully evaluated by means of Matlab® technical computing software.

Fig. 5 shows the results obtained for source S2 at the Baluarte Concert Hall. Sound Pressure Level of solely the direct sound at 2 kHz octave band is represented for one orientation. The SPL_{direct} value is subject to the lobe shape of the dodecahedron loudspeaker, i.e. whether a maximum or a minimum of the source directivity is facing the receiver. Furthermore, the corresponding octave-band directivity balloon plot of the source along with a graph containing measured and simulated values in the test receiver – which is highlighted inside the grid map – can also be observed. Both measurement and simulation values follow a similar pattern.

Variations on the C_{80} parameter are shown in Fig. 6. The same source, concert hall, and receiver test are displayed; however, in this case, 4 kHz octave-band is the frequency chosen for representation. The mean value for C_{80} in the highlighted receiver is in the vicinity of -2 dB but the variation of the parameter value ranges from -3 dB to -1.2 dB. When we evaluated the direct sound along with the whole impulse response, we also found that the coincidence between measured and simulated values favoured the simulation software and its ability to accurately predict even minor changes in measurement conditions.

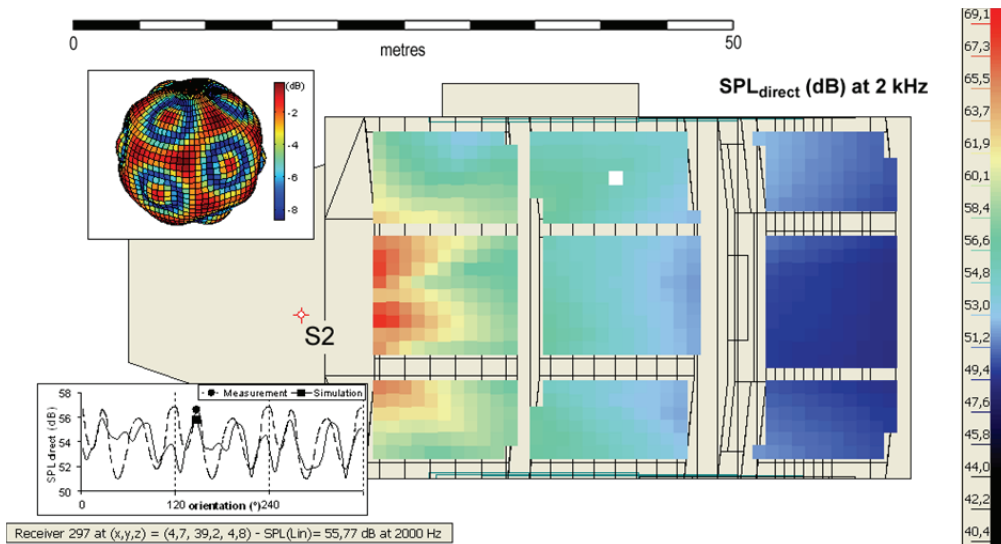


Figure 5. SPL_{direct} for S2 at 2 kHz while turning the source. (Top-left hand window) Directivity balloon plot of the source. (Bottom-left hand window) Measured and simulated values in the test receiver, highlighted. Room: Baluarte Concert Hall.

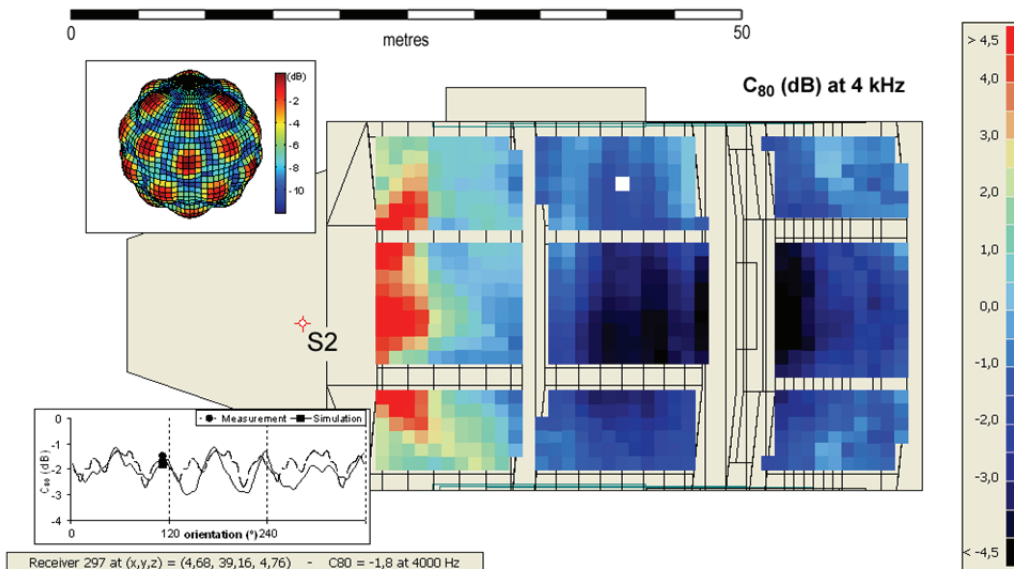


Figure 6. C_{80} for S2 at 4 kHz while turning the source. (Top-left hand window) Directivity balloon plot of the source. (Bottom-left hand window) Measured and simulated values in the test receiver, highlighted. Room: Baluarte Concert Hall.

On identifying the standard deviation including the effect of the source orientation – STD_S – as the parameter that characterised the dispersion of the results observed in each receiver when carrying out the 72 corresponding simulations on each source, it was possible to draw up grid plots as those shown in Fig. 7 covering the different halls. Relative STD_S with the jnd of the respective parameter as a reference was preferred for depiction. Thus, apart from displaying the results on a sole scale for all parameters, the value of relative STD_S was also representative of the change in subjective perception that the uncertainties could produce.

As can be seen in Fig. 7, there are several variations depending on the position within the hall. The use of a grey scale for the diagram enables us to locate the most affected zones. Central areas may be more affected by the directivity of the source. The proximity of a wall and subsequently the arrival of a reflection from others may help to compensate the uncertainty which arises as a result of the difference of levels from the direct sound. Finally, Fig. 8 shows the percentage of receivers affected with STD_S higher than $0.5jnd$ depending on each one of the sources in the five halls under study.

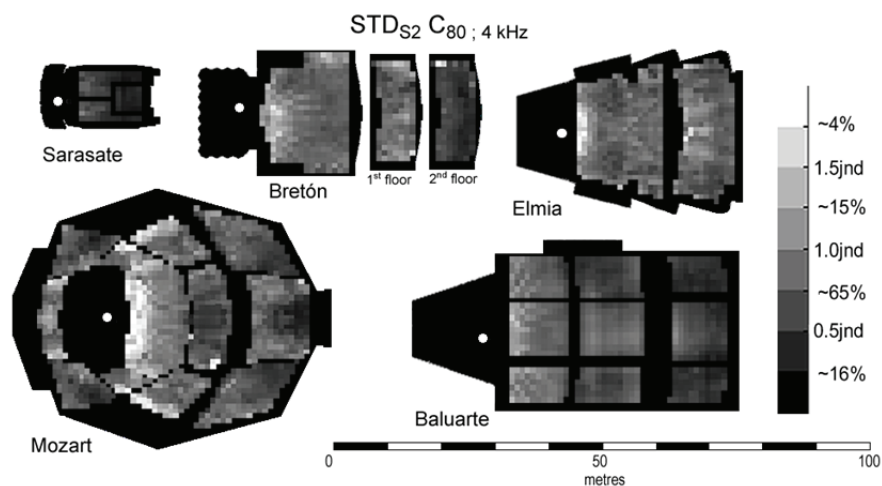


Fig. 7. Relative STD_S for C_{80} parameter obtained for S_2 at 4 kHz for all rooms. Reference: $1\text{dB} - j\text{nd}$ for C_{80} . At colorbar, the percentage of receivers whose STD_S remain within an interval of half a $j\text{nd}$ is also displayed.

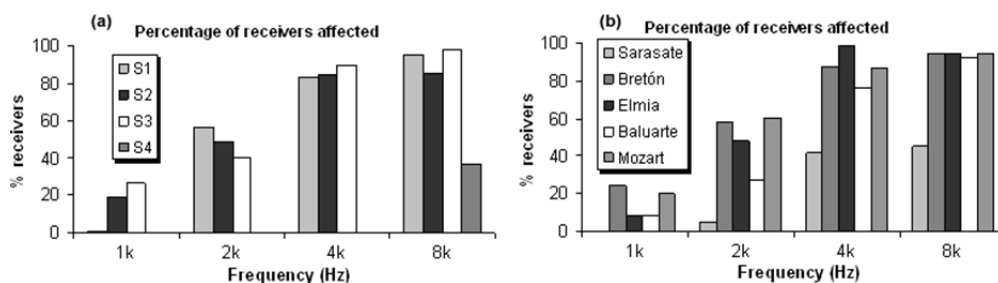


Fig. 8. Percentage of receivers with STD_S for $C_{80} > 0.5j\text{nd}$ (a) for all rooms and (b) for the three commercial dodecahedron loudspeakers (S_4 excluded).

The loudspeakers which were tested delivered satisfactory results up to 1 kHz. Below that frequency band, the bearing of source orientation is negligible for all acoustic parameters. As frequency is increased, sound radiation becomes more directional and the effect on the parameters cannot be neglected any longer. Variations on parameter figures depend on the source, the frequency band, the way those parameters are derived as well as the position within the hall where they are going to be measured. The use of typical commercial dodecahedron sources (as S_1 , S_2 and S_3) could lead to high deviations in wide areas of audience zones of common enclosures for both speech and music. At 1 kHz and 2 kHz octave bands, the percentage of receivers affected with uncertainties higher than the subjectively perceivable change exceeds 15% and 40% respectively. Furthermore, at higher frequencies, a deviation greater than half the $j\text{nd}$ of the parameter could be expected in at least 80% of receivers.

6. CONCLUSIONS

The measurement of impulse responses is a powerful technique to adjust simulations, to make auralizations and for virtual acoustic achievements. It is clear that impulse response is spatial dependent. It is accepted that an only impulse response characterizes a specific source-receiver position-or, at least, possible differences are not perceptible. Nevertheless, even though by using experimental set up meeting all standard requirements, noticeable dispersion appears on results of some acoustic parameters. Minor influence was found with regard to the exact position of the receiver (around the central point) but noticeable differences arise when orientation of the source changes. Detailed observation of the impulse responses obtained from different source orientations revealed that the main deviation is introduced at the very start of the impulse response with the arrival of the direct sound. It depends on the lobe's shape of the dodecahedron loudspeaker and whether a maximum or a minimum of the source directivity is facing the receiver.

The peculiarity of the phenomenon, which appears mainly at higher frequencies, suggests that simulation software – whose main limitation is ray-tracing at low frequencies – is not a limiting tool. It allows us to test the ‘source orientation’ variable spatially in a time-saving way, in sharp contrast to the use of measurements. Percentage of receivers with an STD_s exceeding an interval of half a jnd was calculated for several auditoriums and for different loudspeakers.

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