Uncertainties in acoustic measurements: a case study

Lamberto Tronchin

***Abstract*—** A new method for recording the spatial properties of a soundfield, or for generating a synthetic three-dimensional soundfield, is described. The spatial distribution of sound waves passing at a point in space is sampled by means of a number of virtual directive microphones, covering the surface of a sphere. This corresponds to a discretization of the spatial information, which is exactly the spatial equivalent of the PCM sampling of a waveform.

Moreover, the influence of the height of the microphone in the calculation of the acoustic parameters was analysed. The measurements were repeated at different height and different position on a transversal line in the theatre, and statistically analysed

***Keywords*—**Architectural acoustics; Impulse responses measurements; spherical array; uncertainties.

I. Introduction

THE acoustic measurements in theatre became very important after the burning of two important Italian theatre in last decades, namely the Theatro Petruzzelli in Bari and the Teatro la Fenice in Venice. Since 1975 Gerzon [1] proposed to acquire the sonic behavior of historical theatres, as happened for the Teatro La Fenice in 1996 [2]. Following these catastrophes, many attempts were made to standardise the acoustic measurements in theatre by taking into account several sound source positions, microphone positions and room conditions.

However, only a few attempts were made to analyse and standardise the effect of test signals employed during the measurements and the types of sound source and microphones [3]. These details become crucial when measured Impulse Responses (IRs) are employed for performing 3D auralisation of the room, rather than for simply obtaining the numerical values of ISO 3382 parameters. Moreover, these acoustic data are mainly affected by uncertainty due to the vertical and lateral movement of the receivers. Also the full spatial sonic behaviour of a theatre, which includes information about energy, intensity and location of early reflections in the room, is required to determine and solve some acoustic problems that could not be resolved by only considering mono or 2-channel IRs.

Lamberto Tronchin is with the Industrial Engineering Department, University of Bologna, Viale Risorgimento 2, I 40136 Bologna. +39.051.2093281; (email: lamberto.tronchin@unibo.it).

II. Enhanced 3D-IRs Measurements

A new method to improve the acoustic measurements in room was proposed in 2003 and 2005. This method allows obtaining a complete description of spatial sound propagation in the auditorium [3, 4]. It incorporates all the previously known measurement techniques in a single, coherent approach. Three different microphone systems were mounted on a rotating beam (a binaural dummy head, a pair of cardioids in ORTF configuration, and a Soundfield microphone) and a set of Impulse Responses were measured at each angular position. The ORTF configuration represents a standard method (adopted by French Radio/Television) for recording dual-channel signals, employing two cardioid microphones spaced 170mm and divergent from each other by 110 degrees. The Soundfield microphone, introduced by Gerzon, enabled the measurement of 4-channel Impulse Responses and, therefore, spatial properties of the sound field. A Soundfield microphone captures a set of four signals known as “B-format” signals: one omnidirectional (sound pressure) and three with a polar pattern called “figure-of-eight”, oriented along the three Cartesian axes X, Y, Z (these three channels capture a signal proportional to the Cartesian components of the particle velocity vector). The combination of the three aforementioned different measurement methods provided a general method from which all standard multi-channel playback formats (i.e., 2.0, 5.1, 7.1, 10.2, etc.) could be derived. A further enhancement of this method was recently presented in 2013 [5]. Following this new procedure, the description of spatial sound distribution in a theatre could be retrieved by means of a B-format microphone, without using expensive microphone probes, and also eventually reprocessing previous acoustic measurements in rooms.

III. The sound source

In order to enhance the S/N ratio and to avoid any nonlinear contamination of the acoustic data, a new method to obtain the impulse response of a room was recently introduced. The ESS (Exponential Sine Sweep) method allows for the calculation of the Impulse Response of an electro-acoustical system by avoiding contamination due to distortions, which usually occur in the loudspeaker and provides a large value of the S/N ratio [7], and that could be eventually emulated [8]. The choice of the sound source represents an important issue during the measurements and especially during the subsequent 3D auralisation.

The ISO 3382/2009 standard [9] requires employing an omnidirectional sound source for measurements of room Impulse Responses. The main advantage of the ESS signal method is that it provides a huge dynamic range (often in excess of 100dB) and it is immune from nonlinear effects. The main problem, however, is that the signal must be radiated by a loudspeaker system. Even by employing a state-of-the-art, measurement grade dodecahedron loudspeaker, the source is never really an “omnidirectional point source”. The polar pattern at medium-high frequencies deviates significantly from omnidirectionality, albeit the directivity limits of ISO 3382 are met. Furthermore, the radiated spectrum significantly changes with the direction and even with the distance from the sound source. Thus, for the analysis of spatial properties of rooms, it is better to employ sound sources which provide better omnidirectionality and a spatially-invariant spectrum such as specially-modified starter pistols equipped with an omnidirectional diffuser, or industrial-grade firecrackers, even if these sound sources provide smaller dynamic ranges (although usually better than 80 dB) and a not-perfectly-flat spectrum [10].

Even though an omnidirectional source does not correspond to the effective directivity pattern of real-world sound sources, it is preferable when the purpose of the measurements is to precisely determine the spatial sound distribution in a room. It avoids exploiting room effects (abnormal concentration of energy and focusing for selected orientations of a directive source), as can happen when employing highly directive loudspeakers. However, when the purpose of the measurements is to determine the acoustic response of a room when a particular kind of source is used (a particular musical instrument or the human voice), a directive sound source could be added to the omnidirectional during the measurements. When employing an electrical test signal, the source is usually a dodecahedron or another type of spherical source.

For wide-band Impulse Response measurements to be used for auralisation it is necessary to use a specially-built dodecahedron with wide frequency response (30Hz to 16kHz, minimum) and incorporating a perfectly-flat digital equalisation system. In many cases the need to employ a portable and cheap system makes it preferable to employ “truly impulsive” sound sources such as starter pistols, balloons or firecrackers. Recent studies [11, 12] analysed the properties of balloons and revealed that they are, in general, unsatisfactory sound sources.

IV. THE MICROPHONE SYSTEM

So far, the ISO 3382/2009 standard [9] requires omnidirectional, monoaural microphones to be utilised in the measurement of monophonic acoustic parameters and only specifies the dimension of the microphones (preferably less than 13mm). Moreover, the ISO 3382/2009 standard describes the characteristics of binaural microphones (real heads or dummy heads), which could be used to measure binaural Impulse Responses and IACC. The standard also considers using figure-of-eight microphones to measure some lateral-energy parameters, such as LF and LFC, but does not provide technical specifications for these types of directive microphones. However, it is evident that monoaural or even figure-of-eight microphones cannot provide complete information about spatial sound distribution in the theatre. For this purpose, a multi-microphone system is necessary to capture the complete spatial information.

4.1 B-Format Microphone

Leaving aside binaural measurements, required only for binaural parameters, a B-format microphone (such as the Soundfield^{TM}) has been considered for many years to be the optimal transducer for performing 3D Impulse Response measurements in theatres and auditoriums. The W channel is good for the monoaural parameters (omnidirectional), the Y channel provides the figure-of-eight signal required for computing LF, and the other two directive channels (X and Z) can be used for recreating the entire 3D soundscape inside a playback environment using the well-known 1st-order Ambisonics technology.

V. EMPLOYMENT OF B-FORMAT IRS

The techniques employed to analyse 3D impulse response is based on the work of Farina and Tronchin [5]. It exploits the capabilities of the B-Format signal of detecting the direction-of-arrival of each impinging wavefront by computing the “instantaneous” sound intensity vector I and the instantaneous value of the energy ratio r_E and is based on the same vector decomposition scheme initially proposed in [16], also related to the later SIRR method [12]. The three components of the sound intensity vector can be simply obtained from the B-Format Impulse Response and reproduce ina panoramic picture the results, as reported in [5]. The results can be visualised dynamically by means of a properly developed post-processing tool, plotting at every “frame” a circle, located at position *(a,e)*, having a diameter proportional to the sound intensity modulus $|I|$ and opacity proportional to r_E. The moving circle is plotted over a panoramic 360°x180° photographic image taken from the microphone position, while a synchronised marker moves over the Impulse Response graph so that it is easy to see the arrival direction of each reflection and how much the corresponding wavefront is “polarised”.

This method allows for processing of a large amount of B-format IRs previously measured in the scientific community by means of Soundfield microphones or other tetrahedral probes, obtaining much more information than traditional acoustic parameters.

VI. THE CASE STUDY

The case study here reported was conducted inside the "Teatro 1763" in Villa Mazzacorati, Bologna, Italy. In this experiment the Impulse Responses have been measured to analyze also the variability of sound parameters (particularly clarity, definition and reverberation time) on lateral and vertical moving inside the theatre. The Impulse Responses have been measured with a digitally equalised dodecahedron sound source fed by a SineSweep signal and three different microphones for the measurements.

The teatro 1763 is an important historical theatre located in Bologna. The theatre could host only 80 seats, and is considered as one of the most important private historical theatre still existing in Italy.

Figure 1: Measurements in the Teatro 1763 Villa Mazzacorati, with the three types of microphones

VII. VERTICAL MOVEMENTS

Two different movements have been done. In the first example, the SoundField (B-Format), the BK (omnidirectional) and the Neumann (dummy head) microphones were fixed in only one position of the theatre.

The results for vertical movements are reported in the following figures for the following acoustic parameters: Clarity C50, Center Time and Reverberation Time RT30.

During the experiment on the vertical axe, only the SoundField microphone have been lifted for 15 different heights from 1.10m to 1.40m, while Neumann and BK microphones were used like a reference measurement at the same height. In the second example, during the movement on the lateral axe, the SoundField microphone was moved from right to left side of the theatre in 10 different positions in front of the stage, whereas the Neumann and the BK microphones were fixed in the middle of the room. The measuring pointws are reported in the following figures.

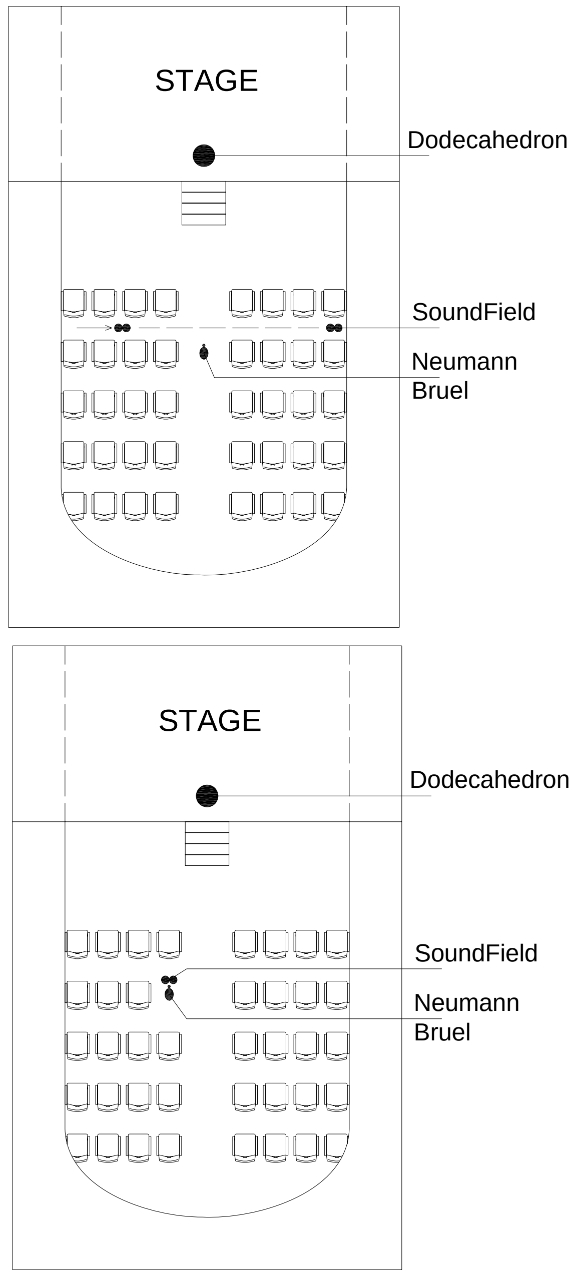


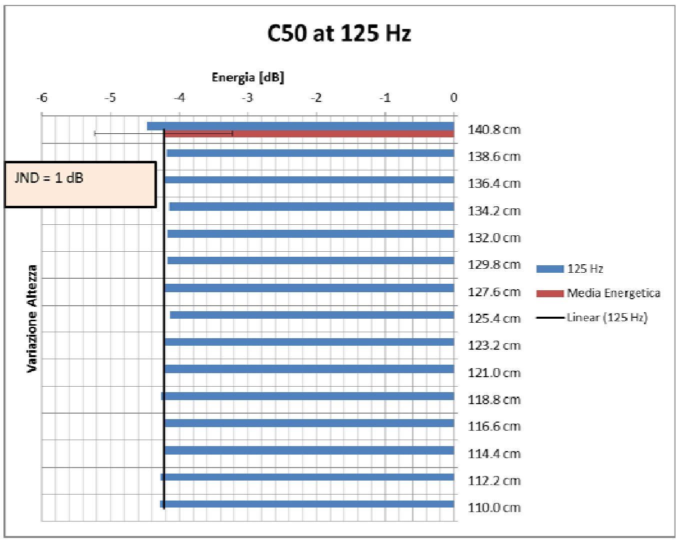
Figure 2: plans of Teatro 1763 Villa Mazzacorati, with positions of microphones for two type of measurements

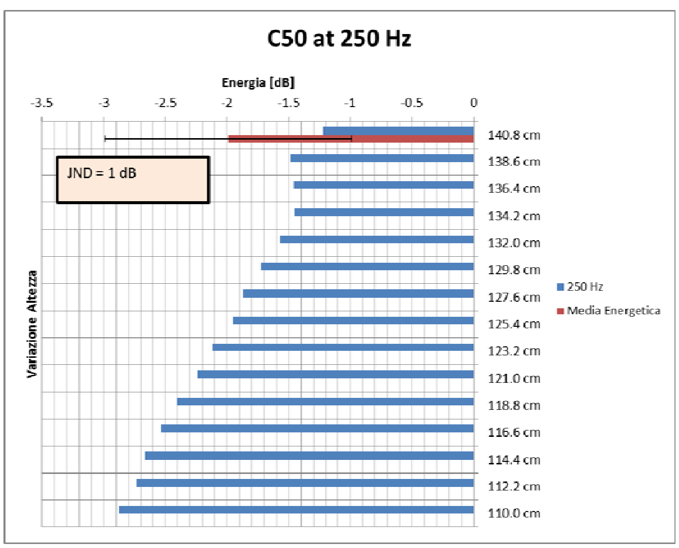
The statistical analysis performed on these measurements, showed some remarkable results, especially with relation to

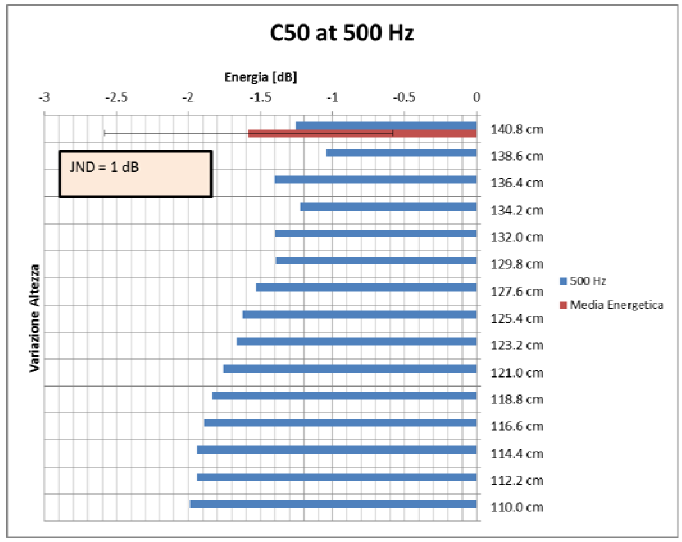
Clarity. This parameter was chosen because it is considered as the most stable energy acoustic parameter in room acoustics.

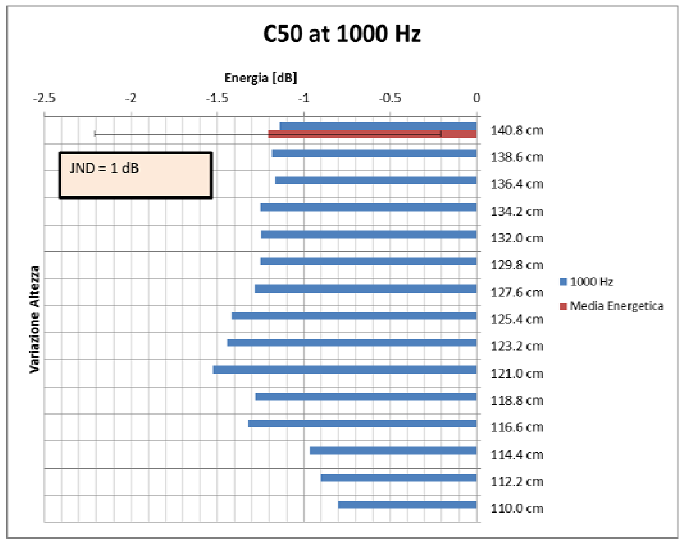
Whilst at 125 Hz Clarity was substantially constant with the movement of the Soundfield Mic, at 250 Hz, the variation of Clarity C50 in the vertical plane is systematic, even though within the JND value. All the reverberation times (i.e. EDT, T20 and T30) slightly vary both during lateral and vertical movement of the microphone. However, their variation at mid frequencies (500 Hz, 1kHz and 2kHz) is always within the JND range (figure 3).

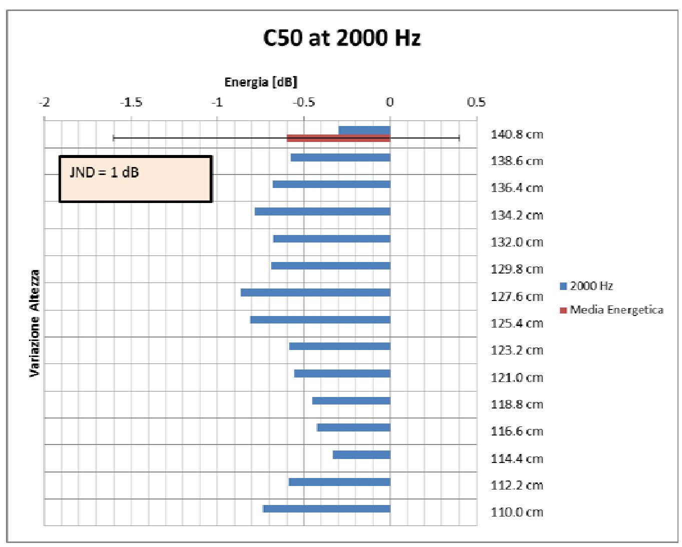
As far as Clarity and Center time is concerned, the variations of those parameters are higher and in some cases the variation is greater than JND, especially for some frequencies. In the following figures, the measured values of the corresponding acoustic parameters are reported for each height, together with the average value (in red) and the JND (continuous line).











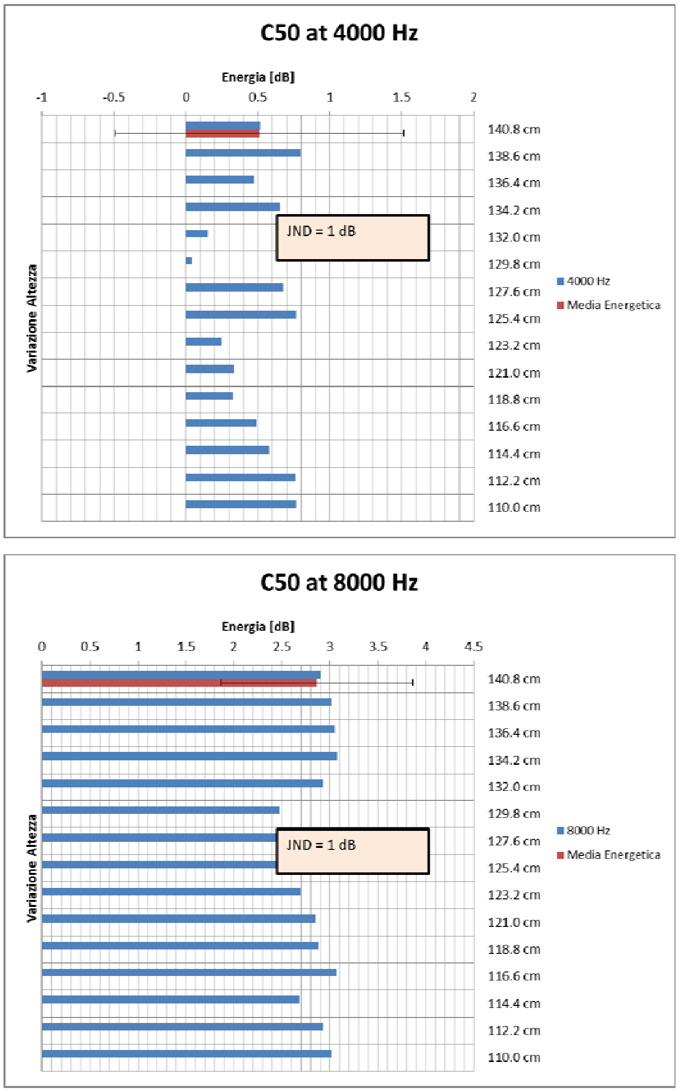
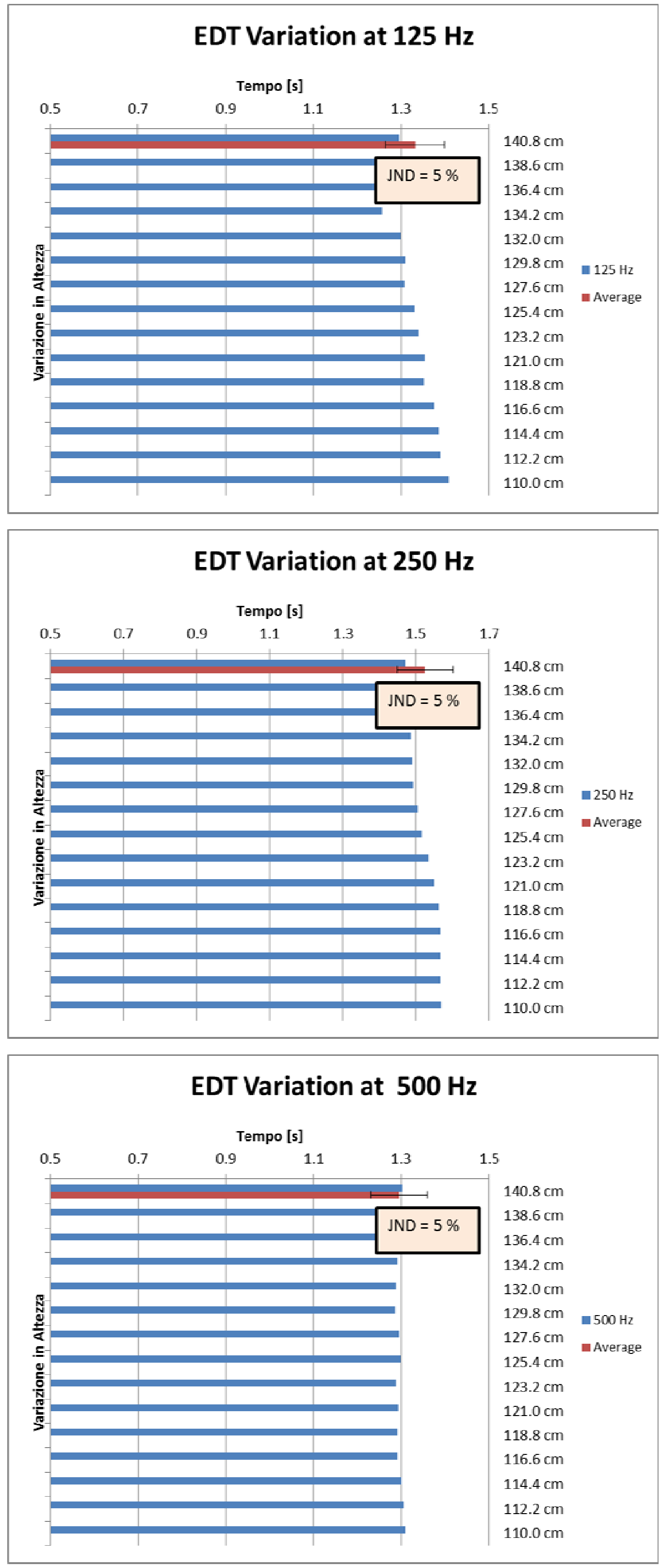


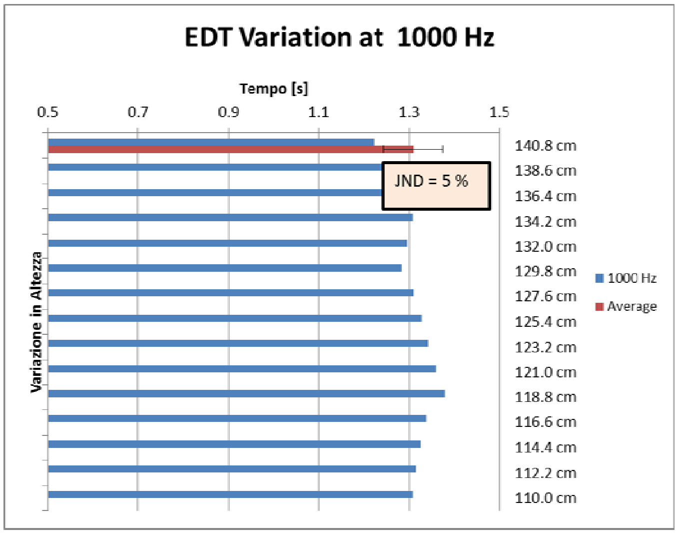
Figure 3: variability of parameter C50 in vertical moving from 125 Hz to 8 kHz for SoundField microphone

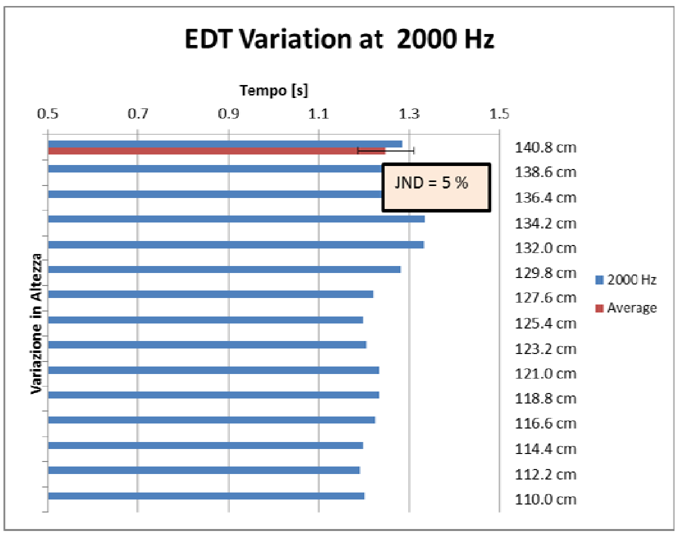
The measurements have been processed with Aurora to extract from every sound signal its Impulse Response and calculate its acoustic parameters. For each measurement, the acoustic parameters have been calculated for each octave-band frequency (from 125 Hz to 8 kHz) and they have been compared with the corresponding JND to analyze the variability.

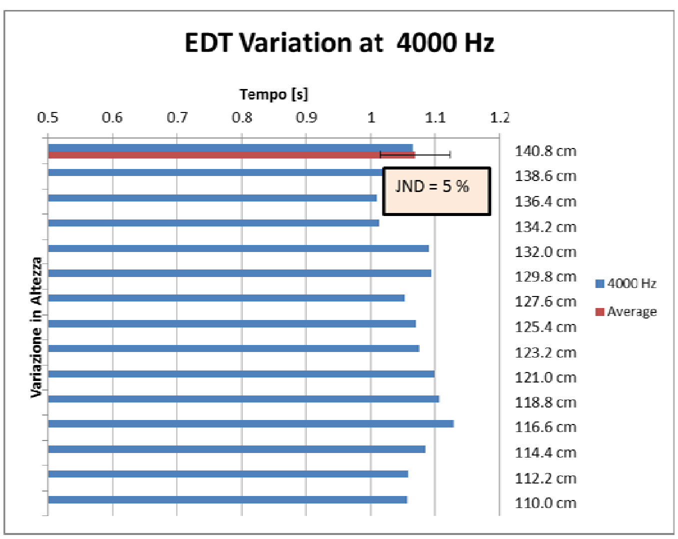
The measurements were repeated twice, in order to verify the time-invariant assumption of the acoustic system, since this aspect is very important during the measurements that were performed in the theatre.

The figure 4 reports the variability of Early Decay Time (EDT), for the same frequency range.









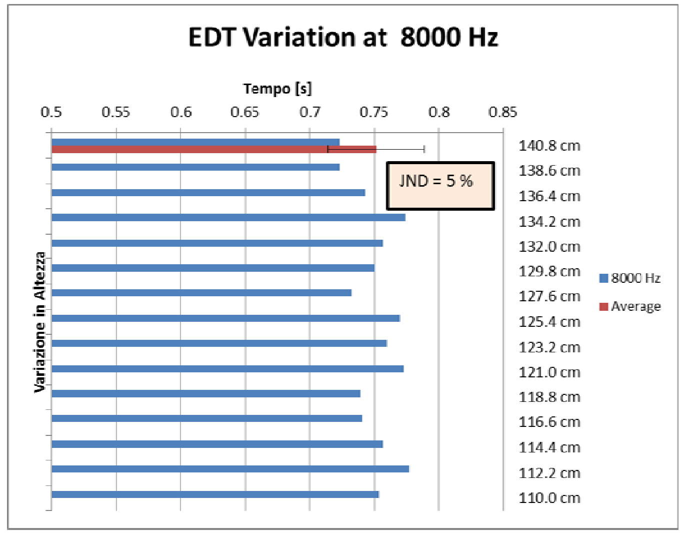


Figure 4: variability of parameter Early Decay Time (EDT) in vertical moving at frequencies from 125Hz to 8 kHz SoundField microphone

In some cases, the variability of the acoustic data were particulartly considerable, especially at high frequencies. In the case of Center time, for example, this variability is reported in figure 6 for 4000 Hz.

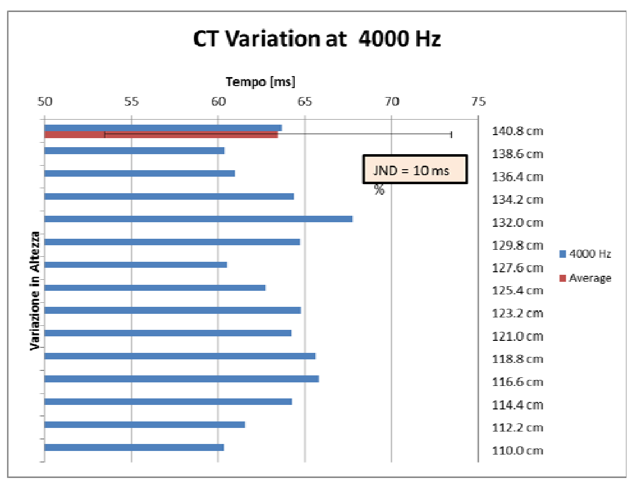


Figure 6: variability of parameter CT in vertical moving at frequencies 4000 Hz for SoundField microphone

It could be noticed that, in any case, also at high frequency the variability of center time is within the JND (i.e. 10 ms), even though there is a certain degree of uncertainty among the different heights.

A part the previous considerations, these results show that the acoustic characteristics of theatre are within JND in every position and at all heights.

VIII. LATERAL MOVEMENT

During the second part of the experiments, the microphone was moved laterally. This movement underlined more variability than the vertical ones. However, these results are not a surprise, since normally the sound distribution in a theatre changes with the position of the receiver in the room. Figure 7 compares the differences among RT30 at 500, 1k and 2k Hz measured in Teatro Villa Mazzacorati with vertical movement (above) and lateral movement (below).

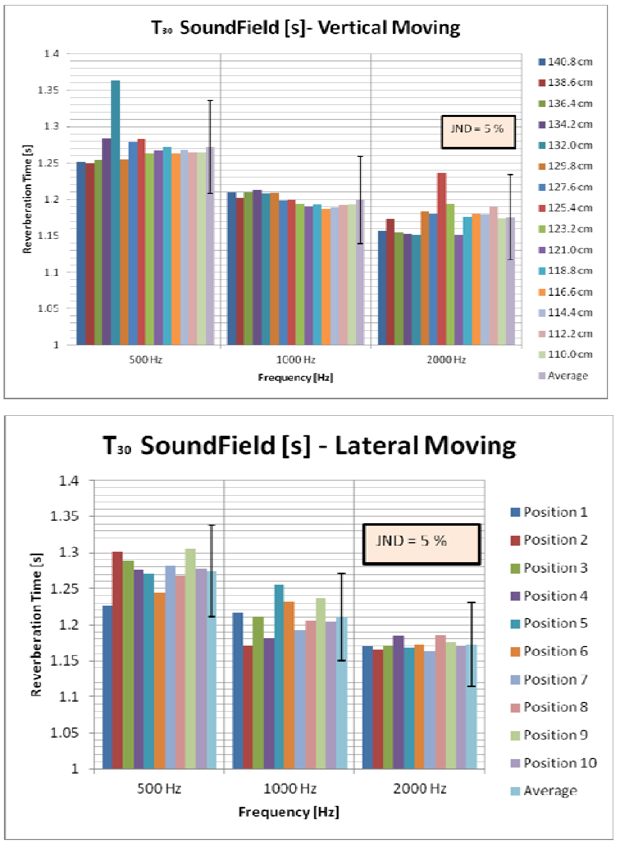


Figure 7: graphics about variability of parameter T30 for lateral and vertical moving at frequencies 500 Hz, 1000 Hz and 2000 Hz.

Considering the lateral movement in the broadband frequencies, the variation of the acoustic parameters resulted greater than JND. However, these results are due to the sound characteristics of the hall and not to uncertainties due to the measurements.

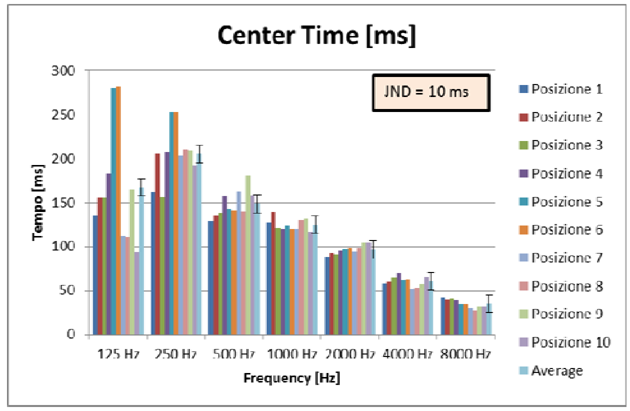


Figure 8: graphics about variability of parameter CT for lateral moving

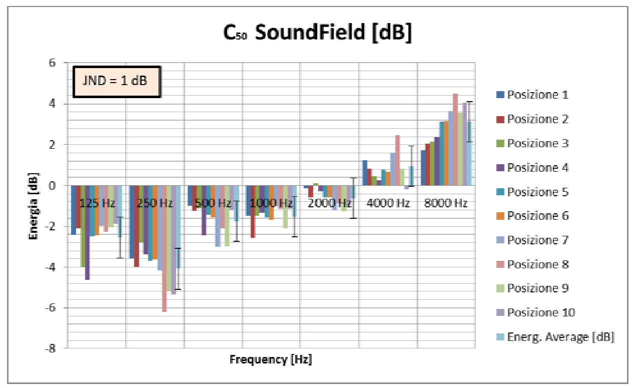


Figure 9: graphics about variability of parameter C50 for lateral moving

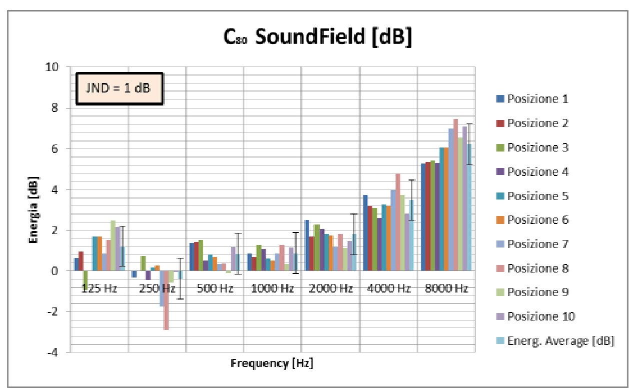


Figure 10: graphics about variability of parameter C80 for lateral moving

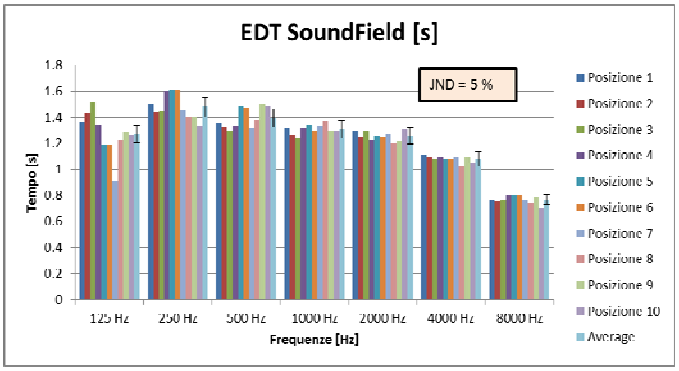


Figure 11: graphics about variability of parameter EDT for lateral moving

IX. Conclusions

The uncertainties due to vertical and lateral movements of the microphones have been investigated in the Teatro 1763 in Bologna. It was shown that some parameters (as Clarity) could vary considerably moving the microphone vertically or horizontally. Nevertheless, these changes are almost within the JND of these parameters, However, further experiments could be necessary to determine the variation of these acoustic parameters (and others) in different (more reverberant) rooms.

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Lamberto Tronchin Dr Lamberto Tronchin is Associate Professor in Environmental Physics from the University of Bologna. A pianist himself, with a diploma in piano from the Conservatory of Reggio Emilia, Dr Tronchin's principal area of research has been room acoustics, musical acoustics, 3D auralisation and signal processing. He is the author of more than 190 papers and was Chair of the Musical Acoustics Group of the Italian Association of Acoustics from 2000 to 2008. Dr Tronchin is a member of the Scientific Committee of the CIARM, the Inter- University Centre of Acoustics and Musical research, has chaired sessions of architectural and musical acoustics during several international symposiums, been a referee for a number of International journals. He was a visiting researcher at the University of Kobe in Japan, a visiting professor at the University of Graz in Austria and Special honored International Guest at the International Workshop, ‘Analysis, Synthesis and Perception of Music Signals', at Jadavpur University of Kolkata, India in 2005. He has chaired the International Advanced Course on Musical Acoustics (IACMA), organised with the European Association of Acoustics, which was held in Bologna, in 2005. In 2008 and 2009 he gave plenary lectures at International Congresses on Acoustics in Vancouver, Prague, Bucharest, Santander, Kos, Malta and Paris. He designed theatres and other buildings, as acoustic consultant, in collaboration with several Architects, among them Richard Meier and Paolo Portoghesi