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Published Version:
Merli F., Tronchin L. (2021). On the influence of thermo-hygrometric conditions in 3D acoustic measurements. Institute of Electrical and Electronics Engineers Inc. [10.1109/I3DA48870.2021.9610895].

Availability:
This version is available at: https://hdl.handle.net/11585/852917 since: 2022-08-30

Published:
DOI: http://doi.org/10.1109/I3DA48870.2021.9610895

F. Merli and L. Tronchin, "On the influence of thermo-hygrometric conditions in 3D acoustic measurements," *2021 Immersive and 3D Audio: from Architecture to Automotive (I3DA)*, 2021, pp. 1-7.

final published version is available online at: https://dx.doi.org/10.1109/I3DA48870.2021.9610895

On the influence of thermo-hygrometric conditions in 3D acoustic measurements

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***Abstract* - Within the frame of SIPARIO, a project recently funded by the Italian region Emilia Romagna, it aims to virtually reconstruct both 3D audio and 360° video of real performances by recording and undertaking acoustic measurements inside the most historical theatres and concert halls spread all over the Europe. However, the measurement of multi-channels IRs is influenced by several other factors, including thermo-hygrometric conditions. This paper deals with the experimental analysis concerning the influence of temperature, relative humidity, and air velocity on acoustic parameters. Thermo-hygrometric variables have been varied and the variation of several room acoustic parameters has been analized. The data have been collected in order to obtained a relation between the variation of the acoustic parameters with the variation of the thermo-hygrometric variables. In further steps, a statistical analysis will be conducted to determine possible correlations between room acoustic parameters and thermo-hygrometric parameters.**

I. INTRODUCTION

The changes of measured acoustic parameters could depend on different issues:

- skill of the operator;
- characteristics of the equipment;
- number and position of the source/receivers;
- measurement method;
- post-processing methods;
- thermo-hygrometric conditions.

These differences are commonly considered as an uncertainty in the measurement.

The following description could be considered as a definition of uncertainty in the acoustic measurements: “a parameter related to the measured result, characterising the scatter of results, which can be reasonably attributed to the measured value” [1, 2]. This sentence states that uncertainty estimation corresponds to an approximate description of the imperfections of the experiments. This means that uncertainty represents an error caused by several aspects, which are related to the measurements itself.

The correct experimental value and its assessment in acoustics are of fundamental importance in those sectors of acoustics, especially building acoustics and environmental acoustics, where they must be compared with fixed values imposed by standards and laws.

Starting from building acoustics, some important studies have shown the importance of several factors that might influence the determination of the final value of the acoustic parameter. For example, Öqvist [3] considered uncertainty during the measurements of airborne and impact sound insulation in industrially prefabricated Cross Laminated timber structures. Other researchers like Scrosati and Scamoni [4] analysed the possibility to find a link between uncertainty repeatability and reproducibility in case of building acoustics measurements. Mahn and Pearse [5] studied the evaluation of flanking transmission in structures following the EN ISO 12354-1 standard.

Other significant papers in the field of uncertainty in building acoustics in the last 15 years are for example the papers by Wittstock [6], Hongisto et al [7], and then those by Kylliäinen [8], Wittstock [9], Ljunggren and Öqvist [10] and Wittstock [11]. These papers consider variables linked to the skill of the operators and specific measurement conditions, but neglect to consider thermo-hygrometric conditions during the measurements. Another relevant article for this work was authored by Ljunggren et al [12]. It considered the link between sound insulation and measurement of reverberation time at low frequencies.

Moving to noise control, Wszołek and Engel [2] analyzed the estimation of uncertainty during noise measurements, focusing on sound level meter and microphones in free field conditions.

The uncertainty in room acoustics has been less considered because there are fewer legal consequences in this field when considering the experimental (measured) values and the values fixed by law. Important work was authored by Pelorson et al In their paper of 1992 they statistically described the variability of some room acoustical parameters [13]. De Vries et al. in their paper [14] found some uncertainty for spatial parameters (i.e.: LF and IACC) in a little variation of the position of microphones. In more recent years, San Martìn et al [15], have studied the sound source orientation as a cause of uncertainty. In other papers, Witew et al [16]; [17], [18] and Knüttel et al [19] considered the effects of loudspeaker directivity in room acoustics measurements.

These works demonstrated that the directionality of the sound source has a significant influence especially at high frequencies on the results obtained for acoustic parameters derived from the impulse responses. This was found to be true also for loudspeakers (dodecahedron) which meet the requirements of the ISO 3382 standard regarding the directional patterns of sound sources. The parameters most sensitive are C50, G and IACC. However, also in the group of reverberation times, the EDT seems to be more sensitive than the T30, because the integration interval is shorter.

The link with temperature and humidity has been considered in the field of voice alarm (VA) systems. For example, Gomez-Agustina et al [20] as well as Yang and Moon [21] studied their effects in the voice reproduction systems. These researches showed that reverberation time increases at high frequencies when temperature and humidity increase. As a result, speech-related parameters (e.g. STI) were decreasing with rising temperatures and humidity values.

Other studies have reported other aspects of variability in room acoustics measurements. For example, Guski and Vorländer considered noise in measurements as an important component to be considered [22]. Recently, Tronchin et al [23], [24] found that a variation of acoustic parameters could be found simply by elevating the microphones.

Another possible source of uncertainty (variability) is the numerical procedure employed for the post-processing of the measurements. The works by Chu [25] and Hirata [26] have reported the relevance of the post-processing method used for the calculation of the acoustic parameters. Furthermore, Lundeby et al [27] showed that the determination of room acoustical parameters could depend on the algorithms utilized, which introduce systematic differences caused by differences in noise compensation, time-windowing and filtering, reverse-time integration.

Actually, only a few standards consider the importance of thermo-hygrometric conditions during acoustic (especially noise) measurements or propagation. A noticeable example is the ISO 9613-1 [28], which analyses the air absorption effect in outdoor noise propagation, evaluating a direct correlation with temperature, relative humidity and static pressure.

Other standards simply mention the necessity to consider temperature and relative humidity without providing a method that could assess their effects. For example, ISO 354 [29] standard recommends maintaining the relative humidity between 30 and 90% and the temperature of 15 Celsius. Also, the ISO 3740 series [30] consider the "environmental correction" during the evaluation of sound power measurements of noise sources.

II. THE AIM OF THE PAPER

When considering the sound attenuation caused by the medium in which the acoustic waveforms propagate, it is common to refer to large distances, especially in outdoor propagation. The sound attenuation is caused by three effects: shear viscosity, molecular relaxation and thermal conductivity. Among them, molecular relaxation perhaps represents the most consistent component of sound attenuation in the audio frequency ranges [31]. These effects normally increase proportionally with the square of the frequency [32]. In such a way, the total absorption area A_{air} could be calculated with the following formula (1):

$$A_{air} = 4\ m\ V\ (m^2) \tag{1}$$

Where m is the air intensity attenuation coefficient. Table 1 shows the values of m [33].

Although it is normally neglected, another important effect is the variation of the speed of sound, which is obtained with the following equation (2):

$$c=331.4\sqrt{1+\frac{t}{273}}\quad \left({}^{m}\!/_{s}\right) \tag{2}$$

From (2) it is evident that if temperature varies, the speed of sound varies as well, and therefore there will be a change in Sabine's equation for reverberation time:

$$RT=55.3\ \frac{V}{c(A+4mV)}\quad (s) \tag{3}$$

The reverberation time is directly proportional to the distance and therefore RT is linked to the air sound attenuation.

These effects provoke a variation of sound propagation due to the variations of the medium (air), and therefore of the acoustic parameters.

For these reasons, this paper reports the influence of the main environmental variables on some of the most important acoustic parameters which are normally considered in room acoustics. In particular, the parameters are strength (G), clarity (C50 and C80), definition (D50), reverberation time (T30), Early Decay Time (EDT), Inter Aural Cross-Correlation (IACC), Lateral Efficiency (LE) and Lateral fraction (LF). They have been measured by varying temperature, relative humidity and velocity of air.

III. EXPERIMENTS

The experiments here reported were conducted at the University laboratory of the School of Engineering, in Bologna, Italy. The survey was conducted for more than 25 hours in the summer season, with a sampling of 5 minutes. Globally, 301 sets of measurements were obtained.

This period has been chosen because in Bologna the variability of temperature and relative humidity during the day/night period is considerably higher rather than winter of other periods. In that period there are no students or other activities which could have compromised the data, and the external background noise is very small. The same equipment, fixed in one specific position and orientation, was employed and controlled by one operator, located in a different room, for minimizing the uncertainty of the not thermo-hygrometric variables. A specific script (MatLab) was developed to perfectly synchronize in the time all the measurements.

The room under test is reported in Figure 1. It has an area of about 650 m^2. The laboratory is exposed to the sun for approximately 80% of the outer surface. This condition causes a relevant temperature range. The room is also provided with a variable intensity mechanical ventilation system which allows varying the velocity of the air up to a maximum of about 0.5 m/s.

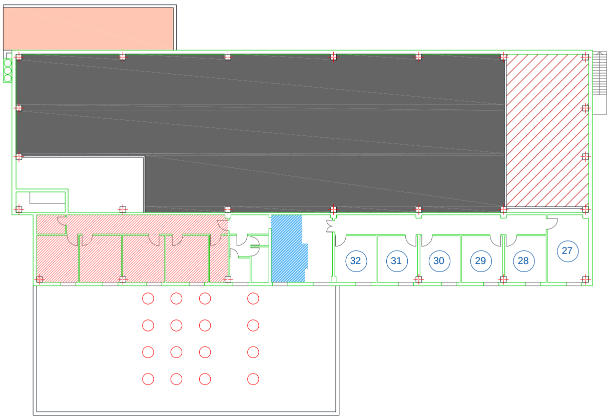

Fig. 1. The building. In grey: the room

The following equipment was employed for the recordings of the acoustic measurements:

- Digitally equalized dodecahedron (Look Line)
- B-format Microphone (Soundfield MK V)
- Dummy head (Neumann KU 100)

An exponential sine sweep (chirp) ranging from 40 Hz to 20 kHz was played during the measurements. The outputs were acquired by a sound card and stored as waveforms with 96 kHz sample rate and 32 bit.

Figure 2 reports the scheme of the measuring method.

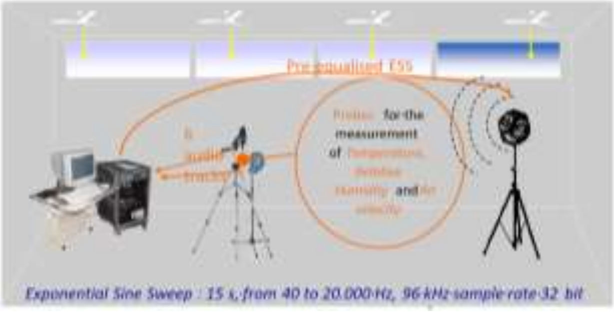

Fig. 2. The measurement' scheme.

From the recordings, the 1806 tracks were convoluted with the corresponding inverse filter. Afterwards, the acoustic parameters were then calculated using Adobe Audition software and the Aurora system [34].

To calculate the monoaural parameters (W channel) and the spatial parameters (LE and LF), a B-Format microphone was employed. The parameters have been calculated after having processed the B format impulse responses. Conversely, the dummy head allowed to measure Binaural impulse responses (BIR), from which the IACF and IACC values have been finally calculated.

Both the B-Format and the binaural impulse responses were collected for further psychoacoustics tests, with the purpose to check whether the different thermo-hygrometric conditions could have influenced the 3D sound perception of different musical motifs in a listening room.

The measurements of the thermo-hygrometric parameters were obtained using two separated systems. The first was used for temperature and relative humidity. It allowed detecting the temperature and humidity at regular intervals, every 5 minutes. The second consisted of a hot wire anemometer for air velocity measurements. In the following, the mean value over a time interval of one minute was considered.

IV. EXPERIMENTAL ANALYSIS

The experiments included measurements at regular time intervals, except of course for the thermo-hygrometric parameters. The aim was to identify and distinguish the variations of the uncertainty due to the physical characteristics of the medium.

Theoretically, the measurements of the acoustic parameters need the linearity and time invariance of the system. These situations are almost impossible in normal enclosed space. The methodology reported below is therefore aimed to check this hypothesis and attempts to quantify the variations of the acoustic parameters of a room changing indoor temperature, relative humidity and air velocity.

The measurements were carried out using a pre-equalized ESS signal. Afterwards, all the recorded tracks were post-processed by using the inverse filter of the ESS, and finally, the acoustic parameters were calculated.

In order to minimize the uncertainty of the thermo-hygrometric variable, only one operator, the same instruments and a fixed position and orientation of the microphone and the sound source have been chosen. The surveys have been repeated 301 times, every 5 minutes. The wave files from the microphonic probes have been recorded, and the thermo-hygrometric values have been stored.

In the initial 200 measurements, the ventilation system was also operated increasing regularly the intensity, as regular as possible, up to the maximum value, and then in a similar way back until it was completely switched off.

Each cycle lasted 2 hours, from the value of v=0 up to v_{Max} and back. Globally, 24 measurements. The remaining 100 measurements were conducted when the ventilation system was switched off (v=0).

To compensate for the non-linearities of the loudspeaker, the signal generated was pre-equalized. The B-Format microphone and the dummy head were positioned close to each other and at a distance of about 16 meters from the dodecahedron.

All the measurements were synchronized as follows:

- measurements of the acoustic parameter, every 5 minutes, duration of 20 seconds (15 seconds of signal followed by 5 of no signal);
- thermo-hygrometric measurements, every 5 minutes;
- anemometer measurements, every 60 seconds.

The thermo-hygrometric data were collected after 10 seconds from the beginning of the acoustic measurements, to have the parameters of the central instant of the sound event.

The anemometer was started 20 s before the starting of the acoustic measurements. In such a way, the average air velocity of 60 seconds was also centred with reference to the recording of the sine sweep signal. Figure 3 reports the synchronization of all the measurements.

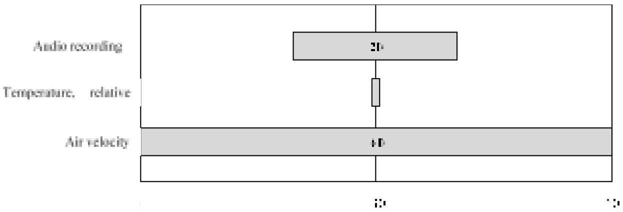

Fig. 3. Synchronisation of the measurements

The survey allowed recording 1800 audio tracks (6 tracks for each measurement: 2 for binaural and 4 for Soundfield relating to 301 measurements). Afterwards, the impulse responses have been extrapolated by employing Aurora plugins. From the impulse responses, some acoustic parameters have been calculated at the octave bands of 125, 250, 500, 1000, 2000 and 4000 Hz.:

- Strength, G [dB];
- Clarity, C50 [dB] and C80 [dB];
- Definition, D50 [%];
- Reverberation time, T30 [s];
- Early-Decay Time EDT [s];
- Cross-Correlation Inter Aural, IACC;
- Lateral Efficiency, LE;
- Lateral fraction, LF.

V. DATA ANALYSIS

The analysis of thermo-hygrometric conditions involved temperature, relative humidity and air velocity. In a further step, an analysis of the acoustical parameters measured, as well as the investigation of some relations between these values and the variations of temperature, relative humidity, and air velocity has been conducted.

Figure 4 shows temperature, relative humidity and air velocity values.

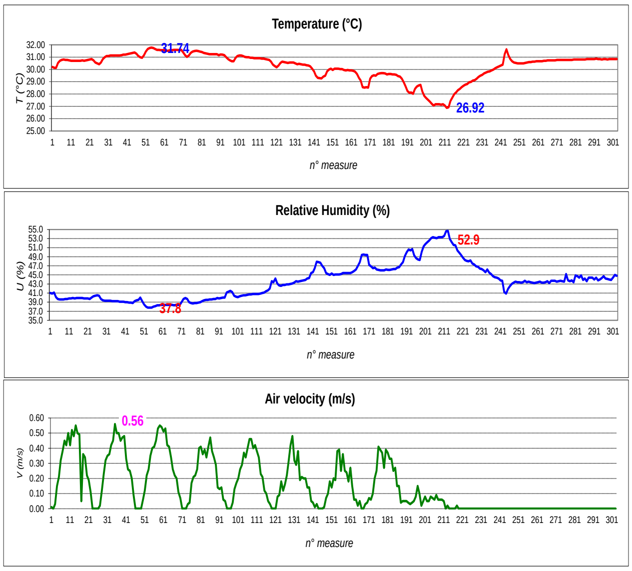

Fig. 4. Analysis of temperature, relative humidity and air velocity.

Considering figure 4, we see that when temperature decreases, the relative humidity increases, and vice-versa. This is a normal thermo-hygrometric relation: the two parameters have an inverse correlation. The measurements were carried out on 25 consecutive hours to maximize the temperature variations, which were nearly 5 °C. The variation of relative humidity during the experiment was approximately 17 % and the variation of the air velocity was 0.56 m/s (Table 1).

TABLE I. DESCRIPTIVE ANALYSIS OF THE THERMO-HYGROMETRIC PARAMETERS

	Temperature [°C]	**Relative humidity [%]**	**Air velocity [m/s]**
Average	30.28	43.52	0.15
Min	26.88	37.80	0.00
Max	31.77	54.70	0.56
Range	4.89	16.90	0.56

The only independent parameter was the air velocity, which has been artificially varied through the ventilation system. Since the absolute humidity (moisture) in the air can be considered almost constant, the temperature and relative humidity are linked by an inverse proportionality. Moreover, in the proximity of the air velocity minimum, could also be present temperature minimum (and therefore greatest relative humidity).

This phenomenon is explained by the fact that since the test room was rather high with a not uniform temperature, the warmer air tends to rise towards the ceiling. The action of the fans provokes a mixing of the air and a higher uniformity of the temperature distribution.

When the fans were stopped, the lower layers of air, i.e. not far from where measuring equipment has been positioned, show lower temperatures (and highest relative humidity). When the fans were active and carried hot air from the ceiling, higher temperatures (and consequently lower humidity) were shown.

Another aspect was that the trend of the temperature and relative humidity is generally rather regular when the ventilation system was turned off permanently.

From the acoustic analysis, some observations can be made from a qualitative analysis of the results obtained from the graphs here reported (Figure 5), showing a pattern of parameters for different frequencies. For sake of simplicity, the graphs here reported referring only to Strength (G), Clarity (C_{80}) and Reverberation Time (T_{30}). It is possible to identify three types of curves, which are reported as many significant examples:

- similar trends, even if with more or less markedly different amplitudes (Strength G, Soundfield W);
- different trends, in some cases also inverted but still recognizable and similar to the curves of the parameters thermo-hygrometric (C_{80}, from Soundfield W);
- inconsistent trends, which seem not to be dependent on hygrometric parameters, at least for some frequencies (Reverberation Time T_{30}, Soundfield W).

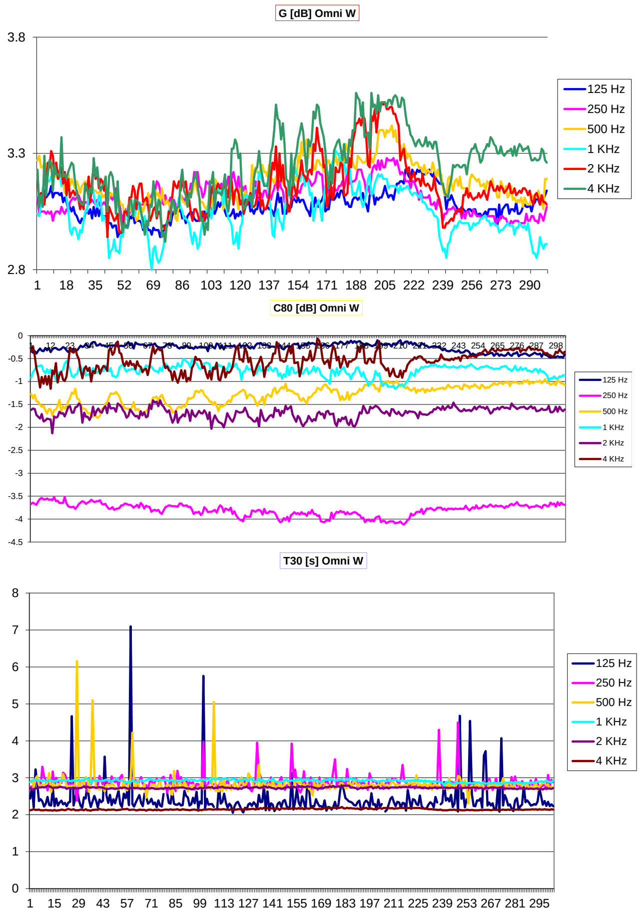

Fig. 5. Representation of Strength G; Clarity C_{80}; Reverberation Time T_{30} for all the measurements.

VI. DISCUSSION

Considering the results from the acoustic survey, the following points are particularly relevant.

1) In the first part of the measurements (from 1 to 200 measures) the acoustic parameters were strongly influenced by the air velocity. This result is reported in the graphs. When the air-conditioning system was switched off (i.e. no air velocity at all), the variation of the acoustic parameters reduced significantly. The variation of air velocity in the room represented the most relevant environmental parameter for the variation of the acoustic parameters.

2) Some acoustic parameters showed a high influence not only with air velocity but also with temperature and relative humidity. It should be noted that when there is a high not-uniform distribution of air temperature in a room (for example caused by a not properly designed heating system), the temperature gradient could provoke convective air flows among different seat positions, causing an important variation of acoustic parameters (i.e. of the sound perception), and also a variation on the tuning of musical instruments. This effect is particularly relevant for the wind instruments (like brasses, organ pipes, …), where the sound is directly generated by the airflow in between them. The temperature differences could cause thermal dilatations of the metals, and consequently an out-of-tuning of the musical instruments.

3) The link between thermo-hygrometric conditions and acoustic parameters varied noticeably with frequency. Figure 5 reports the variation of Strength, Clarity (80 ms) and T_{30}, in which Strength and Clarity are less influenced by changes in air velocity at low frequencies, whilst the link is more evident and mid-high frequencies. On the other hand, Reverberation time varies noticeably at low frequencies, whilst at mid-high frequencies, it resulted almost stable.

ACKNOWLEDGMENTS

The authors wish to thank Angelo Farina and Nicola Granzotto, for their help in supporting the realization of this study. This research was partially funded by the project “SIPARIO - Il Suono: arte Intangibile delle Performing Arts – Ricerca su teatri italiani per l’Opera POR-FESR 2014-20”.

REFERENCES

[1] ISO/IEC Guide 98-1 Uncertainty of measurement — Part 1: Introduction to the expression of uncertainty in measurement (2009)

[2] G. Wszołek and Z. Engel, Investigations of uncertainty of acoustical measuring instruments applied to noise control, Archives of Acoustics, 29, 2, 283–295 (2004)

[3] R. Öqvist, F. Ljunggren, A. Ågren, On the uncertainty of building acoustic measurements – Case study of a cross-laminated timber construction, Applied Acoustics, 73 pp. 904–912 (2012)

[4] C. Scrosati F. Scamoni, Managing Measurement Uncertainty in Building Acoustics, Buildings 5(4), 1389-1413 (2015) doi.org/10.3390/buildings5041389

[5] J. Mahn and J. Pearse, On the Uncertainty of the EN12354-1 Estimate of the Flanking Sound Reduction Index Due to the Uncertainty of the Input Data, Building Acoustics, 16(3) 199–231 (2009)

[6] V Wittstock, On the Uncertainty of Single-Number Quantities for Rating Airborne Sound Insulation, Acta Acustica united with Acustica, 93(3), pp. 375-386(12) (2007)

[7] V. Hongisto, J. Keränen, M. Kylliäinen, J. Mahn, Reproducibility of the Present and the Proposed Single-Number Quantities of Airborne Sound Insulation, Acta Acustica united with Acustica, 98 (5), 811-819 2012 doi.org/10.3813/AAA.918563

[8] M. Kylliäinen The Measurement Uncertainty of Single-Number Quantities for Rating the Impact Sound Insulation of Concrete Floors, Acta acustica united with acustica, 100(4) 640-648 (2014) doi.org/10.3813/aaa.918743

[9] V. Wittstock, Determination of Measurement Uncertainties in Building Acoustics by Interlaboratory Tests. Part 1: Airborne Sound Insulation, Acta Acustica united with Acustica, 101(1), 88-98 (2015) doi.org/10.3813/AAA.918807

[10] F. Ljunggren, R. Öqvist, Variations in sound insulation from 20 Hz in lightweight dwellings, Noise Control Engineering Journal, 66(1) 56-65 (2018)

[11] V. Wittstock, Determination of Measurement Uncertainties in Building Acoustics by Interlaboratory Tests. Part 2: Sound Absorption Measured in Reverberation Rooms, Acta Acustica united with Acustica, 104(6), 999-1008 (2018) doi.org/10.3813/AAA.919266

[12] F. Ljunggren, R. Öqvist, C. Simmons. Uncertainty of in situ low frequency reverberation time measurements from 20 Hz - An empirical study, Noise Control Engineering Journal, 64(6) 706-715 (2016)

[13] X. Pelorson, J.P. Vian, J.D. Polack, On the variability of Room Acoustic Parameters: Reproducibility and Statistical Validity, Applied Acoustics, 37(3), pp 175-198 (1992)

[14] D. De Vries, E.M. Hulsebos, J. Baan. Spatial fluctuations in measures for spaciousness, Journal of the Acoustical Society of America; 110(2) 947-954 (2001)

[15] R. San Martín, I. B. Witew, M. Arana, M. Vorländer, “Influence of the Source Orientation on the Measurement of Acoustic Parameters”, Acta Acustica united with Acustica 93(3) 387-397 (2007)

[16] I. Witew, T. Knüttel, and M. Vorländer, A model to predict measurement uncertainties due to loudspeaker directivity and its validation, The Journal of the Acoustical Society of America 131, 3244 (2012) doi.org/10.1121/1.4708108

[17] I. Witew, Mark Müller-Giebeler, and M. Vorländer Evaluation and improvement of a model to predict the measurement uncertainty due to the directivity of room acoustical sound sources, Proc. Mtgs. Acoust. 21, 015004 (2014); doi: 10.1121/1.4895587

[18] I. Witew, M. Vorlaender, Uncertainties of room acoustical measurements - Influence of the exact source and receiver, Proceedings of the Institute of Acoustics 33(2) 23-26 (2011)

[19] T. Knüttel, I. Witew, M. Vorländer. Influence of "omnidirectional" loudspeaker directivity on measured room impulse responses, Journal of the Acoustical Society of America; 134(5), 3654-3662 (2013)

[20] L. Gomez-Agustina, S. Dance, B. Shield, The effects of air temperature and humidity on the acoustic design of voice alarm systems on underground stations, Applied Acoustics 76 262–273 (2014)

[21] W. Yang, H. J. Moon, Cross-modal effects of noise and thermal conditions on indoor environmental perception and speech recognition Applied Acoustics 141, 1-8 (2018)

[22] M. Guski, M. Vorländer, Comparison of Noise Compensation Methods for Room Acoustic Impulse Response Evaluations, Acta Acustica United with Acustica Vol. 100(2) 320–327 (2014)

[23] L. Tronchin, F. Merli, M. Manfren, On the acoustics of the Teatro 1763 in Bologna, Applied Acoustics, 172, 107595 (2021)

[24] L. Tronchin “Uncertainties in acoustic measurements: a case study”, International Journal of Mechanics, 4(7), (2013)

[25] W. T. Chu, “Comparison of reverberation measurements using Schroeder's impulse method and decay-curve averaging method”, The Journal of the Acoustical Society of America 63(5) (1978)

[26] Y. Hirata, “Method of eliminating noise in power response”, Journal of Sound and Vibrations 82(4), 593-595 (1982)

[27] A. Lundeby, T. E. Vigran, H. Bietz, M. Vorlander, “Uncertainties of Measurements in Room Acoustics”, Acustica Vol. 81 (1995)

[28] ISO 9613-1:1993 Acoustics - Attenuation of sound during propagation outdoors- Part 1: Calculation of the absorption of sound by the atmosphere

[29] ISO 354:2003 Acoustics - Measurement of sound absorption in a reverberation room

[30] ISO 3740 series Acoustics. Determination of sound power levels of noise sources

[31] H Kuttruff, Room Acoustics, 6th Edition, Taylor & Francis, 2017.

[32] C.M. Harris Absorption of Sound in Air in the Audio - Frequency Range, The Journal of the Acoustical Society of America, 35(11) (1963); doi.org/10.1121/1.1918406

[33] H.E. Bass Atmospheric absorption of sound: Further developments The Journal of the Acoustical Society of America (97), 680 (1995); doi.org/10.1121/1.412989

[34] Aurora plugins www.aurora-plugins.it