MEASUREMENTS IN ROOM ACOUSTICS – HOW GOOD ARE WE AT IT?

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1 INTRODUCTION

Regardless of the field, measurements are essential for validating theories and making well-founded decisions. In architectural acoustics, the impulse response has proven to be a very useful concept from system theory. Room impulse responses can be measured with special equipment and contribute to the acoustic planning process by providing the data to place future design decisions on solid ground and quantify the effectiveness of previous design decisions. The suitability of measurements as the basis for a valid argument depends a lot on the data's associated uncertainties.

Modern measurement methods (ISO 18233, 2006) to measure transfer functions and their associated impulse responses (IR) using maximum length sequences or swept sine signals are common tools in all areas of acoustics (Müller & Massarani, 2001). In architectural acoustics, room impulse responses are regularly analysed to determine single-number quantities that serve as predictors for sound perception. Provided that the measured environment features the properties of linear time invariant (LTI) systems and that a sufficient signal-to-noise ratio is achieved, acoustical measurements of impulse responses and room acoustic quantities are usually considered to be rather accurate.

This perspective was briefly challenged in a reflex reaction to findings of de Vries, Hulsebos, and Baan (2001). Under quasi-repeatability conditions at Concertgebouw Amsterdam, RIRs were measured every 5 cm along a line following a row of seating. The data de Vries and his team collected shows how room acoustic single number quantities fluctuate over the surveyed distance. In facetious discussions, auditoria were compared with random number generators and the question of explanatory power in room acoustics measurements was raised. Of course, this fabricated perspective does not appreciate the deterministic character of sound propagation adequately, but the reference to a reproduction problem in measurements is well-founded: If room acoustic quantities change over such small distances, how can measurements be reproduced at another time? How can the acoustic effectiveness of a modification to a building be verified when the expected acoustic change is obscured by strong fluctuations?

Against this background, it is important to discuss the uncertainty of room acoustic measurements. Using the standardized "Guide to the Expression of Uncertainty in Measurement" (GUM) framework, this contribution discusses the uncertainties of room impulse response measurements and the calculation of room acoustical single-number quantities. A further emphasis is placed on the investigation of spatial fluctuations of the sound field in auditoria. The influence of an uncertain measurement position on the overall measurement uncertainty is discussed. This goes hand in hand with the question how accurately measurement positions need to be defined. The discussion leads to a hierarchical ranking of contributions that affect the uncertainty in room acoustical measurements and indicates where to direct efforts to reduce uncertainty. The presented methods form a foundation that can be flexibly extended in future investigations to include additional influences on the measurement uncertainty.

2 PREVIOUS WORK

Measuring acoustical transfer functions or their corresponding impulse responses is part of the standard repertoire in research and practical applications. Müller and Massarani (2001) give a detailed general introduction into today's methods to measure transfer functions using electroacoustic systems. The applicability of these techniques in architectural acoustics is described in ISO 18233 (2006). The systematic structure of a typical measurement chain by today's standard is shown in Figure 1: a digital computer with its software marks the starting point. In the most crude of strategies the software serves as a mere signal generator to produce an excitation signal. The signals are converted into the analogue domain and amplified to excite the device under test (DUT) with an appropriate transducer. In architectural acoustics the device under test is typically a room that is excited by a dynamic loudspeaker.

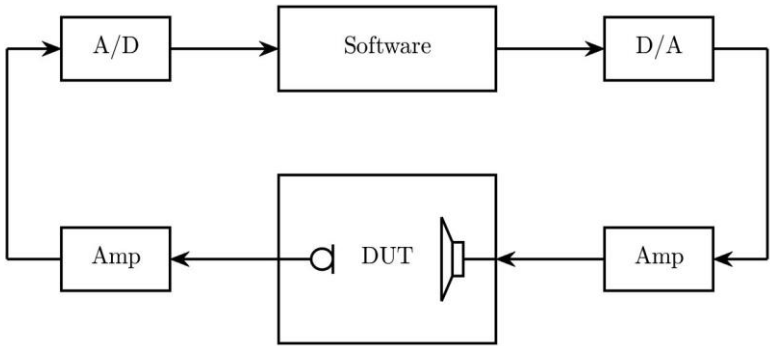

Figure 1: Systematic drawing of the acoustical measurement chain.

Modern measurement methods recognize the measurement chain and all its parts as a linear time invariant (LTI) transmission system where, according to system theory, all measurement chain properties are included in its impulse response (IR). Under this paradigm an input is linked to the output through convolution with the system's IR. The flow of information in modern measurement methods is shown in Figure 2.4. A deterministic excitation signal s(t) is fed into the acoustic transmission channel and the system's impulse response is determined through deconvolution (two channel FFT method). Output quantities such as the SPL or other parameters are calculated from the IR using standardized algorithms.

At first glance it may seem that de Vries et al. (2001) merely confirm findings from earlier investigations that were conducted in the advent of the ISO 3382 (1975) revision (e.g., J. S. Bradley & Halliwell (1988); Hidaka, Beranek, & Okano (1995); Pelorson, Vian, & Polack (1992)). After all, these studies also discuss strong variations in room acoustic parameters with relatively small spatial displacements of sources or receivers. The key difference is in the way the collected data was analysed and interpreted. Prior to de Vries, the determined spread in room acoustic parameters was discussed statistically, such that an adequately large sample size would be sufficient to correctly determine the variance in a statistical population. Consequently, these findings lead to the requirement to measure at numerous positions distributed throughout the auditorium and, hence, provide a sufficiently large sample size to calculate average values (ISO 3382, 1997).

But with growing experience in using the revised standard it soon became more and more evident that the underlying cause-and-effect chain was not fully factored in: J. S. Bradley (1994) demonstrated that calculating hall-spanning parameter averages comes with the potential to flatten out characteristic patterns. This may lead to a point where auditoria, fundamentally different in shape, are no longer distinguishable in their summary statistics. Today, there is a common understanding that averaging over all measurement positions to gain a hall mean value seems (except for the reverberation time) generally unhelpful (Barron, 2005; J. S. Bradley, 2005). This interpretation is justified within the large-scale dimensions of an auditorium, but it does not recognize the parameter variations encountered within smaller distances. Follow-up investigations by Nielsen, Halstead, & Marshall (1998), Sekiguchi & Hanyu (1998) and Okano, Beranek, & Hidaka (1998) indicate that the phenomenon continued to be a target of interest.

The increasing availability of digital measurement technology and the desire to modernize the established measurement standards (ISO 3382, 1975) have triggered numerous key investigations in the 1990s. At the same time, adding new concepts required some groundwork to confirm the new contents' significance and explanatory power (e.g., J. S. Bradley (1996); Lundeby, Vigran, Bietz, and Vorländer (1995); Pelorson et al. (1992)). To this present day, many users developed a rich experience using this standard. In this light, Barron (2005) or J. S. Bradley (2005) discuss the context in which measurement results have to be interpreted. The perspective on uncertainties in room acoustical measurements has shifted in the years since the revision of ISO 3382 (1997). Today the measurement procedure can be considered generally accepted and research discusses different influences and their effect on the uncertainty. Among other influences investigations target the directivity of sound sources (Knüttel, Witew, & Vorländer, 2013; Leishman, Rollins, & Smith, 2006; San Martin, Witew, Arana, & Vorländer, 2007; Vorländer & Witew, 2004; Witew, Knüttel, & Vorländer, 2012; Witew, Müller-Giebeler, & Vorländer, 2014), the directivity of receivers (Witew & Behler, 2003; Witew, Lindau, et al., 2013), the position of the receiver (de Vries et al., 2001; Witew, Behler, & Vorländer, 2004; Witew & Vorländer, 2011) but also the algorithm to analyse impulse responses (Guski & Vorländer, 2015; Katz, 2004; Witew & Behler, 2005). This multitude of individual studies makes it difficult to reach an aggregate perspective and thus to distinguish significant from more moderate influences.

With the "Guide to the expression of uncertainty in measurement" (GUM, ISO Guide 98-3 (2008)), a standardised framework exists that permits combining different influences to the measurement uncertainty leading to the combined measurement uncertainty. GUM places the original principles of Gaussian error propagation on a wider foundation and serves as a capable too to discuss questions of measurement uncertainty.

3 INFLUENCES ON THE MEASUREMENT UNCERTAINTY

The available knowledge about the measurement has to be gradually brought into a form so that a GUM-conforming model can be derived. The aspect of interest in this step is the search for the factors that potentially have an influence on the measurement. Identifying uncertainty contributions thus becomes a creative process in which potential influence factors are collected through brainstorming sessions, a process that is difficult to control since the participants' contributions cannot be operationalised. To organize the search, the factors contributing to quality management (Ishikawa, 1996) can be used as a starting point. As an extension to Ishikawa's original "5M" approach from the manufacturing industry, an "8M" model (e.g., E. Bradley (2017), Ch. 5) can be used to structure the search for uncertainty contributions. Not all of the eight manufacturing categories seem to relate to questions of measurement uncertainty; however, the available explanations identify the basic idea behind the grouping and, thus, an adaptation to the concepts in measurement uncertainty is possible. A list of potential uncertainty categories is shown in Table 1. Assigning the last category of calibration in Table 1 to the measurement equipment-group, an Ishikawa diagram with seven categories as shown in Figure 2 emerges.

Table 1: Root causes of manufacturing reliability according to an Ishikawa (1996)-inspired 8 category model and their interpretation in an (acoustical) measurement uncertainty context.

Tautogram	Clarification	Translation to measurement uncertainty
Man	Human recources	Observer
Machine	Technology	Equipment I (Measurement chain)
Method	Process	Measurement method (logic)
Milieu	Environment	Environmental conditions
Materials	Raw materials Consumables Information	Measurement object (documentation)
Mission	Purpose	Equipment II (Special measurement objective)
Management	Leadership	Measurement procedure (Organization)
Maintenance		Calibration

4 UNCERTAINTY OF IMPULSE RESPONSE MEASUREMENTS

the uncertainty budget of room acoustical impulse response measurements is presented based on a detailed evaluation outlined in the "Guide to the expression of uncertainty in measurement" (GUM) ISO Guide 98-3 (2008) and its introductory document JCGM 104 (2008). Even though a clear focus is placed on the equipment used in this study, the presented method may serve as a blueprint for other studies to evaluate the capabilities of their own measurement chains. For reasons of brevity, the reader is referred to Witew (2022) for the detailed discussion leading to the combined uncertainty in room acoustical measurements. The influences given in Table 2 are considered. The uncertainty inventory is sorted, starting with the largest uncertainty contribution.

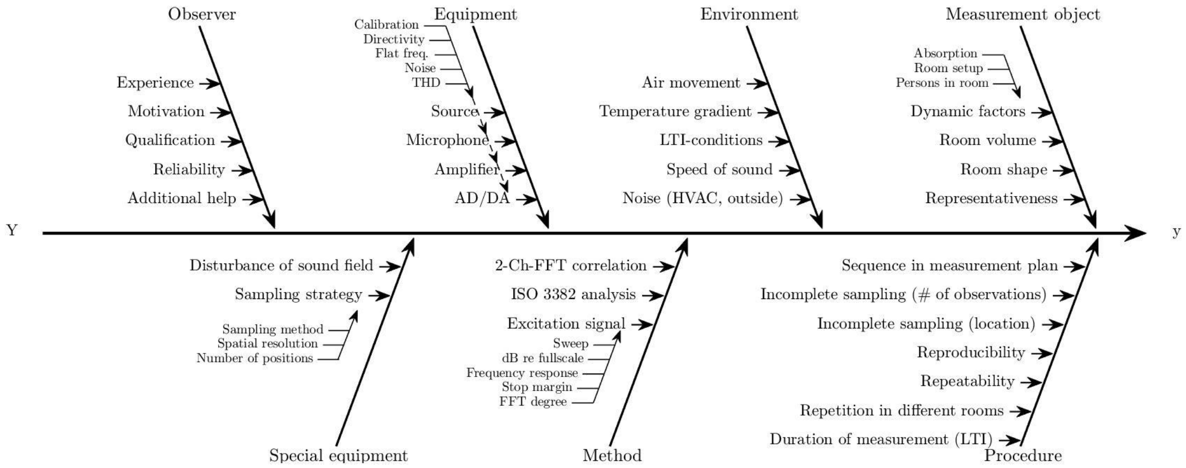

Figure 2: Ishikawa Diagram of a generic measurement process.

5 UNCERTAINTY OF ROOM ACOUSTIC QUANTITIES

The uncertainty of room acoustical quantities, i.e., strength and clarity, has already been discussed by Vorländer (2013) in regard to room acoustical simulations. Although the presented method is also valid for acoustical measurements, there are some particular differences that warrant an independent discussion: In simulations, uncertainties are due to the implemented physical (sound propagation) model and the input data of the calculated scenario, whereas in measurements inadequacies of the measuring equipment play a prominent role. Additionally, for measurements, the uncertainties of the input quantities are available in logarithmic scale. Also, the findings of Vorländer's (2013) fundamental investigation are extended by the uncertainties of other room acoustical quantities that have not been discussed before.

To discuss the uncertainty of room acoustical quantities, the standardized GUM framework’s principle of uncertainty propagation is used. The RIR’s uncertainty summarized in the previous section is propagated through the algorithm to determine quantities like “Reverberation time”, “Definition”, “Strength” and “Center time”. The algorithm to calculate these quantities is published in ISO3382. From the GUM’s perspective this algorithm can be interpreted as the measurement function. To apply the principle of uncertainty propagation the partial derivatives of the measurement function in respect to all uncertain input variables has to be determined. For the sake of brevity the reader is once again referred to Witew (2022) for the mathematical calculation of the uncertainty. Although the uncertainty of room acoustic quantities depends on the individual underlying RIR, an upper bound on the uncertainty can be estimated based on the large number of measurements made in this study. The uncertainties are given in Table 3.

Table 2: Measurement uncertainty budget for room acoustical impulse response measurements.

Uncertainty Source	Knowledge base	Uncertainty contribution
Source Directivity	Behler and Vorländer (2018)	0.38 dB
Calibration measurement	Wittstock and Bethke (2005) with revised contributions	0.26 dB
Phistonphon calibration	Wittstock and Bethke (2005)	0.21 dB
Long term repeatability	Measurements in 2 auditoria	0.2 dB
Equalization measurement	Revised contributions based on Wittstock and Bethke (2005)	0.16 dB
Flatness of microphone freq. response	32 measurements	0.15 dB
Octave-band filtering	Wittstock and Bethke (2005)	0.12 dB
Change in temperature	Payne (2004)	0.12 dB
Change in athm. Pressure	Payne (2004)	0.07 dB
Microphone directivity	Measurements in 3° resolution	0.07 dB
Sound field distortion	Payne (2004)	0.011 dB
Change in rel. humidity	Payne (2004)	7.5E-3
Loudspeaker nonlinearities	Behler and Vorländer (2018)	1E-3
Power amplification	Technical documentation	1E-4
Amplification linearity	Payne (2004) with revised contributions, own experience	1E-4
Amplification noise	Technical documentation	1E-6
Microphone noise	Technical documentation	1E-6
D/A noise	Technical documentation	1E-8
D/A distortion	Technical documentation	1E-8
Clock jitter	Neu (2010)	1E-8
Microphone nonlinearities	Technical documentation	1E-9
A/D conversion	Technical documentation	1E-9
Quantization noise	Havelock, Kuwano, Vorländer (2008)	1E-10
Combined uncertainty		0.62 dB
Expanded uncertainty	(k=2))	1.24 dB

Table 3: Standard uncertainty of broadband room acoustical quantities based on more than 400 000 uncertain impulse response measurements.

Room acoustic quantity	Standard uncertainty
EDT	2.5E-4 s
T30	4.8E-5 s
C80	8.4E-2 dB
D50	0.5 %
G	0.053 dB
Center time	0.9 ms

6 UNCERTAINTY DUE TO SPATIAL FLUCTUATIONS OF THE SOUND FIELD

Based on the theoretic considerations of Davy et al (1979) and the measurements of de Vries et al. (2001) it is well known that the sound field changes measurably over short distances. At the same time, the wave field analysis of sound fields in concert halls (Witew & Vorländer, 2018) provides visual and intuitive evidence of the deterministic nature of sound propagation. Against this background, if measurement scenarios are described as precisely and meticulously as possible measurement uncertainties should not play a significant role. In regard to spatial fluctuations, this implies that the measurement position (source and receiver), if not precisely controlled, leads to a considerable variance in measured results. Consequently, it needs to be investigated how exactly the measurement location must be documented or reproduced in order to achieve a given maximum measurement uncertainty.

The strategy to address this research question is a two step process: First, the measurement function needs to be established. This function shows how a change in measurement position translates into a change in the sound field. In a second step the law of propagation of uncertainty (ISO Guide 98-3, 2008, 5.1.2) is used to study how an uncertain measurement location leads to an uncertain measurement of the sound field. Due to the complexity of sound fields the measurement function is determined empirically and the uncertainty propagation is calculated using Monte Carlo simulations.

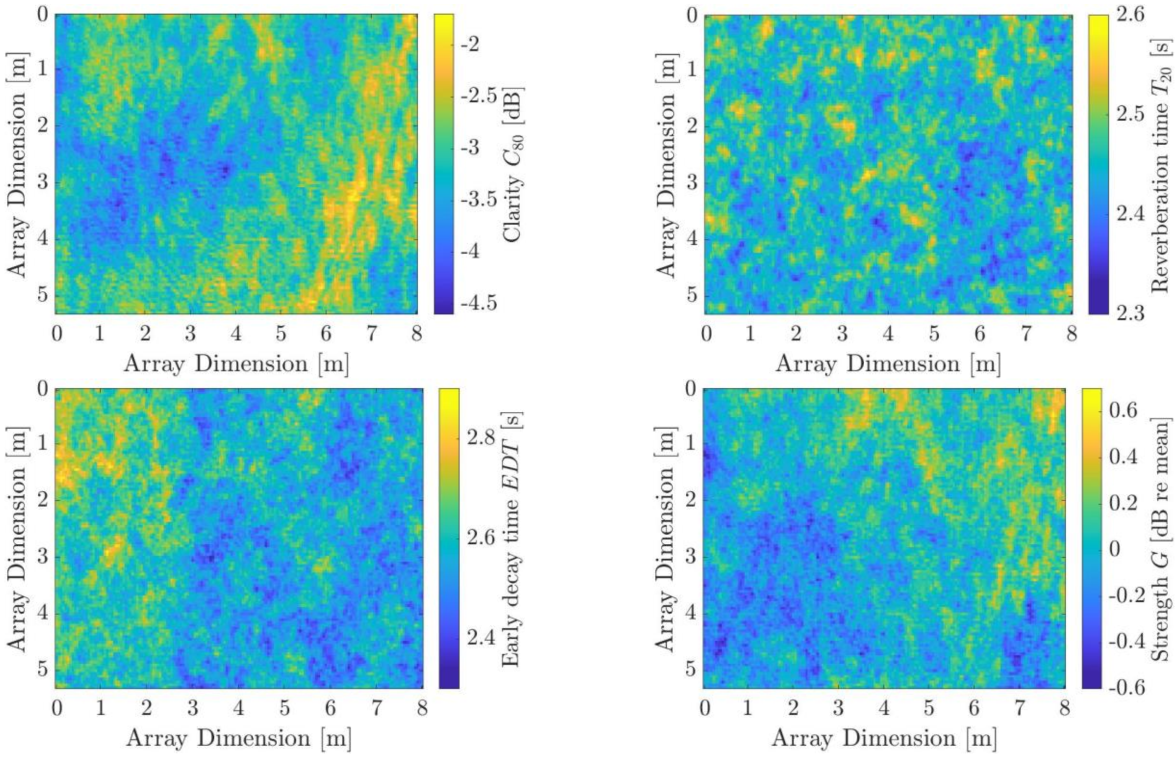

Figure 3: Broadband distribution of room acoustical quantities at Eurogress Aachen.

In 26 measurement series using a large array, the sound fields of 6 auditoria were measured. The investigated rooms include an orchestra rehearsal room with variable acoustics, large lecture halls with about 5000 m³ volume, a multifunctional hall (20000 m³) and concert halls for classical music. A detailed description of the measurement setup can be found in Witew, Vorländer & Xiang (2017). A visual description of the collected measurement data was presented by Witew & Vorländer (2018). Figure 3 provides an example and shows the broadband distribution of room acoustical quantities measured across the sampling area in the multi-purpose hall of Eurogress Aachen. This particular scenario shows that the measured quantities vary over a range indicated by the colour bar in the respective images. Depending on the room acoustical quantity, fluctuations are evident both on a local scale of a few decimetres and on a larger scale (of a few metres) through gradients from front to back or left to right. Each set of these measurements consists of 16 960 RIRs that were uniformly measured over a sampling area of 5:3 m x 8:0 m in a rectangular 5 cm resolution grid.

Goal of the first step is to quantify how the sound field changes from one position to another. While the comparison of individual sampling positions may be interesting to highlight extreme and perhaps spectacular cases this perspective is not very helpful in determining the general magnitude of the fluctuations. A statistical approach is taken to permit a more balanced view. In a full pair comparison between all of the 16 960 impulse responses a probability density function is empirically determined. Plotted as a function of distance between any two sampling locations the observed change in the sound field as characterized through room acoustic ISO 3382 quantities. Figure 4 shows this for the example of EDT. Since there is a multitude of pairs that have the same distance between them there is a wide range of differences in EDT that can occur. Figure 4 shows that it is most likely that differences in the sound field are relatively small. Larger differences have been observed, however, with increasing difference in room acoustic quantity they become increasingly rare. Furthermore, as the distance between the considered sampling locations increases, it can be observed that the average change in the sound field quickly shows a significant increase even at small distances. With larger distances, the initial difference hardly increases and only shows a weak further tendency at relatively large distances. According to GUM, ISO Guide 98-3 (2008) the relationship shown in Figure A can be understood as a measurement function that forms the foundation for the following uncertainty discussion.

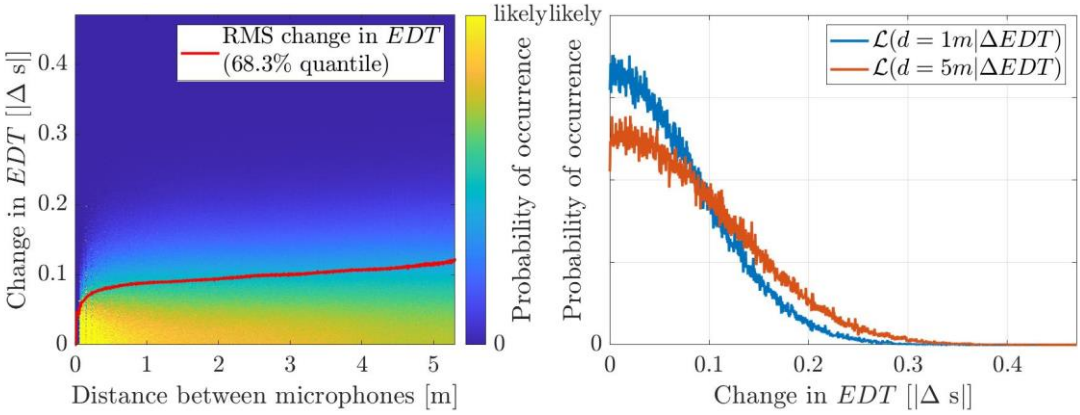

Figure 4: Likelihood $\mathcal{L}$(d|ΔEDT) of a change in EDT at Eurogress Aachen.

From the classical GUM method's point of view, a challenge arises because the measurement function of this study is not a binary relation that maps the input to a unique output. Instead, it relates the input to a distribution of possible outputs, as illustrated in Figure 4. In line with JCGM 101 (2008) a Monte Carlo method can be used is such cases. To do so, in a first step a plausible GUM-Type B distribution is established that reasonably describes the uncertainty of the measurement location. From practical experience, the $|\mathcal{N}(0,\sigma^2)|$ half-normal distribution (Johnson et al., 1994, Sec. 13.10.1).seems to be a plausible representation of the distances that occur between the assumed and the actual source or receiver position. The shape of the Gaussian distribution reflects the expectation that small discrepancies in the compared locations are somewhat more likely than larger deviations. Larger distances are supposed to occur increasingly less frequently, and thus have a lower probability. The infinite extent of the half-normal distribution introduces disadvantages as the measurement function was determined with a measurement device of finite extent. Consequently the evaluation of the half-normal distribution is limited to the [0 2.1σ] interval and thus removes 3.57% of the largest distances. To the authors, this truncation represents a defensibly small constraint. In repeated simulations, this input distribution is sampled and the corresponding change of the sound field is determined on the basis of the uncertainty propagation. This process is terminated as soon as the determined distribution of sound field changes is sufficiently stable.

The broadband results of this investigation are shown in Figure 5. The graphic representation show a solid blue line that indicates the mean expanded uncertainty for each of the investigated quantities. The x-axis indicates the expanded uncertainty of the measurement position in meter. The y-axis represents the room acoustical quantity's associated uncertainty. The shaded area marks the 2_ interval in which the expanded uncertainty curves of the 26 sets run. The dashed line results from the segment-wise linear regression of the mean uncertainty curve and forms the basis of the summary statistics given in Table 4. In this table, the second column lists the expanded uncertainty due to spatial fluctuations, and the third column shows the expanded position uncertainty, above which the uncertainties are fully pronounced.

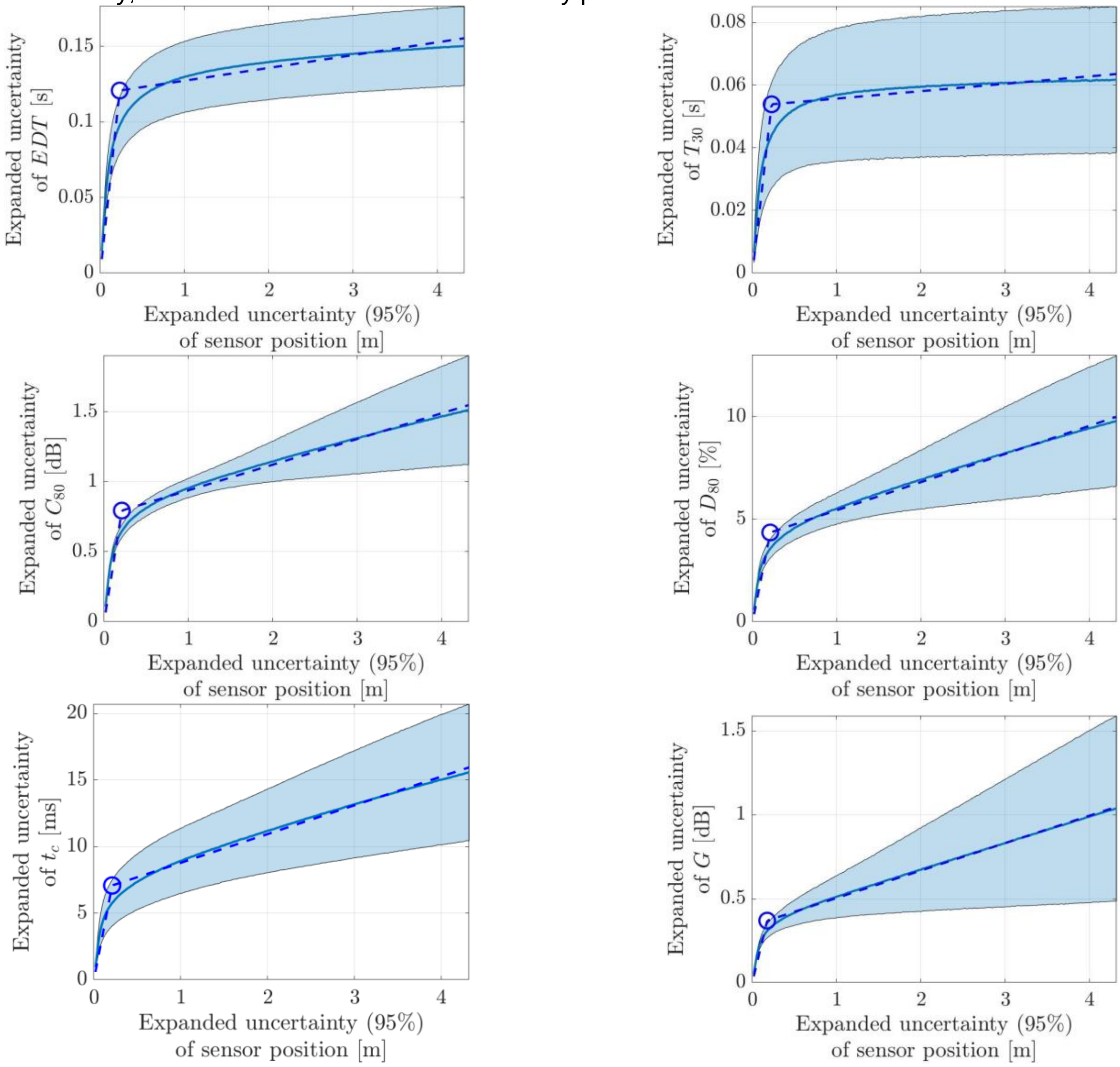

Figure 5: Expanded uncertainty of diffrent broadband room acoustical quantities as a function of uncertainty of the sensor position

Table 4: Expanded uncertainty (95%) of broadband room acoustical quantities and the expanded position uncertainty (95%) above which the fluctuations are fully pronounced.

Room acoustical quantity	Expanded uncertainty of room acoustical quantity due to spatial fluctuations	Expanded uncertainty of position with fluctuations fully pronounced [m]
T30	0.05 s	0.23 m
EDT	0.12 s	0.23 m
C80	0.79 dB	0.21 m
D50	4 %	0.21 m
tc	7 ms	0.21 m
G	0.37 dB	0.18 m

7 DISCUSSION

The discussion of uncertainties is not yet part of the standard repertoire in the field of auditorium acoustics, probably due to the relative complexity of the problems discussed in this field. While generic questions can be addressed using mathematical closed-form solutions, more challenging scenarios often feature an abundance of input variables that can only be approached with simulation tools on a case-by-case basis. When the flow of information can only be determined in individual scenarios, it is difficult to identify higher-level influence factors and how they contribute to the output. At the same time, it is not uncommon that the many input quantities are not known down to the last detail. In such conditions, it tends to be challenging to distinguish the important aspects from the less relevant ones.

This discussion stresses the importance of recording and quantifying all contributing influence quantities to investigate the propagation of uncertainties. Referring to the previous discussion of Ishikawa diagrams, it is important to recall that identifying influence quantities is a qualitative process with no guarantee of reaching comprehensive results. Against this backdrop, it is important to move forward in a granular and diligent manner to minimize the likelihood of overlooking uncertainty contributions. This argument holds even if that means discussing contributions that turn out to be factors of lesser significance. At the same time, such a comprehensive approach allows adjusting existing uncertainty contributions or introducing new ones whenever new findings suggest a reassessment.

As far as it concerns the measurement uncertainty of room impulse responses the hierarchical listing of key uncertainty contributions provides a structure and context how to target remaining open questions. For instance, the discussion about the measurement loudspeaker's directivity or the influence of nonlinearities can be put into context by relating their contribution to the combined uncertainty. Depending on the individual setup and equipment used, adjustments to respective entries may be necessary. The procedure pursued in Witew (2022) to compile this table can serve as a practical example to quantify one's own measurement capabilities. Finally, the shown data provides clear evidence for which influence quantities to target in order to have the greatest impact in affecting the combined measurement uncertainty.

The uncertainty in the measurement of room impulse responses was propagated through the algorithms to determine room acoustical quantities. The resulting uncertainties of the quantities are so small that one may well ask whether this meticulous effort is really justified. Of course, this objection is especially valid in that it is already known from ray tracing simulations (Vorländer, 2013) that many of the metrics can be determined quite accurately with very few sound particles.

As a rebuttal, it should be pointed out that, until now, a quantitative uncertainty estimate for measured room acoustical quantities was unavailable, and thus the presented findings add to the body of knowledge. This step forward holds, even if it were only to serve the conclusion that other, more prominent uncertainty contributions deserve more attention in future investigations.

The uncertainties of room acoustical quantities due to spatial fluctuations may be regarded as the most significant findings of this study. Compared to all other known sources of uncertainty, spatial fluctuation is by far the single most important one.

So far, knowledge about the sound field's spatial fluctuations is essentially based on the groundbreaking studies conducted when revising ISO 3382 (1997) in the early 1990s (e.g., Pelorson et al. (1992), J. S. Bradley & Halliwell (1988)), or the study by de Vries et al. (2001) in Concertgebouw Amsterdam that has brought new attention to the matter. The fundamentals of Kuttruff & Thiele (1954), Bodlund (1977) & Davy et al. (1979) provide a solid theoretical framework for discussing spatial variances in exponentially decaying sound fields.

This present study builds on the previous work and attempts to add to the existing state of knowledge. A major contribution is establishing the uncertainty due to spatial fluctuations as it depends on the uncertainty of the measurement position. This is a new finding compared to existing work both empirical and theoretical. The reasonable discussion of room acoustical quantities thus requires a sufficiently precise specification of the measurement location (source and receiver). This is important so that results can be reproduced in the presence of spatial fluctuations.

A second advance is the uncertainty of room acoustical quantities like clarity, definition, centre time and strength that cannot be discussed based on theoretical considerations alone. The comparison of the different quantities indicates that they are affected differently by spatial fluctuations. Consequently, their uncertainties are not solely due to spatial variances in the sound field's exponential decay, but also due to changes in the early reflection patterns.

Furthermore, the psychoacoustic relevance of the fluctuations needs to be discussed. It is hardly possible that the perceived clarity varies significantly within the area of a concert hall seat. This means that the clarity perception may be better described by using more appropriate psychoacoustic models such as the one from van Dorp Schuitman (2011).

8 CONCLUSIONS

Based on the results shown and the previous discussion a GUM conforming strategy was described according to which the main uncertainty contributions to the measurement of room impulse responses were discussed. The method allows considering additional factors or adjusting existing factors when new knowledge becomes available.

A hierarchical listing of the most important uncertainty contributions to the measurement of room impulse responses was created. Based on this list, the effort for accurate measurements can be targeted to the most relevant influencing factors to improve the efficiency of measurements. The Even though determined uncertainty depends on the individually used elements of the measurement chain the associated uncertainty is probably sufficiently low for general purpose measurements.

The uncertainty of room acoustical quantities due to uncertain room impulse responses is very low and in most cases probably not a significant factor.

Spatial fluctuations are by far the single most significant uncertainty contribution to room acoustical quantities. For many of the investigated quantities (i.e., T30, EDT, C80, D50, tc, G), this study marks the first time that spatial fluctuations have been studied with such precision. The uncertainty due to spatial fluctuations has to be recognized independently for the source and the receiver (reciprocity). In order to reasonably interpret room acoustical quantities, a sufficiently precise specification of the measurement location (source and receiver) is necessary.

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