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ASSESSMENT OF THE UNCERTAINTY IN ROOM ACOUSTICAL MEASUREMENTS

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ABSTRACT
Every measurement of a physical quantity is affected by uncertainties. For reasons of completeness and in order to make measurements comparable, it is mandatory to state the uncertainty of a measurement. ISO/BIPM's "Guide to Uncertainty in Measurement" (GUM) standardises the procedure to establish the uncertainty in all areas of measurement.
In a number of preceding works it has been found that despite standardisation (ISO3382) the measurement of room acoustical parameters show differences when the results of different measurement teams or repeated measurements are compared. With the goal of establishing a range of uncertainty that is smaller than the just noticeable difference (jnd) and in order to develop a strategy to reduce the range of uncertainty in a measurement, a linear cause-and-effect-model is presented for assessment of the combined measurement uncertainty for room acoustical parameters.
The main contributing uncertainties are determined on the basis of special room acoustical measurements that match the model used. It is discussed how the presented procedure can be used to determine the GUM-conform range of uncertainty for measurements in room acoustics. Finally, a practical strategy is derived how the uncertainty of room acoustical measurements can be reduced.

INTRODUCTION
In architectural acoustics the measurement of room impulse responses (RIR) and the derivation of room acoustical parameters play a key role. This is not only due to the fact that many aspects of the perception of sound in enclosures are related to physical properties of sound fields but also due to the common practice of evaluating the success of constructional efforts in an objective manner. However, even the most carefully designed experiments with state-of-the-art instruments yield results that are still afflicted with various sources of error.
In order to quantify the quality of measurements and with the goal of making the results of different measurement teams comparable, it is mandatory to state the range of values, that can reasonably be attributed to the measurand along with its best estimate of the "true value".
In order to propagate this concept the International Standardisation Organisation (ISO) released its *Guide to the expression of uncertainty* (GUM) [1]. Although GUM-methods are readily applied in many measurements related standards the discussed concepts have not yet found their way into practical room acoustical measurement strategies.

BASICS OF GUM
Following the principles formulated in the GUM the paradigm of classical Gaussian error calculus is shifted towards the mathematical modelling of a measurement procedure and the estimation of the input quantities with the use of probability density functions (pdf). For practical applications the standard GUM procedure is structured into 7 steps. Some of these segments can be demonstrated using Figure 1.

1. **Collecting information on the measurement and its input quantities x_i.**
   Information about measurement procedures are often summarised in the relevant standards, e.g. ISO 3382-1:2006 [2] and ISO 18233:2006 [3].
2. **Modelling of the measurement in terms of a model function f.**
   The concept of modelling is based on the idea that a signal is propagated through a

measurement chain from its cause to its effect. The “transfer function” of the measurement is mathematically modelled by the function f. In order to apply the principals of Gaussian error propagation (in case $g(\xi)$ is a normal distribution) the model equation is simplified using a first order Taylor-series expansion yielding the sensitivity coefficient c. (see Figure 1)

3. **Evaluation of the input quantities x_i.**
   The quantities that have an influence on the measurement result are identified and their uncertainties are formulated by assigning appropriate pdfs to the input quantities. (see Figure 1)
4. **Combination of the results to obtain the value y and the uncertainty $u(y)$.**
   On the basis of the input quantities x_i, their pdf $g(\xi)$ and the sensitivity coefficient c the expected value y and the associated standard uncertainty $u(y)$ can be calculated. In case $g(\xi)$ is a normal distribution this is done using the concepts of Gaussian error propagation. (see Figure 1)
5. **Calculating the expanded uncertainty $U(y)$.**
   Depending on the application it might be necessary to state intervals which comprise a higher percentage of results. In such cases the standard uncertainty is expanded by a coverage factor k which depends on the pdf.
6. **Statement of the complete measurement result $y \pm U$ and the coverage factor k.**
7. **Preparation of the measurement uncertainty budget.**
   In the measurement uncertainty budget all information for the evaluation and the improvement of the measurement process are collected.

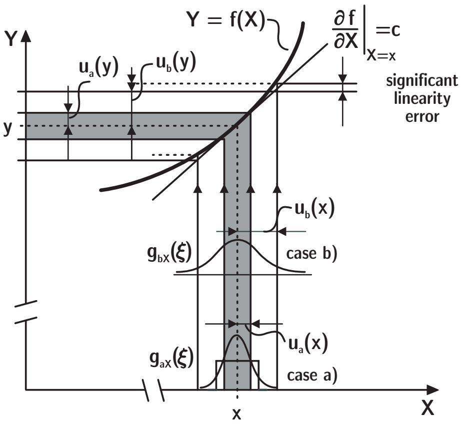

Figure 1.-Graphical representation [4] of the relationship between input- and output quantity.

Especially steps 2 and 3 of the GUM procedure are in some cases non-trivial tasks since they require complex modelling of the error propagation [4]. For many applications it is a major challenge to develop an analytical expression of the model function and to identify the influence factors, especially when the latter are not directly measurable. In such cases Monte-Carlo Simulations have proven to be a helpful tool [5], however, the intricacy of such approaches may have prevented a widespread GUM application.

A LINEAR CAUSE-AND-EFFECT-MODEL FOR ROOM ACOUSTICAL APPLICATIONS

For room acoustical applications the common state of knowledge is reflected in standards such as ISO 3382 and ISO 18233. These works define how the acoustical properties of rooms are to be measured and how the data is to be processed.

Despite the wide acceptance of these measurement procedures it turns out to be quite a task to represent the modus operandi described in the standard in terms of a model function. Not only are the mathematical operations that are used for the two-channel-FFT-measurement technology beyond elementary arithmetics, but also the impulse response may hardly be considered a simple “in-between quantity” that is readily used for an error assessment.

In order to start the discussion on how to apply the GUM-concepts to room acoustical measurement tasks it is appropriate to develop a simple and practical model that avoids a detailed analytical formulation of the model function in its first step. The linear and scalable model presented in Figure 2 illustrates how different sources of error can be grouped into room-, equipment- and evaluation errors. With respect to the boundary condition to avoid an excessive model function this representation may be transferred to the linear dependence graph in Figure 3.

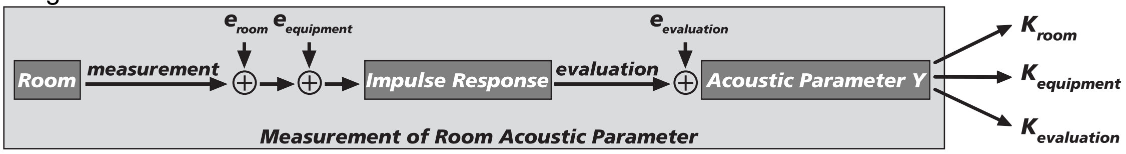

Figure 2.-Capsuled sources of measurement error

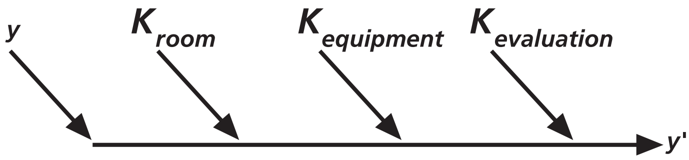

Figure 3.-Linear uncertainty dependence graph

The significant advantage of this approach is that the output quantity, i.e. a single number parameter such as T_{30} or C_{80}, can be directly analysed to investigate the influences of different sources of error. Otherwise elementary input quantities themselves, possibly of the type of source- or receiver characteristics, would have to be investigated. Such quantities, however, have the potential to be cumbersome considering that in some cases they are not accessible or even not measurable for the different elements of the measurement chain. The simplicity of this model becomes evident in Figure 1, when it is pointed out that the room acoustic parameter (C_{80}, T_{30}, etc.) is considered to be both: the output quantity as well as the input quantity which is propagated through a model function with $c = 1$. The uncertainty contributions are considered in terms of the correction factors K_i, which correspond to the standard deviation of the input quantities' pdf $u(K_i)$.

The waiving of a detailed analytical model function, however, implies relying on findings from previous studies about the sources of error in room acoustical measurements. From previous investigations, such as [6,7,8], different sources of error have been highlighted. Figure 4 shows how some of these contributions may be grouped into the three major classes of correction factors.

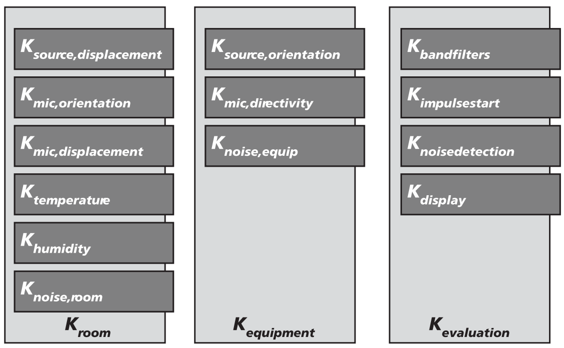

Figure 4.-Groups of correction factors in detail

On the grounds of the presented model the further considerations will be targeted at developing appropriate measurements that allow the quantification of the correction factors K_i.

ROOM ACOUSTICAL MEASUREMENTS

With the goal of developing an understanding to what extent the different sources of uncertainty have an influence on the measurement result, special experiments have been designed. The effect of noise, the directivity of the source and the variability of the result as a function of small changes in the position of the source or the microphone are of major interest in this investigation.

In order to investigate the extent to which room acoustical measurements are corrupted by background noise repeated overnight measurements have been conducted. Following the procedure as presented in [7] the influence of the loudspeakers directivity is quantified by placing the dodecahedron speaker on a controlled turntable and conducting repeated measurements while gradually rotating the source. In reference to the findings of de Vries [6] measurements with microphone arrays have been carried out to scan the sound field at a seat

in different auditoria in order to determine how much the sound field changes within the dimensions of a seat. A similar measurement was conducted by moving a sound source on the stage of different auditoria in order to determine how much this changes the final measurement result.
The results obtained from these measurements can be used to feed the investigated uncertainty model and subsequently to carry out the uncertainty evaluation of the output quantities. In the scope of this study the focus is placed on the clarity index C_{80} and the reverberation time T_{15} as output quantities. This procedure could be carried out for any other parameter.

Source Rotation
Witew and Behler [7] have previously investigated the influence of a dodecahedron source's directivity on the measurement result. As an example the surface plot Figure 5 brings into mind that commonly used sound sources deviate from omnidirectionality at higher frequencies.

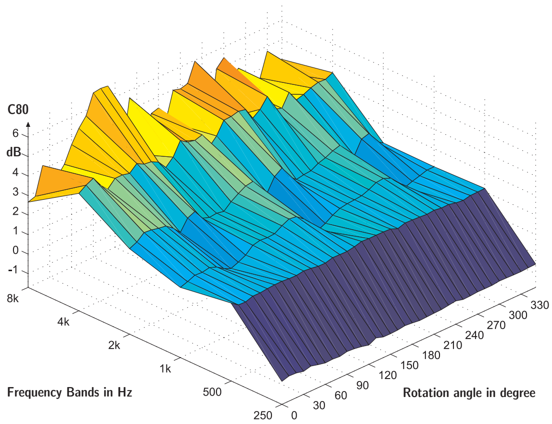

Figure 5.-Effect of the directivity of a sound source on C_{80} in a concert hall

Receiver Position
Even though common experience suggests that the listening impression does not vary significantly within the dimensions of a seat it is also a common observation [6] that a measurement result will vary notably within a seat's extent. Since a measurement position in a concert hall is frequently given with the accuracy of the dimensions of a seat, the uncertainty of the measurement result due to this precision needs to be assessed. Figure 6 shows the inner seat variation of C_{80} for different frequencies. Unexpected result of these diagrams is that despite the Schroeder frequency being well below the considered frequency (up to 1 kHz) bands the distribution of the single number parameter shows a sinusoidal characteristic. It is assumed that this is due to the lower modal density at lower frequencies, which allows an exposed singular mode at a specific measurement area to dominate the overall result.

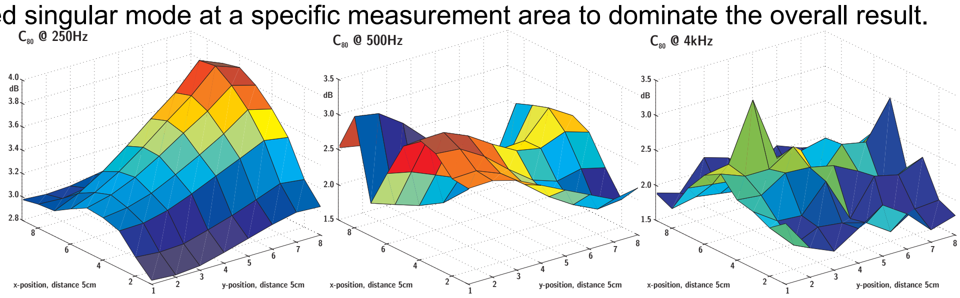

Figure 6.-Inner seat variation of C_{80} for 250 Hz, 1 kHz and 4 kHz octave bands

Source Position
The line of argument concerning the precision with which a microphone is positioned in the audience area remains valid when the accuracy with which a source is positioned on the stage is considered. Frequently the position of the source on stage is identified as the first soloist position or the barycentre of an instrumental section of an orchestra. Considering that stage sizes vary from 130 m² - 250 m² in area, a positioning accuracy of ± 1 m has to be expected. Figure 7 shows the fluctuation of two single number parameters in different concert halls in terms of standard deviation due to moving the sound source from a centre position in two steps of 0.5 m to the left, right, front and rear.

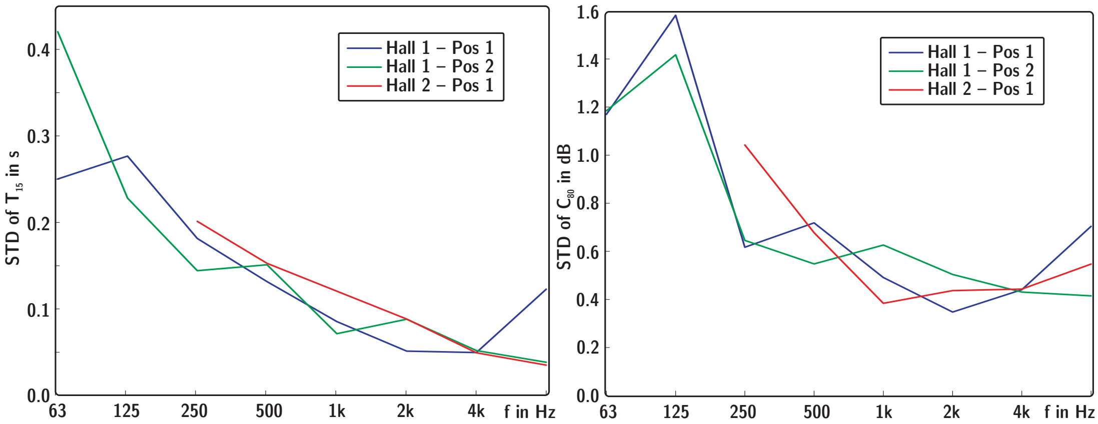

Figure 7.- Measured standard deviation due to source displacement for T_{15} (l.) and C_{80} (r.)

Influence of noise

In the final experiment the influence of background noise has been investigated. With this goal repeated overnight measurements have been conducted. Table 1 shows the signal/noise-ratio for the different measurement positions and in Figure 8 the measured standard deviation is plotted for T_{15} and C_{80}.

Frequency Band	SNR at Pos 1 [dB]	SNR at Pos 2 [dB]	SNR at Pos 2 [dB]
250 Hz	25	20	20
500 Hz	40	35	35
1000 Hz	60	55	50
2000 Hz	60	55	50
4000 Hz	60	55	50
8000 Hz	60	55	50

Table 1.- Measured SNR during overnight measurements in a concert hall

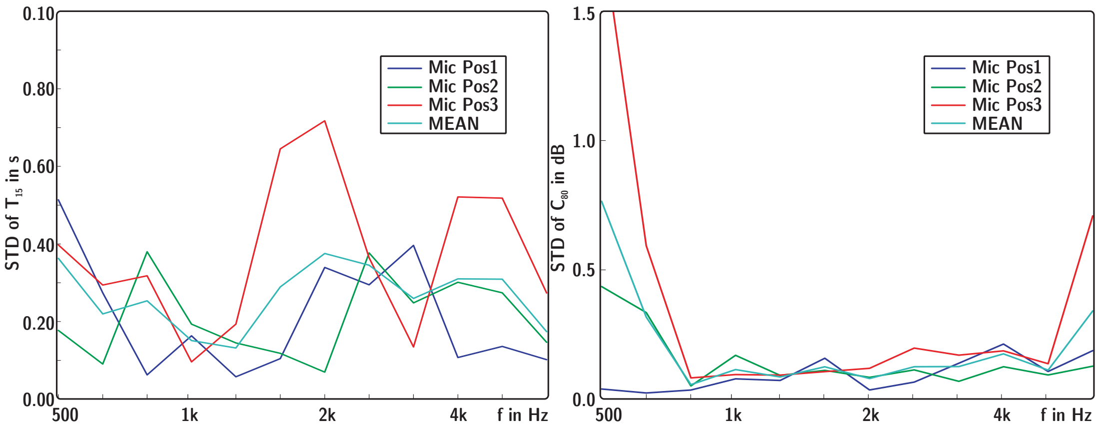

Figure 8.- Standard deviation of overnight measurements for T_{15} and C_{80}

UNCERTAINTY EVALUATION

On the basis of the previously described measurements it is possible to compile the uncertainty budget, using equations (1) and (2), disregarding any correlations between the input quantities:

$$u(x_i) = \sqrt{\frac{\sum_{k=1}^{n} \left(q_{i,k} - \overline{q}_i\right)^2}{n(n-1)}} \qquad (1)$$

$$u_{comb}(x) = \sqrt{\sum_{i=1}^{N} u(x_i)^2} \qquad (2)$$

With n representing the number of observations, N the number of input quantities and $\overline{q}_i$ the arithmetic mean of all observations of one specialised set of experiments. Figure 9 shows a graphic representation of the uncertainty contributions, the combined uncertainty and the just noticeable differences of the respective parameter. Since this diagram also identifies the input quantities which cause the largest deviations, it can be seen that a displacement of the source or the receiver result in the largest variation of the result.

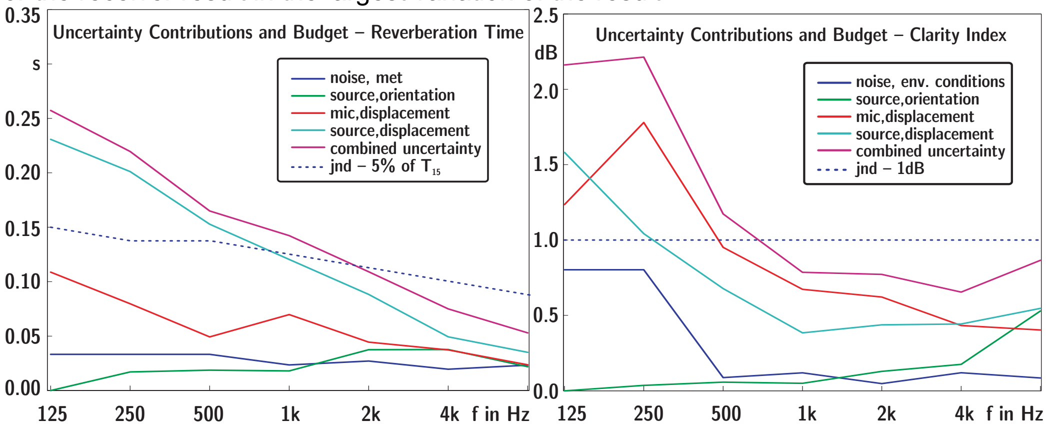

Figure 9.- Uncertainty contributions and combined uncertainty for T_{15} and C_{80}

CONCLUSION – STRATEGY TO REDUCE THE UNCERTAINTY IN MEASUREMENTS

In this study an approach of applying the GUM methods to room acoustics has been presented, using a scalable, linear uncertainty model. The main influence factors and their relevance regarding measurement uncertainty have been analysed on the grounds of practical experiments. The conducted measurements also yield a ranking of which uncertainties account for the deviations of a measurement result.

With the goal of improving the quality of measurement results, Figure 10 shows that the combined uncertainty of a measurement can be significantly reduced by conducting only a few extra measurements (to quantify the input quantity under consideration) and calculating the average. Using this approach it is possible to reach a combined uncertainty smaller than the just noticeable difference of the respective parameter under consideration.

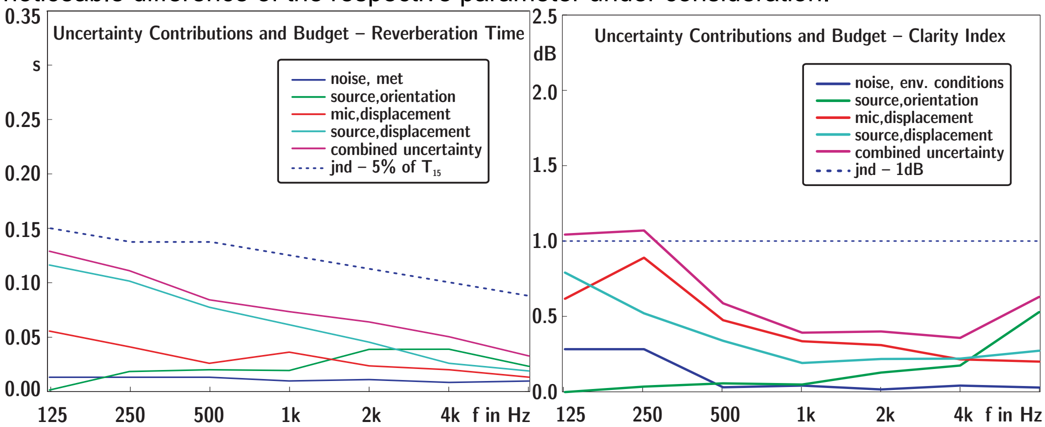

Figure 10.- Reduced Uncertainty contributions due to averaging for T_{15} and C_{80}

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