**Proceedings of the International Symposium on Room Acoustics, ISRA 2010**

29-31 August 2010, Melbourne, Australia

# Uncertainty of room acoustic measurements – How many measurement positions are necessary to describe the conditions in auditoria?

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**PACS:** 43.55.MC, 06.20.Dk

## ABSTRACT

ISO 3382 sets the framework for conducting acoustical measurements in auditoria, as this standard defines how many source-receiver combinations – depending on the room size – have to be measured in to derive general properties of the acoustic conditions. Over the years, however, it turned out that some parameters, such as Early Decay Time (EDT) or Strength (G), depend on the source-receiver distance, and hence, averaging over a number of source-receiver combinations will lead to a loss of information that will make proper conclusions impossible. In 1999 detailed measurements, carried out at Concertgebouw Amsterdam, showed that small changes in the microphone position are already sufficient to produce measurable fluctuations in parameters of lateral sound incidence. In other auditoria measurements have been carried out to cover entire audience areas. In this case study the tools of the "Guide to the Expression of Uncertainty in Measurements" (GUM) are used to gain new insights concerning the question of how many source-receiver combinations are necessary to describe the acoustic conditions in an auditorium. In this paper it will also be discussed to which extent singular measurements are suitable to describe the acoustical properties of entire audience areas.

## INTRODUCTION

ISO 3382 [1] defines the framework for room acoustical measurements that are carried out in auditoria. Apart from a definition how to calculate room acoustical single number parameters, procedural aspects for measurement surveys, such as the number of source and receiver combinations that have to be evaluated, are outlined as well. Depending on the size of the auditorium a number of 3 source positions and at least 6 – 10 microphone positions are to be used to evaluate the acoustic conditions in performance spaces. This translates to an average of about 80 – 200 seats for every microphone position. In contrast to such spatial sampling requirements are the results of array measurements conducted in the Concertgebouw in Amsterdam [2]. While discussing lateral energy fraction LF it was shown, that already small changes in the microphone position yield a measurable difference in the single number parameter. A question that arises from these results is which degree of detail is required to sufficiently characterise the position the measurement was taken at (e.g. seat, row or audience area). The tools of the "Guide to the expression of uncertainties in measurements" (GUM) [3] are used to develop an understanding of this aspect and determine the measurement uncertainty that goes along with a statement of measurement position. To simplify matters a focus is put on Clarity ($C_{80}$). The results are discussed with respect to the just noticeable difference (jnd).

## GUM CONCEPT AND GENERAL STRATEGY

The summarised strategy to discuss measurement uncertainties according to GUM relies on developing a model of the measurement process. First of all, an understanding about the input quantities that have an influence on the final measurement result has to be acquired. Secondly, a model is required to reflect how these input quantities are processed to yield the final measurement result. This algorithmic procedure is quantified by the model function *f*. In ideal scenarios *f* is determined analytically. In many cases, however, this is a rather complex task and consequently avoided for reasons of practicability. In these cases *f* may alternatively be determineed experimentally by evaluating how the final measurement result, i.e. the output quantity $Y$ (here: $C_{80}$), changes due to changes of the input quantity $X$ (here: displacement $d$ of the microphone). The actual measurement uncertainty is derived in a subsequent step based on the probability density functions (PDF), associated to the different input quantities $X_i$, which are propagated through the model, yielding a PDF for the output quantity $Y$. In situations where the model function $f$ is nonlinear or the requirements of the standard GUM framework are not fully met, Monte Carlo Simulations (MCS) can be used to determine the PDF of the model output [4].

## ACOUSTICAL MEASUREMENTS TO DETERMINE THE MODEL FUNCTION

Given the complexity of the acoustical measurement chain and the algorithms used to derive the output quantity ($C_{80}$) analytic modelling of the measurement process was waived in favour of a strategy to empirically determine the model function *f*. In order to establish how a change in the microphone position is reflected in the final $C_{80}$ result the measurements conducted at Concertgebouw Amsterdam [2] (figure 1) were re-evaluated. For this analysis 509 room impulse responses, measured along an array of microphone positions distributed with 0.05 m intervals over almost the full hall width (27.7 m), are available. All different combinations of two microphone positions are understood as a pair. Due to the regular spacing of the microphones a large number of microphone pairs are available which are at distances of multiples of 0.05 cm from another apart. The difference between the $C_{80}$ results of each pair of microphones indicates how much $C_{80}$ changes over distance. Statistical evaluation of these, up to 508 $C_{80}$-pairs (depending on the distance between microphones), showed that $C_{80}$ differences are almost perfectly normally distributed around a mean of $\mu = 0$ and a standard deviation $\sigma_{C_{80}}$ that is shown in figure 1 as a function of distance between the two microphones. This implies that in average a displacement of the microphone has no effect on the $C_{80}$ result. For individual displacements, however, a change in microphone position will alter the $C_{80}$ result according to an additive white Gaussian noise (AWGN) process with a normal standard deviation as shown in figure 2.

**Figure 1** Concertgebouw Amsterdam (photo ©: Het Concertgebouw, Hans Samsom)

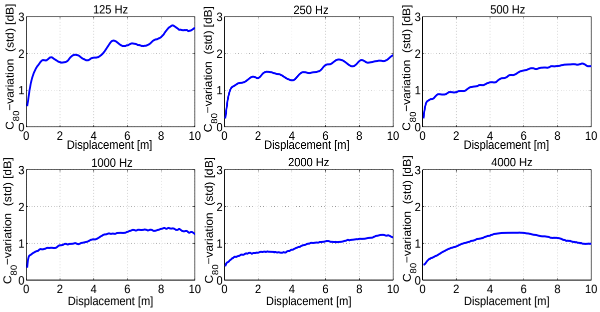

**Figure 2** Change of $C_{80}$ (normal standard deviation) due to a movement of the microphone by the distance *x* in meter.

Modelling this measurement in GUM-terms requires two steps. In the first step a flat model function $f(x) = 0$ is used to take the average effect of microphone displacement into account. In the second step an AWGN-process with $\sigma_{C_{80}}(x)$ as shown in figure 2 considers the individual $C_{80}$-change that has to be expected when moving the microphone. In GUM-terms this latter step considers “incomplete knowledge” about the underlying measurement process since it takes other factors (e.g. room shape, position of the microphone pair in the room, etc.) into account which otherwise could not be considered in this empiric approach.

## MONTE CARLO SIMULATIONS

Figure 2 shows the model function depending on the displacement distance *x*. Due to its nonlinearity this function may not be approximated with a low order Taylor series without a significant approximation error. Hence, Monte Carlo Simulations (MCS) are used to determine the PDF of the output quantity ($C_{80}$). This is initiated by selecting a PDF to reflect the statistical properties of the input quantity. Based on inaccurate information about the location a microphone was placed for measurements (e.g. only the seat or the row the microphone was placed in was given), it is expected that it is more likely that the microphone was actually placed at the centre of the indicated object than at its perimeter. Hence, it seems appropriate to assume a normal distribution with a mean of $\mu = 0$ cm and a standard deviation $\sigma_x$. $\sigma_x$ is chosen to be in the order of magnitude of half the dimension of the indicated object (e.g. ca. 0.25 m for a seat and up to a few meters for a row).

In a set of Monte Carlo simulations random selections for the input quantity (microphone position), with a fixed $\mu = 0$ and $\sigma_x$, are used to determine the statistical properties of the output quantity ($C_{80}$). For this study a MCS-set is completed when the 68 %- and 95% probability interval has been determined with an accuracy of 3 significant digits. In 50 MCS sets the standard deviation $\sigma_x$ of the input quantities PDF was gradually incremented from 0 cm to 2.50 m.

## RESULTS – MEASUREMENT UNCERTAINTY

The results of the MCSs are shown in figure 3. For different frequencies the standard uncertainty (68%, solid) and the expanded uncertainty (95%, broken) of $C_{80}$ are shown as a function of $\sigma_x$ ranging from 0 m to 2.50 m.

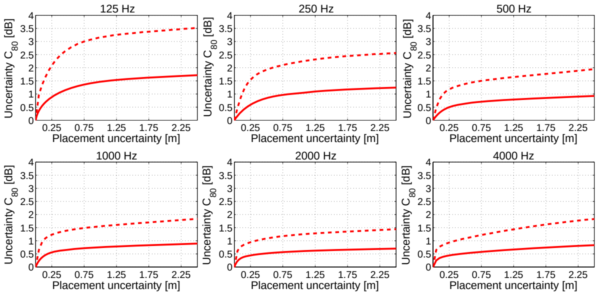

**Figure 3** Change of $C_{80}$ (normal standard deviation) due to a movement of the microphone by the distance *x* in meter.

If, for instance, it is unclear where a microphone was placed within a group of 9 chairs in the Concertgebouw (width of each chair 0.5 m) it can be read from figure 2 at 2.25 m (half the dimension of the object in question) that the standard uncertainty for $C_{80}$-measurements varies between ±1.69 dB for low and ±0.81 dB for high frequencies. The expanded uncertainty ranges from ±3.47 dB to ±1.77 dB for low and high frequencies respectively. In case information is available that a measurement was carried out at a specific seat the uncertainty is reduced to ±0.88 dB for low and ±0.44 dB for high frequencies (respectively to ±2.09 and ±0.93 dB for the expanded uncertainty).

The relevance of these results has to be discussed in view of the jnd for $C_{80}$. ISO 3382 states that the $C_{80}$ difference limen is 1.0 dB as published by Cox [5]. It would thus be necessary to document measurement positions with an accuracy of about 0.3 m considering the standard uncertainty for low frequencies. It should be noted, however, that in a survey by Höhne et al. [6] the difference limen for $C_{80}$ was determined to have a value of about 2.5 dB. This value has been confirmed by my own experiments in 2006 [7] and seems to be closer to practical experience. Such findings suggest that the required accuracy when it comes to reporting measurement position is much lower (e.g. > 2. 50 m).

## LIMITATIONS DUE TO CHOICE OF SAMPLING

In order to check the plausibility of these findings the type of measurement sampling is reconsidered. Even though the measurements carried out in Amsterdam provided us with a good impression of how single number parameters are prone to changing over short distances, it has to be stated that using a one dimensional array only allows us to consider the variability due to movements in one direction. Some parameters (i.e. C80, D50, G, EDT) have proven to be strongly dependent on the microphone distance to the sound source. This aspect my not be fully reflected by the presented data.

**Figure 4** Europasaal in Aachen, Germany

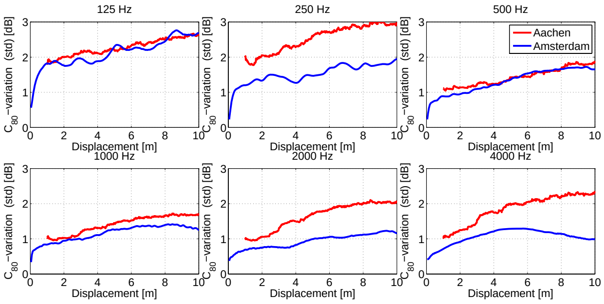

**Figure 5** Change of $C_{80}$ (normal standard deviation) due to a movement of the microphone by the distance *x* in meter.

In order to determine the effect of sampling the data collected in Amsterdam is compared to measurements conducted in a 15’000 m³ fan/rhombic-shaped multi purpose hall (Europasaal at Eurogress) in Aachen, Germany (figure 4).

In previous measurement sessions [8] 74 impulse responses have been measured on the ground floor of Eurogress Aachen. While these measurement positions cover the entire main parquet they are not positioned as close to each other as for the Amsterdam measurements. In a second aspect the distances between all combinations of microphones do not show the regular discretisation of a one dimensional array with regular microphone distance. Consequently a number of differences between the results of the two measurement series are evident. Firstly the smallest distance beween a microphone pair in the Amsterdam data is much smaller compared to microphone distances available in the Aachen data. Secondly the regular microphone spacing in Amsterdam gives a large number of microphone pairs that are the exact same distance from each other apart. This facilitates calculating summary statistics such as the standard deviation. The irregular microphone spacing in Aachen results in unique distances between any two microphones. In order to make both measurement series comparable to each other a spatial smoothing is applied to the data set collected in Aachen. This is done using a distancial raised cosine window with a length of 1m to calculate the gliding standard deviation of the $C_{80}$-results of neibouring microphone pairs. In figure 5 the results of the measurements in both rooms are shown. The data has been prepared as described for figure 2. It can be seen, that while showing a similar tendency, the variance of $C_{80}$ measurements in Aachen is slightly higher compared to results obtained in Amsterdam.

## CONCLUSIONS

In this paper it was shown which accuracy is required when reporting the position where a receiver was placed for room acoustical measurements when $C_{80}$ is discussed. These results have been compared to established references of just noticeable differences of clarity. As a result it was shown that the measurement position has to be reported with an accuracy of about 0.3 m when the jnd (1.0 dB) quoted in ISO 3382 is used. The jnds from other studies (2.5 dB) suggest that an accuracy of less then 2.50 m is required.

It has to be noted, however, that the presented results are of preliminary nature since the data used for this study was collected in a single auditorium using a one dimensional array.

## ACKNOWLEDGEMENTS

The authors would like to thank the administration of Concertgebouw Amsterdam and Eurogress Aachen for their great support in allowing us to conduct extensive acoustical measurements on more than one occasion.

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