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Error and uncertainty of IACC measurements introduced by dummy head orientation using Monte Carlo simulations

Ingo Witew, Pascal Dietrich and Michael Vorländer

Institute of Technical Acoustics, RWTH Aachen University, Templergraben 55, D-52056 Aachen, Germany

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ABSTRACT

In ISO 3382 IACC is identified as a single value parameter to predict the perception of spatial impression in auditoria. Although the perceptual relevance of interaural cross correlation has been shown by different researchers, the general significance of IACC measurements in auditoria is still being discussed. One of the questions that remain is, for instance: which are the relevant frequency bands that should be used to evaluate IACC. Moreover , the usage of IACC measurements to draw conclusions on the acoustic properties of auditoria is still subject to research due to a lack of measurement experience. In this paper a step is taken to determine the reliability of IACC measurements. In order to limit the multitude of factors that might have an influence on IACC results, a concise focus is placed on the alignment accuracy of the receiver (artificial head) with the sound source. In a first step extensive measurements have been carried out to obtain empirical data that show the influence of receiver misalignment. In a second step these data are used in Monte Carlo Simulations to identify measurement errors and uncertainties according to the GUM framework (Guide to the expression of Uncertainties in Measurements) and its supplement 1 (Monte Carlo Simulations). The presented results will show how sensitive IACC is concerning the discussed uncertainty factor.

INTRODUCTION

Although IACC is identified by standardisation bodies [1] as a single number parameter to predict the perception of spatial impression in auditoria, it seems that the measurement of binaural impulse responses and cross correlation processing is an approach used primarily by a few academic members of the room acoustical community. A possible reason for this hesitance might be the fact that some practical aspects appear not to have been dealt with conclusively. Among those is the question which frequency bands ought to be used to calculate IACC. Suggestions vary from using all octave bands ranging from 125 – 4000 Hz or averaging over neighbouring frequency band to calculate $IACC_{E,Low}$, $IACC_{E,Mid}$, $IACC_{E,High}$ [1] or $IACC_{E3}$ [2]. Another factor might be that, due to a lack of measurement experience, the reliability of IACC results is difficult to assess. Furthermore, with early and late lateral energy ratios, alternatives are available which yield information about spatial impressions, too. There seem to be two groups of experts, the one preferring LF and LG, and the other IACC.

There is very little literature on how sensitive IACC measurements are to changes in the measurement setup. This factor is addressed in a first approach which is taken to gain new insights on the significance of IACC measurements. This is done using the ISO *Guide to the expression of Uncertainties in Measurements* (GUM) [3]. In order to keep complexity at a level that can be handled within the scope of this paper, a concise focus is put on the measurement error and uncertainty that is introduced by inaccurately aligning the artificial head with the sound source. The significance of the measurement error and uncertainty is discussed with respect to 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: IACC), changes due to changes of the input quantity X (here: azimutal angular deviation α of the artificial head from the orientation towards the source). 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 (IACC) 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 misalignment of the dummy head is reflected in the final IACC result binaural room impulse response (BRIR) measurements were carried out by mounting an artificial head (ITA-head) on a computer controlled turn table. Automated measurements were taken in a 15’000 m³ fan/rhombic-shaped multi purpose hall (Europasaal at EUROGRESS) in Aachen, Germany (figure 3). The two source and six receiver positions were evenly distributed on the stage and on the ground floor respectively. BRIRs were measured for horizontal head orientation angles of ± 45° in 1° steps.

Measurement setup

The PC-based measurement setup, as schematically shown in Figure 1, uses a modern 24 bit, 44.1 kHz audio interface for data acquisition. The dummy head used is depicted in figure 2 [5]. A controllable turntable is used to automatically modify the orientation of the dummy head. The two dodecahedron loudspeaker systems [6] (figures 2 and 3) are capable of reproducing the audible frequency range with a good concordance with the omni-directional radiation pattern. Since the 3-way loudspeaker system was designed for the measurement of impulse responses for auralization purposes, the system is equalized using a FIR loudspeaker controller accounting for the frequency and phase response of the sound source resulting in a flat frequency response.

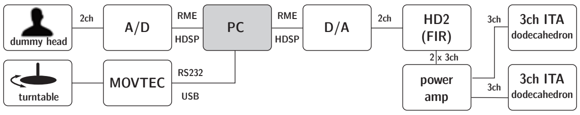

Figure 1 Measurement system layout

Figure 2 Artificial head (ITA [5]) and dodecahedron loudspeakers (ITA [6]) during measurement with a misalignment of α

A new measurement technique using interleaved excitation signals was used to reduce measurement time significantly [8, 9]. In a single measurement two impulse responses for two different source positions are obtained. Exponentially swept-sines of approx. 6 seconds are used enabling the separation of linear and non-linear system responses.

All signal processing, turntable control and IACC evaluation was realized in MATLAB using the ITA-Toolbox [7].

Figure 3 Europasaal in Aachen, Germany

Classification of the measurement results

A meaningful discussion of IACC errors and uncertainties requires an awareness of the range and context of the parameter. A first aspect that has to be taken into account with regard to IACC results is the fact that possible IACC values only have a range from 0.0 to 1.0. This limits the use of relative or absolute errors because uncertainty intervals exceeding the possible range of values need to be avoided. Secondly, the distribution of measured $IACC_E$ values needs to be assessed in order to determine which summarising quantities assuming a normal distribuion e.g. mean and standard deviation may be used.

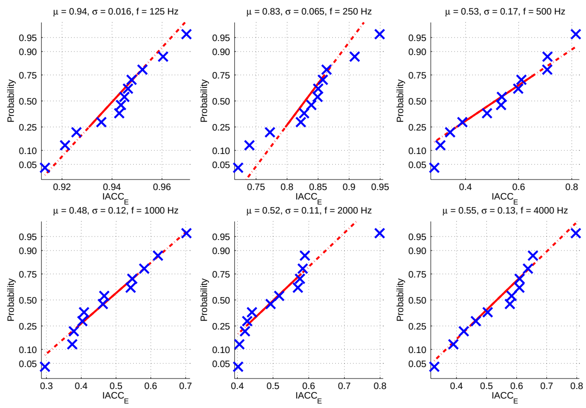

Figure 4 IACC distribution for different source-receiver combination (x) at different frequencies

Figure 4 shows the IACC results measured at 12 different source receiver combinations in a normal probability plot. This plot qualitatively shows how IACC data generally scatters compared to normally distributed samples. Although a Pearson χ^2-test does not yield statistically significant results (probably due to the small sample size), the hypothesis of the data being a sample from a normal distribution does not necessarily have to be rejected, since the measurement results lie along the red line in figure 4. This line illustrates the statistical properties of a normal distribution. Additionally, figure 4 shows the range of IACC values that were measured in the auditorium in Aachen.

These results are used to establish two boundary conditions:

- The IACC results are recognised to be roughly normally distributed. This makes it possible to use standard summary statistics, which includes the calculation of a mean IACC value for the sound field in the auditorium in Aachen. This line of argument is expected to hold for IACC data obtained in conditions of a deterministically misaligned artificial head as well.

- The relative deviation from the mean is deemed suitable for discussing measurement uncertainties. This condition seems appropriate since the extreme IACC-values (0.0 and 1.0) have a distance of more than 2 standard deviations from the mean IACC-value. It is therefore expected that it is unlikely to get uncertainty intervals that lie beyond the possible range of IACC values.

IACC CALCULATION AND DERIVATION OF THE MODEL FUNCTION

The calculation to derive IACC from a BRIR is defined in ISO 3382 [1]. The measurement sets described above are used to assess the relative change of the absolute IACC value that occurs due to a misalignment α of the receiver to the source. To do so, the IACC results are normalised to the reference of the perfect alignment of the receiver (α = 0°) based on the interaural time delay (ITD = 0 s). The results are shown in figure 5.

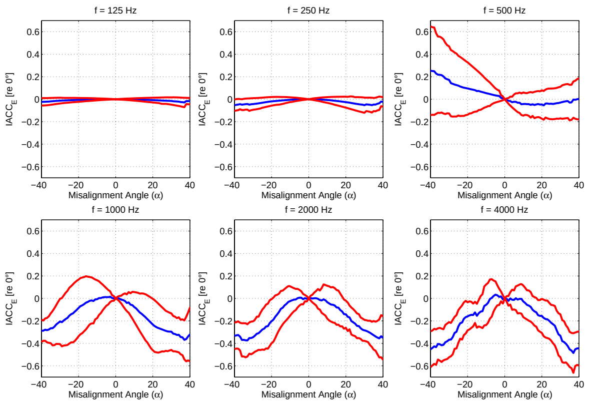

Figure 5 Relative change of $IACC_E$ (blue) due to misalignment of the receiver to the source, normalised to 0 °. Standard deviation (red) based on 12 source receiver combinations.

The blue line highlights the core of the uncertainty discussion of this scenario, since it shows the central aspect of the discussion, i. e. how IACC is changed in average due to a (specific) misalignment of the artificial head. In GUM terms this is identified as the "inner" model function f_{IACC}. It can be seen that for low frequencies a misalignment of the receiver has only little effect on IACC, due to a negligible directivity of the receiver. This can be explained by the small dimension of the receiver compared to the average wave length at those frequencies. At higher frequencies the effect of a head misalignment is more evident. Except for the 500 Hz octave band, a misalignment appears to result in a lower IACC value compared to the perfect alignment.

Since f_{IACC} is determined from 12 sets of measurements, each of the blue curves in diagram 5 has its associated standard deviation, which is a function of α as well. This is shown in red for each of the frequency bands and accounts for influences such as the measurement positions (or others) which may not be included in this empiric approach. Such a concept finds its equivalent in the GUM formalism where it corresponds to *incomplete knowledge* about the underlying measurement process that is modelled.

Recognising f_{IACC} as the "inner" model function requires considering how it joins the entire measuring process reflected by f, as illustrated in figure 6. The primary input quantity is a binaural room impulse response (BRIR) which is affected by secondary input quantities such as the orientation α of the dummy head. In a next step, the BRIR is filtered into octave bands. Two neighbouring bands between 125 Hz and 4 kHz are evaluated to calculate the IACC for low, mid or high frequencies. These two frequencies are also input quantities. The standard formula as published in ISO 3382 is applied to the filtered BRIR to calculate IACC for the respective band.

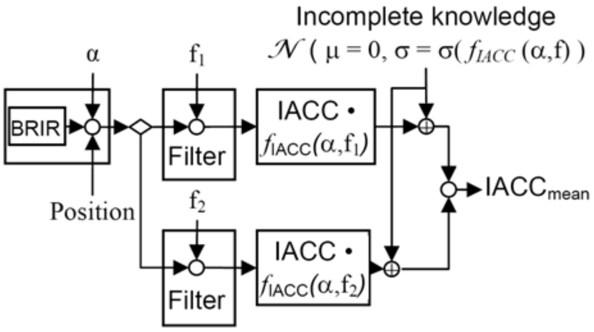

Figure 6 Calculating IACC from the GUM point of view

In case the receiver is not perfectly aligned with the sound source, the data from the measurements shows that the absolute value of IACC is altered. This is reflected in $f_{IACC}(\alpha, f)$ which depends on the angular misalignment α and the frequency f. The factor of *incomplete knowledge* is applied to the IACC value. This is done by adding a Gaussian noise process with a standard deviation that is derived from the deviance of the inner model function σ($f_{IACC}(\alpha$, f)) [see diagram 3].

The IACC calculation is concluded by taking the mean of the neighbouring IACC values which is the IACC for low, mid or high frequencies. For this last operation, the correlation of the different input quantites with each other has to be considered. This will be dealt with at a later part of this paper.

MONTE CARLO SIMULATIONS

It is obvious that the sole discussion of the model function shown in figure 5 cannot be the closing argument to discuss the measurement uncertainty, since this would require knowledge of the specific alignment error that was made during the measurement. If this knowledge would have been available during the measurement, it would have been possible to correct it right away in order to perform a qualified measurement. In most cases, however, precise knowledge about the orientation of the artificial head is only available to an extent that placement is generally possible with a given alignment uncertainty of $u(\alpha) = \sigma_\alpha$. This leads to associating the central input quantity (e.g. misalignment angle) with an underlying probability density function (PDF) which reflects its statistical properties. It is assumed that if a dummy head is placed with a PDF of α for binaural measurements, it can be expected to be normally distributed with a mean μ_α = 0° and a standard deviation σ_α. In order to determine how this domain of input quantity values translates into a range of values of the output quantity (IACC), the input quantities PDF is propagated through the model function f. It is obvious that due to its nonlinearity (especially for higher frequencies), this function may not be approximated with a low order Taylor series without risking significant approximation errors.

In pursuit of the goal to determine the measurement error and uncertainty of IACC measurements due to misalignment of the receiver, 41 sets of Monte Carlo (MC) simulations were carried out.. In each set it is determined how different input PDFs with a stepwise incremented standard deviation σ_α from 0° to 40° alter the final IACC measurement results. The simulations were run with a dynamic number of trials and an abort criterion to obtain the median, and the 68 % and the 95 % probability intervals with an accuracy of 3 significant digits.

RESULTS – MEASUREMENT ERROR AND UNCERTAINTY

The results of the MC-simulations are shown in figure 7 and table 1. The relative measurement error and the uncertainty are presented as a function of the presumed accuracy of aligning the artificial head with the sound source for different frequencies.

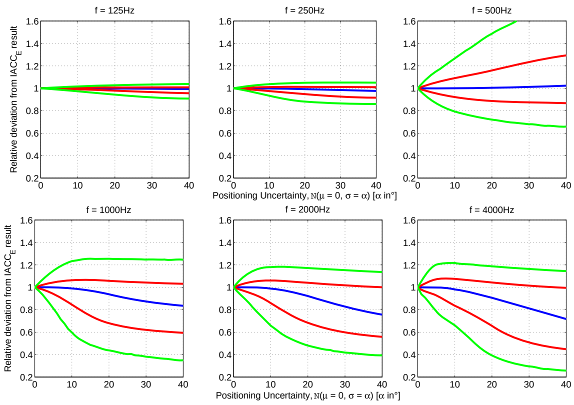

Figure 7 Relative measurement error (blue) and uncertainties (red, green) of IACC_E for different frequency bands as a function of the alingnment uncertainty of the artificial head

If, for instance, it is assumed that the artificial head for an IACC measurement was positioned with an azimutal uncertainty of of ± 20° (assuming the pdf as discussed above), the data in figure 7 and table 1 shows that the measured IACC result of a particular measurement (best estimate) is by the relative factor 0.91 – 1.00 too low, depending on the frequency. The measurement uncertainty may be determined to lie between 0.98 – 1.00, for low, and 0.66 – 1.04 times the best IACC estimate for high frequencies. The measurement error can be corrected on the grounds of the presented data, provided a fair estimation of the alignment accuracy for the particular measurement is available.

Table 1 Relative measurement error and uncertainties of IACC_E for different frequency bands and misalignment angles. All values are given relative to the best estimate.

	10°	*20°*	*30°*	*40°*	*Frequency [Hz]*
Measurement error	1.00	1.00	1.00	0.99	*125*
	1.00	0.99	0.98	0.98	*250*
	1.00	1.00	1.00	1.02	*500*
	0.99	0.94	0.87	0.84	*1000*
	0.99	0.92	0.83	0.76	*2000*
	0.98	0.91	0.81	0.72	*4000*
Standard uncertainty$_+$	1.00	1.00	1.01	1.01	*125*
	1.01	1.01	1.01	1.01	*250*
	1.09	1.16	1.23	1.29	*500*
	1.06	1.06	1.04	1.03	*1000*
	1.06	1.04	1.02	1.00	*2000*
	1.08	1.04	1.01	0.99	*4000*
Standard uncertainty$_-$	0.99	0.98	0.97	0.96	*125*
	0.98	0.95	0.93	0.92	*250*
	0.92	0.89	0.87	0.87	*500*
	0.85	0.68	0.62	0.59	*1000*
	0.86	0.68	0.60	0.56	*2000*
	0.85	0.66	0.51	0.45	*4000*

CORRELATION OF INPUT QUANTITIES

A secondary aspect when discussing IACC uncertainties is the calculation of mean parameters, e. g. $\text{IACC}_\text{E,Mid}$ for the average of the 500 and 1000 Hz octave band. This is usually reflected in a formula similar to equation (1)

$$\text{IACC}_\text{E,mean} = \frac{1}{n}\sum_{i=1}^{n}\text{IACC}_{\text{E}i} \quad (1).$$

In equation (1), n denotes the number of octave bands to be comprised in the average and $\text{IACC}_{\text{E}i}$ represents the IACC value that was measured at a frequency band i. For this arithmetic correlations between the different input quantities have to be taken into account.

For the measurement and analysis process prior to calculating the average, it is reasonable to assume that no correlation between the BRIR and the misalignment angle α has to be expected. Based on results of uncertainty studies in building acoustics [10], however, it becomes evident that the measurement results of different frequency bands are often correlated to each other. Using the GUM framework, the model function presented in equation (1) is differentiated to determine the squared uncertainty (i.e. variance) of $\text{IACC}_\text{E,mean}$ as it is shown in equation (2):

$$u^2\left(\text{IACC}_\text{E,mean}\right) = \frac{1}{n^2}\sum_{i=1}^{n}u^2\left(\text{IACC}_{\text{E}i}\right) + \frac{1}{n^2}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}u\left(\text{IACC}_{\text{E}i},\text{IACC}_{\text{E}j}\right) \quad (2).$$

with $u^2(\text{IACC}_{\text{E}i})$ representing the squared standard deviation of IACC results in the frequency band i based on a given normal distribution of the position uncertainty of the artificial head. $u(\text{IACC}_{\text{E}i}, \text{IACC}_{\text{E}j})$ is the IACC-covariance of two frequency bands that are averaged under the same conditions for the positioning uncertainty. When applying equation (2) it has to be kept in mind that the quoted variances and covariances are not directly available from the measurements performed since they require the sampling of the misalignment angle based on a normal distribution. Such a sampling obviously contradicts the evenly distributed sampling used to determine the model function, as described above. Nevertheless it is reasonable to derive the variances and covariances specified in equation (2) directly from the measured data sets since this approach shows wether correlations of input quantities (i.e. the second line of eq. (2)) have to be considered.

A statistical analysis reveals that the variance can be approximated to values of about 0.02 and the covariance of "neighbouring" frequency bands to roughly 0.075. These figures lead to the conclusion that the correlation of input quantities cannot be neglected. The absolute value of the determined results, however, may not be comparable to the results of the Monte Carlo simulations since the sampling of the input quantity α is not equivalent.

In order to determine how correlations between input quantities affect the uncertainty intervals identified by the Monte Carlo simulations it has to be stated that this aspect will have to be included in the Monte Carlo algorithm in future steps. In this context it will be necessary to observe carefully how the factor of *incomplete knowledge* influences the results. This aspect was introduced to carefully elevate uncertainty intervals under controlled conditions using additive white Gaussian noise. This approach, however, potentially reduces correlation between input quantities and hence might not be the best strategy to address such aspects.

PERCEPTUAL ASPECTS OF IACC

The relevance of these findings has to be discussed in view of the JND for IACC. ISO 3382 states that the IACC difference limen is 0.05. This would translate to a maximum tolerable placement error of about 10° for higher frequencies. It should be noted, however, that in a survey by Kim et al. [11] the results of IACC JNDs range from 0.04 to 0.7 depending on the absolute IACC value and excitation signal used when perceiving a sound field. Although these summarised results are probably more precise when it comes to predicting human perception than the singular threshold quoted in ISO 3382 it is also clear that such findings are difficult to interpret from a measurement point of view since the used excitation, e.g. speech, music or noise, cannot be considered.

CONCLUSIONS

In this work, the error and uncertainty of IACC measurements due to uncertain alignment of the artificial head with the sound source has been investigated along the guidelines of the ISO GUM framework. It was shown that an assessment of the measurement quality stands and falls with a fair estimate of the placement accuracy of the artificial head. Based on this assessment the measurement error can be compensated. The measurement uncertainty, however, remains, but decreases with a more precisely targeted artificial head. The maximum misalignment that may be tolerated depends on the applicable JND for IACC. A tolerance of about ± 10° seemed to be absolutely acceptable in a first practical assessment. The presented strategy is applicable to determine the effect of any controllable uncertainty contribution empirically.

In other measurement uncertainty related research [13] it is an aspect to develop models to reduce the enormous efforts to determine the measurement uncertainty. The presented stratey has the potential to serve as reference when such models to predict the uncertainty of measurements are evaluated.

It has to be realised, however, that a number of boundary conditions exist that narrow the potential to derive general conclusions. Firstly, measurements have been carried out in a single auditorium. In a strict interpretation, these results can only be generalised to the measurement uncertainty in that specific auditorium. A very comparable survey [12] by the authors with measurements performed by the Audio Communication Group at TU Berlin concluded with similar results with respect to the acceptable alignment tolerance for practical applications. Such findings could lead to a generalisation of the presented results.

Secondly, the IACC results that were obtained are around 0.5 ± 0.1 for mid and high frequencies. Since IACC results are confined to a distinct range of possible values it needs to be considered that a receiver misalignment in sound fields with significantly higher or lower IACC values might result in statistically different behaviour of IACC, compared to the ones observed at IACC = 0.5. The applicability of the presented results for extreme IACC results might therefore be limited.

Outlook and open questions

Although the authors are of the opinion that the presented work offers new insights about practical IACC measurements it turns out that the findings give rise to a number of open questions as well that should be subject to further research.. Aspects that will have to be addressed may include:

- Additional measurement series in other auditoria will be beneficial to develop a better understanding how IACC is generally affected by a receiver misalignment to the source.
- Further measurement results will also help to find a better basis to validate the applicability of Monte Carlo simulations. While the presented results are recognised to be helpful and valid for the uncertainty discussion of individual frequency bands (i.e. uncorrelated input quantities) it will be part of future investigations to show how correlations are correctly modelled in Monte Carlo simulations.
- Investigations closing the obvious gap between the high complexity of human perception of spatial impression and the means to predict this with IACC are still required. These aspects are especially obvious when considering the thresholds for JNDs depending on different signals. A better understanding of how different perceptive scenarios find their equivalent in binaural room acoustical parameters will probably enhance the acceptance of IACC.

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REFERENCES

1 ISO 3382 – 1: 2009 Measurement of room acoustic parameters
2 L. Beranek, *Concert Halls and Opera Houses – Music, Acoustics, and Architecture*, (Springer-Verlag, New York, 2004)
3 ISO-Guide 98 – 3: 2008 Guide to the expression of uncertainty in measurement
4 ISO-Guide 98 – 3 / Supplement 1: 2008 Guide to the expression of uncertainty in measurement – propagation of distributions using a Monte Carlo Method
5 A. Schmitz, „Naturgetreue Wiedergabe kopfbezogener Schallaufnahmen über zwei Lautsprecher mit Hilfe eines Übersprechkompensators“, *PhD-Thesis at the Institute of Technical Acoustics, RWTH Aachen University* (1993)
6 G. K. Behler, "Three-Way measurement loudspeaker for automotive-, room- and building-acoustics", *Proc. FIA 2008*, Buenos Aires 2008
7 P. Dietrich, B. Masiero, M. Pollow, R. Scharrer, M. Müller-Trapet, MATLAB Toolbox for the comprehension of acoustic measurement and signal processing, *Proc. DAGA 2010,* Berlin
8 S. Müller et al., "Transfer-Function Measurement with Sweeps," *J. Audio Eng. Soc.* **49**, 443 – 471 (2001)
9 P. Majdac et al., "Multiple exponential sweep method for fast measurement of head-related transfer functions" *J. Audio Eng. Soc.* **55**, 623 – 637(2007)
10 V. Wittstock, "On the uncertainty of single-number quantitis for rating airborne sound insulation" *Acta Acustica u/w Acustica* **93**, 375 – 386 (2007)
11 C. Kim et al., "Initial investigation of signal capture techniques for objective measurement of spatial impression considering head movement", *Proc. AES* 2008, Paper 7331, Amsterdam 2008
12 I. Witew et al., "Uncertainties of IACC related to dummy head orientation", *Proc. DAGA 2010*, Berlin 2010
13 I. Witew et al., "Describing measurement uncertainties in room acoustics with the concept of GUM (A)", *J. Acoust. Soc. Am.* **123**, 2975 (2008)