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# Measuring Room Impulse Responses: Impact of the Decay Range on Derived Room Acoustic Parameters

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**Summary**

Standards for measuring room acoustic parameters, such as ISO 3382, in many cases do not, or only partially, specify the requirements that a measured impulse response should meet to allow calculation of a certain parameter. Among other things, it is often left to the user of the standard to find a practical interpretation of the time infinity that appears in the theoretical formulas defining the parameters. Hence, the parameter value may depend on the decay range and measurement time. Under the most adverse conditions this may lead to variations in the calculated parameter values larger than the Just Noticeable Difference (JND). Using the suggested ISO 3382 'infinite' integration time limits for some parameters and otherwise the crosspoint of decay line and noise level as the 'infinite' integration time limit for the other parameters, the influence of the decay range on the calculated parameter values is investigated. This is done for all ISO 3382-1 parameters: $EDT$, $T_{20}$, $T_{30}$, $C_{80}$, $D_{50}$, $T_S$, $G$, $ST$, $IACC$, $LF$, $LFC$ and $LG$, using the $INR$ (room Impulse response to Noise Ratio) as an estimator for the decay range. The result is a proposal for a minimum decay range value for all ISO 3382-1 parameters, based on the JND and the $INR$.

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## 1. Introduction

Many room acoustic parameters are derived from room impulse responses. Figure 1 shows an example of a measured impulse response and its derived Energy Time Curve (ETC). Examples of room acoustic parameters are the sound strength, which is related to the sound energy level, the reverberation time, which is related to the energy decay rate and the clarity, definition and centre time, which are related to early to late energy ratios of the impulse response.

Standards for measuring these room acoustic parameters, such as ISO 3382 [1, 2, 3], in many cases do not, or only partially, specify the requirements that a measured impulse response should meet to allow calculation of a certain parameter. For instance, to determine the reverberation time, clear requirements are stated with regard to the exponential shape of the decay curve and the associated decay range, i.e. the $T_{30}$ can only be calculated if the decay range is at least 45 dB while for $T_{20}$ the requirement is a decay range of at least 35 dB. To calculate the Sound Strength ($G$) from an impulse response, ISO 3382 requires a minimum decay range of 30 dB, and sets the integration time limit to the point were the decay curve has decreased by at least 30 dB. For the Inter Aural Cross Correlation ($IACC$) an integration time limit in the order of the reverberation time is suggested, irrespective of the noise level. For the Support ($ST$) the integration time limit for the late energy is set to 1 s. For all other room acoustic parameters no practical value is specified for the decay range and/or the late energy integration time limit. It is therefore often left to the user of the standard to find a practical interpretation of the time infinity that appears in the theoretical formulas defining the parameters. Under the most adverse conditions this may lead to variations in the calculated parameter values much larger than the JND. To the knowledge of the authors extended research on this topic has not yet been performed.

In theory the room acoustic formulas hold for infinite measurement times and the absence of noise, while obviously neither of these conditions can be met in practice. For $IACC$ calculations, ISO 3382 suggests using the reverberation time as the integration limit. This may be valid as long as the decay range of the impulse response is sufficiently large, or has been increased artificially using a noise compensation technique. Otherwise a relatively large section of noise might be unintentionally included in

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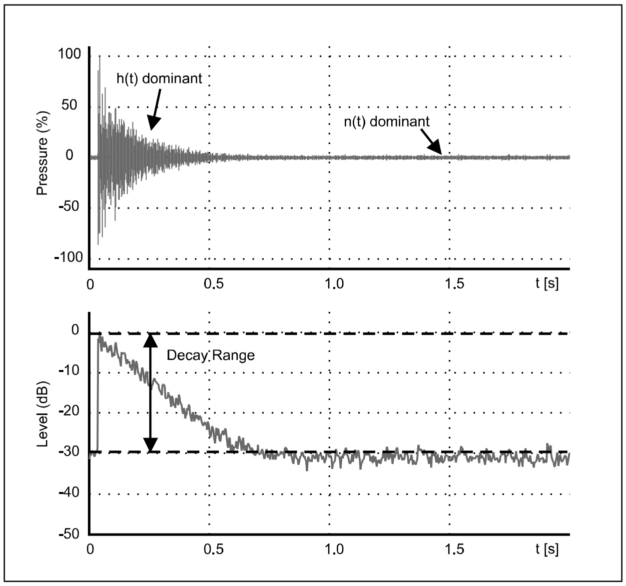


Figure 1. Measured impulse response $p(t)$ and Energy Time Curve $10\lg p^2(t)$, where $h(t)$ is the actual system response and $n(t)$ is the noise.

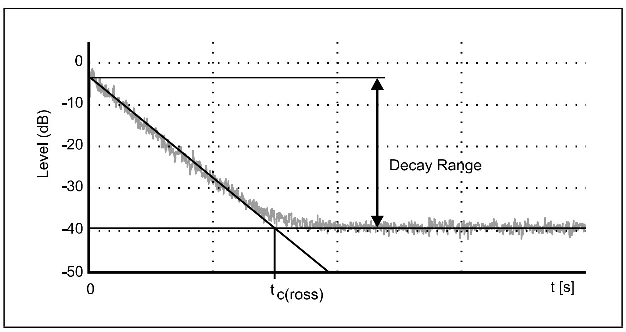


Figure 2. The crosspoint $t_c$ is defined as the point where the impulse response decay line crosses the noise level and is used as the 'infinite' integration limit for calculating room acoustic parameters.

the calculations, making the results dependent on the noise level. For *IACC* it has never been investigated whether the reverberation time as the integration limit is the optimum choice. For all other energy ratio parameters no interpretation of time infinity is given at all.

For practical measurements of finite length, one might equate infinity with the end of the impulse response measurement. However, in the presence of noise this results in parameter values that depend on the length of the measurement and the decay range. It seems most obvious to include as much as possible of the decaying impulse response while excluding most of the noise. Therefore, it is proposed to use the crosspoint of decay line and noise level ($t_{c(ross)}$) as the 'infinite' integration limit as shown in Figure 2. However, this still suggests that the parameter value may depend on the available decay range, as $t_c$ depends on the decay range. To the knowledge of the authors it has never been investigated what decay range is necessary to sufficiently reduce the measurement uncertainty for the ISO 3382-1 parameters. In this paper, the influence of the decay range on all ISO 3382-1 parameters is investigated.

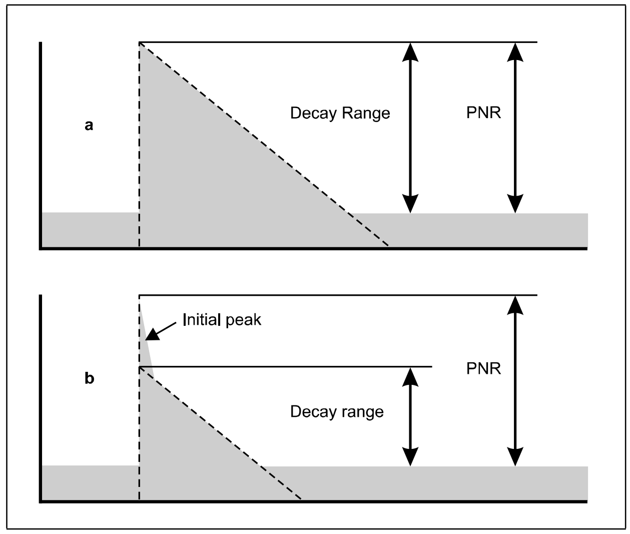


Figure 3. The Peak-to-Noise Ratio (*PNR*) fails to describe the decay range of a room acoustic Energy Time Curve (ETC). The upper graph (3a) shows the ETC of a theoretically diffuse sound field. The lower graph (3b) shows the effect of a high initial peak on the effective decay range.

A description of the investigated parameters with the integration time limit interpretation is presented in Table I. In section 2, a definition of the decay range is given and a decay range estimator is proposed. In section 3 to 5, the error of calculated parameter values is investigated when reducing the decay range of a large set of practical impulse responses.

## 2. Decay range definition

### 2.1. Introduction

The definition of the reverberation time presumes that the (backward integrated) RMS value of a room acoustic impulse response follows a straight line when plotted on a dB scale. The reverberation time is then calculated from the slope of the regression line over the largest useful range of this plot. This regression range is directly related to the decay range, which in turn is limited due to measurement noise. The ISO 3382 standard [1] prescribes a minimum decay range of 35 dB for the measurement of $T_{20}$ (regression range −5 to −25 dB) and of 45 dB for the measurement of $T_{30}$ (regression range −5 to −35 dB). The ISO 18233 [18] standard uses the effective signal-to-noise ratio instead. Although the terms 'decay range' and 'effective signal-to-noise ratio' may be conceptually clear, no definition is given.

The regression range starts at −5 dB in order to avoid the influence of direct sound or strong early reflections. The lower limits of the regression ranges of −25 dB and −35 dB respectively should exceed the impulse response noise level by at least 10 dB. The regression range is therefore mainly based on a 'diffuse decay curve', excluding initial sound. Similarly the prescribed minimum decay ranges of 35 and 45 dB are defined relative to the initial level of a diffuse decay curve rather than to random initial peak values.

Table I. Measured room acoustic parameters [1]. To avoid confusion in relation to previous research the $LF$ and $LFC$ are used as parameter name for the early lateral energy fraction and $LG$ for the late lateral sound level. In the latest standard $J_{LF}$, $J_{LFC}$ and $L_J$ are used. "$t_\infty$": used integration time limit; $\mathrm{RIR}_{\mathrm{length}}$: Room Impulse Response measurement time length; $t_{\mathrm{cross}}$: cross point of noise tail and decay line; JND: Just Noticeable Difference. EDR: evaluation decay range. *: *Estimated value obtained from a personal conversation with A.C. Gade in 2009.*

| Acoustic Parameter | Formula | "$t_\infty$" | JND | Ref. |
|---|---|---|---|---|
| Sound strength $G$ [dB] | $G = 10\lg \frac{\int_0^\infty p^2(t)\,\mathrm{d}t}{\int_0^\infty p^2_{\mathrm{dir10m}}(t)\,\mathrm{d}t}$ [dB] | $t_{\mathrm{cross}}$ | 1 dB | [4] |
| Early Decay Time $EDT$ [s] (EDR: 0 dB to −10 dB) | $L(t) = 10\lg \frac{\int_t^\infty p^2(t)\,\mathrm{d}t}{\int_0^\infty p^2(t)\,\mathrm{d}t}$ [dB] | $\mathrm{RIR}_{\mathrm{length}}$ | 5% | [5] |
| Reverberation Time $T_{20}$ [s] (EDR: −5 dB to −25 dB) | $L(t) = 10\lg \frac{\int_t^\infty p^2(t)\,\mathrm{d}t}{\int_0^\infty p^2(t)\,\mathrm{d}t}$ [dB] | $\mathrm{RIR}_{\mathrm{length}}$ | 5% | [6, 7] |
| Reverberation Time $T_{30}$ [s] (EDR: −5 dB to −35 dB) | $L(t) = 10\lg \frac{\int_t^\infty p^2(t)\,\mathrm{d}t}{\int_0^\infty p^2(t)\,\mathrm{d}t}$ [dB] | $\mathrm{RIR}_{\mathrm{length}}$ | 5% | [6, 7] |
| Clarity $C_{80}$ [dB] | $C_{80} = 10\lg \frac{\int_0^{80\mathrm{ms}} p^2(t)\,\mathrm{d}t}{\int_{80\mathrm{ms}}^\infty p^2(t)\,\mathrm{d}t}$ [dB] | $t_{\mathrm{cross}}$ | 1 dB | [8] |
| Definition $D_{50}$ | $D_{50} = \frac{\int_0^{50\mathrm{ms}} p^2(t)\,\mathrm{d}t}{\int_{0\mathrm{ms}}^\infty p^2(t)\,\mathrm{d}t}$ | $t_{\mathrm{cross}}$ | 0.05 | [9] |
| Centre Time $T_S$ [ms] | $T_S = \frac{\int_0^\infty t\,p^2(t)\,\mathrm{d}t}{\int_0^\infty p^2(t)\,\mathrm{d}t}\,1000$ [ms] | $t_{\mathrm{cross}}$ | 10 ms | [10] |
| Early Lateral Energy Fraction $LF$ | $LF = \frac{\int_{5\mathrm{ms}}^{80\mathrm{ms}} p_L^2(t)\,\mathrm{d}t}{\int_{0\mathrm{ms}}^{80\mathrm{ms}} p^2(t)\,\mathrm{d}t}$ | n.a. | 0.05 | [11] |
| Early Lateral Energy Fraction $LFC$ | $LFC = \frac{\int_{5\mathrm{ms}}^{80\mathrm{ms}} \lvert p_L(t)\,p(t)\rvert\,\mathrm{d}t}{\int_{0\mathrm{ms}}^{80\mathrm{ms}} p^2(t)\,\mathrm{d}t}$ | n.a. | 0.05 | [12] |
| Late Lateral Sound Level $LG$ [dB] | $LG = 10\lg \frac{\int_{80\mathrm{ms}}^\infty p_L^2(t)\,\mathrm{d}t}{\int_0^\infty p^2_{\mathrm{dir}}(t)\,\mathrm{d}t}$ | $t_{\mathrm{cross}}$ | 1 dB | [13] |
| Inter Aural Cross Correlation $IACC$ | $IACC_{t_1,t_2} = \lvert IACF_{t_1,t_2}(\tau)\rvert_{\max}$ for $-1\ \mathrm{ms} < \tau < +1\ \mathrm{ms}$ | $t_{\mathrm{cross}}$ | 0.075 | [14] |
| Early Support $ST_{\mathrm{early}}$ [dB] | $ST_{\mathrm{early}} = 10\lg \frac{\int_{20\mathrm{ms}}^{100\mathrm{ms}} p^2(t)\,\mathrm{d}t}{\int_0^{10\mathrm{ms}} p^2(t)\,\mathrm{d}t}$ [dB] | n.a. | 2 dB* | [15, 16, 17] |
| Late Support $ST_{\mathrm{late}}$ [dB] | $ST_{\mathrm{late}} = 10\lg \frac{\int_{100\mathrm{ms}}^\infty p^2(t)\,\mathrm{d}t}{\int_0^{10\mathrm{ms}} p^2(t)\,\mathrm{d}t}$ [dB] | 1000 ms | 2 dB* | [15, 16, 17] |

The decay range of a room impulse response can be approximated in different ways.

One could be tempted to use the Peak-to-Noise Ratio ($PNR$), which expresses the ratio between the highest momentary peak value in the initial part of the Energy Time Curve (ETC) and the RMS value of the noise present. Figure 3a illustrates that in case of a theoretically diffuse sound field $PNR$ will indeed approximate the decay range. The mentioned peak however will always exceed the initial RMS value by a random value, and the $PNR$ will therefore in general exceed the decay range obtained from visual inspection of the ETC. Also in case of a high initial peak of direct sound or strong early reflections, the momentary peak will largely exceed the apparent start of the diffuse decay curve as is illustrated in Figure 3b. This shows that the $PNR$ describes the dynamic range of the measurement, but fails to describe the decay range.

A more satisfactory approach could be obtained if the peak value is replaced by the RMS value of the initial part. This however requires the choice of an averaging interval, the length of which depends on the frequency range as well as the decay time: the interval should be long enough to include the longest period of interest, and short enough to avoid a significant decay within the interval. The latter condition minimizes the impact of the chosen interval length on the resulting initial RMS value.

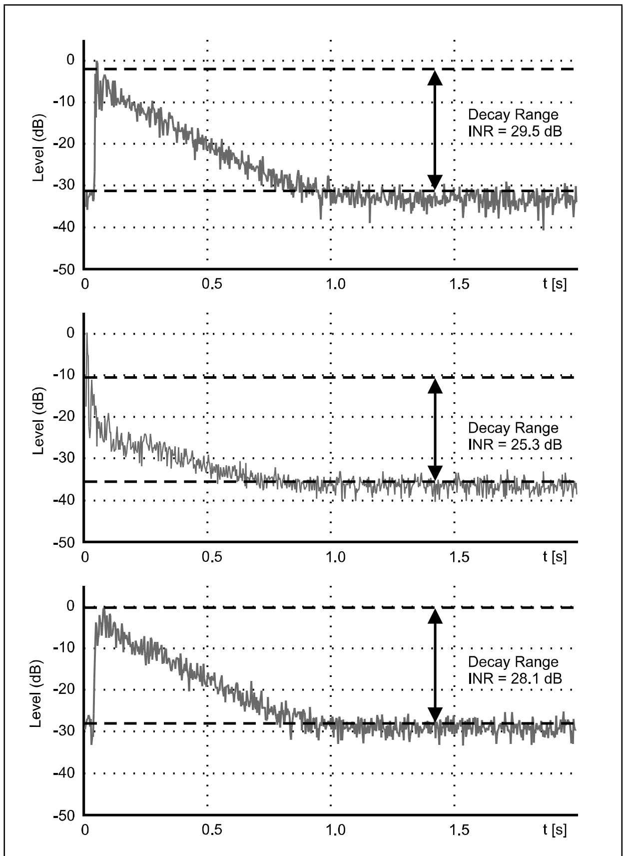


Figure 4. Three examples of Energy Time Curve (ETC) types derived from practical impulse responses. The upper graph shows a 'normal' measurement in a more or less diffuse sound field. The middle graph shows an ETC with a 'high-initial-peak' measured at a short distance from a loudspeaker for instance when measuring stage parameters. The lower graph shows an ETC with a 'slow-attack' measured with a figure-of-eight microphone for instance when measuring the lateral energy fraction.

In the next paragraph a further optimized definition is introduced, which is based on averaging over a presumed exponentially decaying signal level. The averaging interval then has no upper limit, making it independent of the frequency of interest. Therefore, to calculate this so called *INR* or room Impulse response to Noise Ratio [19], only an estimated decay time is required.

### 2.2. Definition of the *INR*

The *INR* is defined as

$$INR = L_{IR} - L_N \qquad [\text{dB}], \tag{1}$$

where $L_{IR}$ is the maximum RMS level in dB of $p(t)$ and $L_N$ is the noise level in dB [20]. To define $L_{IR}$, the backward integration method [6, 7] is as useful as it has already proven to be for the accurate determination of the slope. The maximum of the Schroeder plot is easy to find, but its exact relation with $L_{IR}$ is not obvious.

Although there is no simple relation that is valid for all impulse responses, a good approximation can be made under the assumption that the RMS value of a room acoustic impulse response is essentially exponential with a decay rate of $60/T_{60}$ dB/s,

$$h(t) = h_0\, U(t - t_d)\, C(t - t_d)\, 10^{-3(t-t_d)/T_{60}}, \tag{2}$$

where $h(t)$ is the approximated system response, $h_0$ is the maximum impulse response value, $t_d$ is the time for the direct sound to travel from source to receiver, $U(t)$ is the unit step function (0 for $t < 0$, 1 for $t = 0$), $C(t)$ is any carrier signal with unit RMS value, and $T_{60}$ is the reverberation time. The maximum RMS level is

$$L_{IR} = 10 \log \left(h_0^2\right) \qquad [\text{dB}]. \tag{3}$$

Integrating $h(t)$ backwards according to Schroeder results in

$$S(t) = 10 \log \left( \int_t^\infty h^2(t) \right) \qquad [\text{dB}] \tag{4}$$

and

$$S(0) = 10 \log \left( \frac{T_{60}}{6 \ln 10} h_0^2 \right) \qquad [\text{dB}]. \tag{5}$$

Therefore, starting from an exponential impulse response and substituting (5) into (3), we obtain

$$L_{IR} = S(0) + 10 \log \left( \frac{6 \ln 10}{T_{60}} \right) \qquad [\text{dB}]. \tag{6}$$

In words: $L_{IR}$ is defined as the level of the total impulse response energy normalized to the reverberation time $T_{60}$, where $T_{60}$ is estimated from the 'available' initial decay of the Schroeder curve (equation 4).

### 2.3. *INR* evaluation

Since 1998 for many impulse responses, measured in various sound fields, the *INR* has been calculated by the authors. In general, these impulse responses can be roughly divided into three types, based on the overall envelope shape: 'normal', with a 'high-initial-peak' or with a 'slow-attack'. The ETC (Energy Time Curve) for such impulse responses are shown with the corresponding calculated *INR* values in Figure 4.

As could be expected, the *INR* of the 'normal' impulse response corresponds very well with visual inspection of the ETC plot. The *INR* of the 'high-initial-peak' impulse response is clearly affected by the direct sound peak and much more difficult to determine unambiguously from the ETC plot. This is due to the fact that the curvature violates the presumption of an exponential decay. However, the *INR* correctly takes into account the RMS energy level of the initial peak, i.e. the width as well as the height, both of which affect the decay range. The *INR* of the 'slow-attack' impulse response can exceed the maximum RMS to noise level ratio in the ETC. Although here again the curvature does not represent a purely exponential decay, the constant initial level lifts the regression interval a little from the noise floor which is reflected by an increase in the *INR*. It can be concluded that the *INR* value is well in line with the visually estimated decay range for these three most common cases.

In particular *INR* values from low noise impulse responses are accurate. Therefore in this research low noise impulse responses have been started from in order to be able to accurately determine their decay range. Lower decay ranges have then been obtained accurately by adding well-defined noise. Finally a large set of practical impulse responses is investigated on the error in calculated parameter values versus the decay range.

Because at high noise values the estimation of $T_{60}$ becomes less accurate, a low *INR* is inherently a less accurate estimator for the decay range than a high *INR*. Thus, the decay range can be described best using the *INR*, but only accurately at high decay range values.

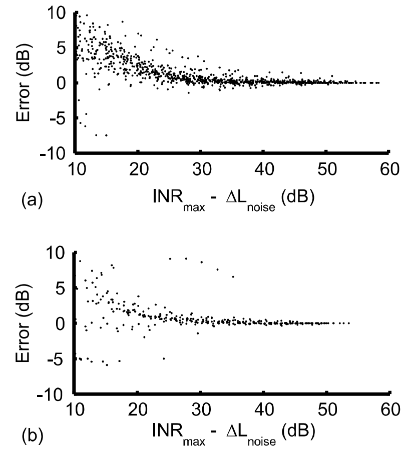


Figure 5. Measurement errors for *INR* as a function of the decay range $INR_{\max} - \Delta L_{\text{noise}}$ for far field impulse responses using an omnidirectional microphone. a) measurement type 1 in Table II, b) measurement type 2 in Table II.

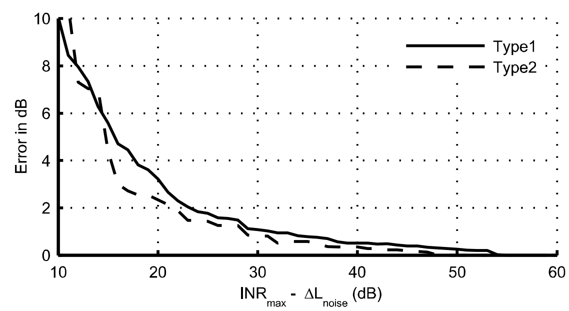


Figure 6. Measurement error for *INR* as a function of the calculated decay range $INR_{\max} - \Delta L_{\text{noise}}$ calculated from a gliding 5 dB average over the absolute maximum error values after discarding the extreme 5% of all measurement errors.

## 3. Method

The influence of the decay range is investigated by analysing 26 high quality impulse responses, measured at various locations using different microphone configurations, in accordance with the ISO 3382-1 standard. Table II shows all investigated room acoustic parameters related to the used microphone types and measurement locations with the corresponding average decay range and reverberation time range. All impulse responses are stepwise mixed with synthetic white noise with a 2.5 dB increase per step to obtain 19 different decay ranges per original impulse response. The addition of synthetic white noise resulted in 26×19 new impulse responses, with a decay range varying from 10 through 55 dB. The highest *INR* value $INR_{\max}$ reflects the decay range for the 26 impulse responses with the lowest noise floor. For all other impulse responses, the decay range is determined from their difference in noise floor from the impulse response with the lowest noise floor. So the decay range can be written as $INR_{\max} - \Delta L_{\text{noise}}$. This approach allows the decay range to be controlled accurately, and consequently the error in *INR* at low decay ranges to be investigated. This will be described further in section 4.

In accordance with ISO 3382-1 the starting point of the measured impulse responses was determined from the broadband impulse responses and defined as the point where the signal level rises significantly above the noise floor but is more than 20 dB below the maximum. Where the starting point could not be found because of the high noise level (25% of all cases), the original files were used to determine the starting point. The chosen integration time limit for the late Support ($ST_{\text{late}}$) is equal to a fixed value of 1 s as suggested in the ISO 3382-1 standard, although a recent study by Wenmakers *et al.* [17] shows that stage impulse responses having $INR > 45$ dB obtain the same results using $t_{\text{cross}}$ instead as integration time limit. For all other parameters the crosspoint time value was used. From the obtained new impulse responses all ISO 3382-1 parameters were calculated for the octave bands from 125 Hz through 4 kHz, resulting in 380 up to 912 calculated values for each room acoustic parameter.

## 4. Results and discussion

Figure 7 shows the parameter value errors as a function of the decay range $INR_{\max} - \Delta L_{\text{noise}}$ for all ISO 3382-1 room acoustic parameters, depicted in scatter plots. These errors are obtained by subtracting the parameter values from the original files with $INR_{\max}$ from the values derived from the impulse responses with lower decay ranges. The errors in reverberation time parameters are expressed in percentage while all other parameter errors are expressed in absolute differences. Although there are differences between the separate octave band values, for the sake of simplicity the results are presented over all frequency bands from 125 Hz through 4 kHz as overlapping points in each graph. The reverberation time $T$ is calculated from the squared impulse response by backwards integration [6] using noise compensation [21]. *EDT* with its evaluation decay interval from 0 to −10 dB, $T_{20}$ with its evaluation decay interval from −5 to −25 dB and $T_{30}$ with its evaluation decay range

Table II. Investigated room acoustic parameters (ISO 3382-1) and used microphone type, measurement location, number $N_{orig}$ of original files with their properties ($DR_{avg}$: Average Decay Range and $T_{30}$) and the total number $N_{opt}$ of obtained parameter values. *: *A switchable microphone was used to obtain the figure-of-eight and omnidirectional characteristics.* **: *For the stage impulse responses the 125 and 250 Hz octave bands are omitted in the analysis, because of limited measurement time of the available original files.*

| Type | Parameter | Microphone type | RIR | $N_{orig}$ | $DR_{avg}$ [dB] | $T_{30}$ [s] | $N_{opt}$ |
|---|---|---|---|---|---|---|---|
| 1 | $G$, $EDT$, $T_{20}$, $T_{30}$, $C_{80}$, $D_{50}$, $T_s$ | Omnidirectional | Random rooms | 7 | 51.4 | 0.5–3.0 | 798 |
| 2 | $ST_{early}$, $ST_{late}$ | Omnidirectional | Stages of concert halls and theatres | 5 | 52.2 | 1.0–2.4 | 380** |
| 3 | $LF$, $LFC$, $LG$ | Figure-of-eight and omnidirectional* | Concert halls | 8 | 47.0 | 1.7–2.4 | 912 |
| 4 | $IACC$ | Head and Torso Simulator (HATS) | Concert halls | 6 | 52.9 | 1.1–2.3 | 684 |

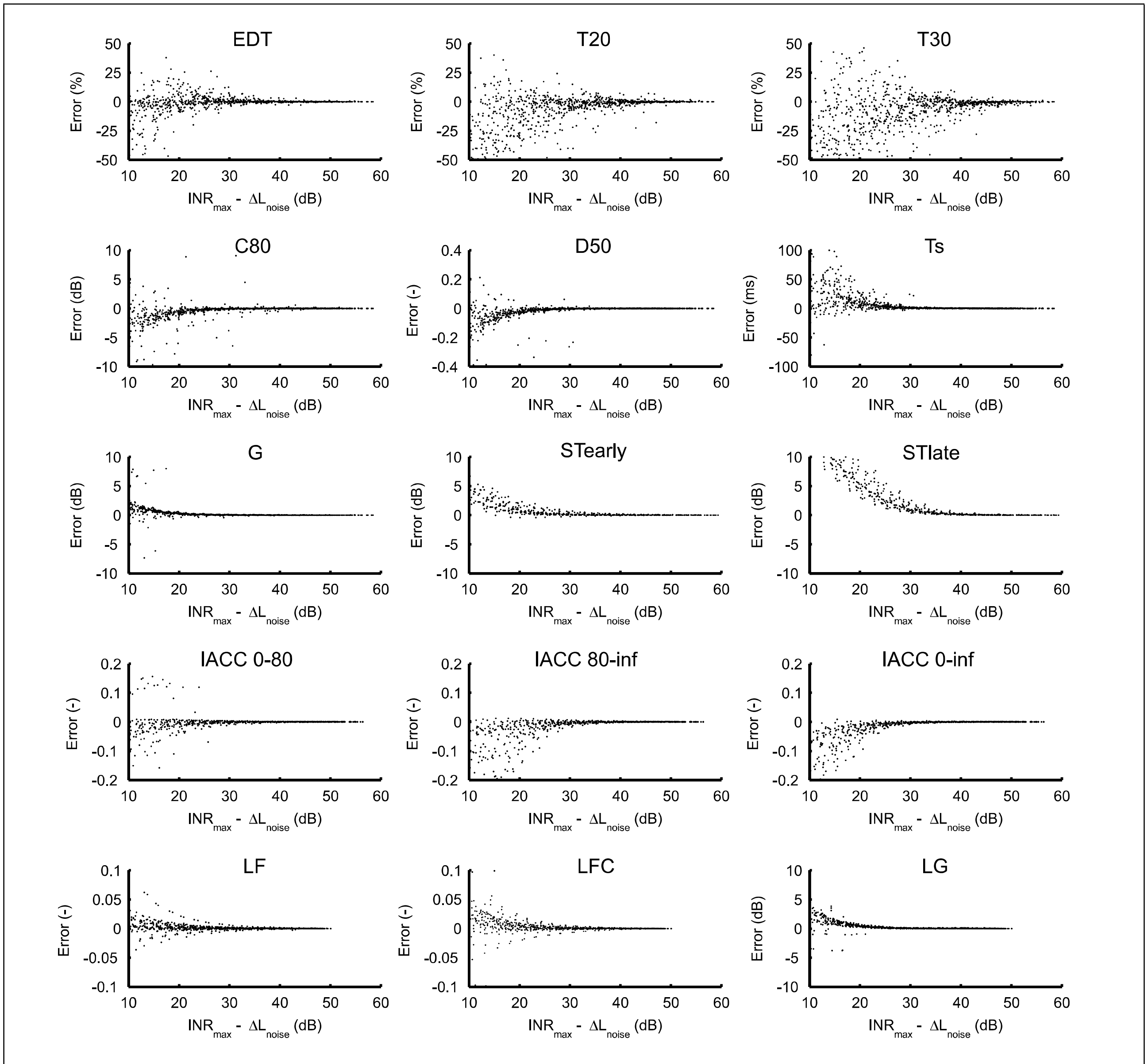


Figure 7. Measurement errors for all ISO 3382-1 parameters, depicted as a function of the decay range $INR_{max} - \Delta L_{noise}$, obtained by subtracting the parameter values from the original files with $INR_{max}$ from the values derived from the impulse responses with lowered decay ranges.

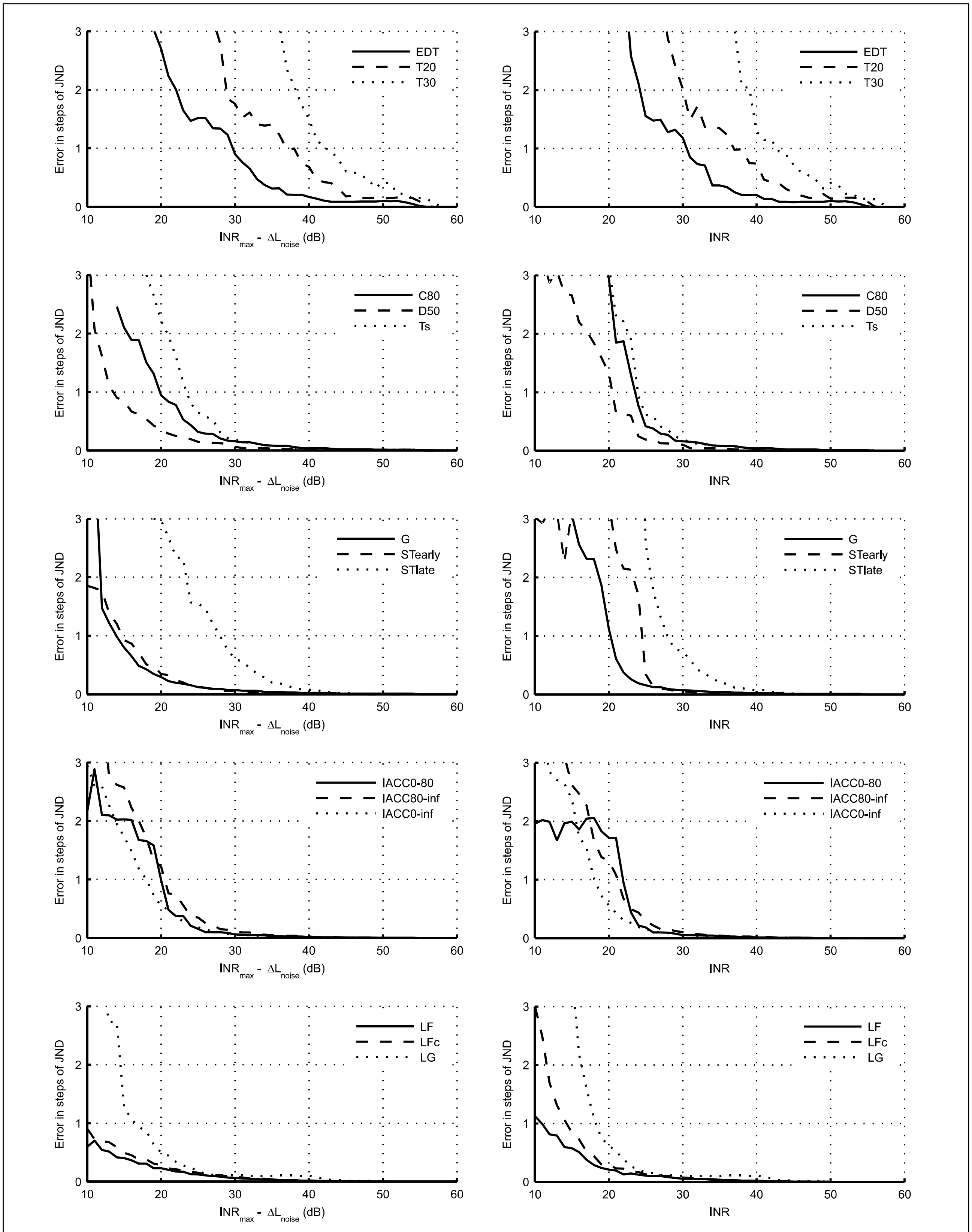


Figure 8. Measurement errors for all ISO 3382-1 parameters shown in steps of the just noticeable difference (JND) as a function of calculated decay range $INR_{\max} - \Delta L_{\text{noise}}$ (left) and the estimated decay range $INR$ (right), calculated from a gliding 5 dB average over the absolute maximum error values after discarding the extreme 5% of all measurement errors.

Table III. Minimum required decay range $INR_{\max} - \Delta L_{\text{noise}}$ and minimum required estimated decay range $INR$ for maximum parameter value errors of 0.1, 0.5, and 1 JND for all ISO 3382-1 room acoustic parameters. *: *Hard to detect impulse response starting point.*

| Parameter | $INR_{\max} - \Delta L_{\text{noise}}$ [dB] < 0.1 JND | < 0.5 JND | < 1 JND | $INR$ [dB] < 0.1 JND | < 0.5 JND | < 1 JND |
|---|---|---|---|---|---|---|
| $G$ | 27 | 17* | 14* | 28 | 22 | 21 |
| $EDT$ | 43 | 33 | 30 | 43 | 34 | 31 |
| $T_{20}$ | 55 | 41 | 37 | 55 | 41 | 37 |
| $T_{30}$ | 57 | 48 | 43 | 57 | 48 | 43 |
| $C_{80}$ | 34 | 24 | 20* | 34 | 25 | 24 |
| $D_{50}$ | 30 | 19* | 14* | 31 | 24 | 21 |
| $Ts$ | 34 | 28 | 24 | 34 | 27 | 24 |
| $LF$ | 27 | 14* | 4* | 26 | 17 | 11 |
| $LFC$ | 29 | 16* | 9* | 28 | 18 | 15 |
| $LG$ | 41 | 21 | 17* | 41 | 22 | 19 |
| $IACC_{0-80}$ | 26 | 21 | 20* | 26 | 23 | 22 |
| $IACC_{80-\infty}$ | 31 | 24 | 21 | 31 | 23 | 22 |
| $IACC_{0-\infty}$ | 28 | 21 | 18* | 27 | 21 | 19 |
| $ST_{\text{early}}$ | 27 | 19* | 15* | 28 | 25 | 25 |
| $ST_{\text{late}}$ | 39 | 32 | 28 | 39 | 32 | 28 |

from −5 to −35 dB all are used to determine $T$, even where the decay ranges do not meet the minimum requirements of ISO 3382.

With decreasing decay range all room acoustic parameter plots diverge to a fuzzy cloud of values, the shape of which depends on the characteristics of the impulse responses, calculation model and parameter types. The plots can be divided into symmetric and asymmetric shaped. The decay rate related parameters $EDT$, $T_{20}$ and $T_{30}$ show a symmetric distribution of the measurement errors. Parameters using a more or less fixed reference value ($G$, $ST_{\text{early}}$ and $ST_{\text{late}}$), the lateral energy parameters ($LF$, $LFC$ and $LG$) and $T_S$ predominantly show positive measurement errors. All other parameters mainly show negative measurement errors. The $LF$, $LFC$ (measured with an 'omnidirectional/figure-of-eight' microphone) and the $IACC_{0-80}$ appear to be less sensitive to low decay ranges due to the fact that only the first 80 ms of a measured impulse response is taken into account. With increasing decay range all room acoustic parameter values converge to the value for the theoretical case where no noise is present in the response signal (Error = 0).

The $INR$ value, reflecting the estimated decay range, relies on the estimation of the reverberation time $T_{60}$ and the noise floor. In general the early part of a room impulse response substantially determines the acoustic characteristics of a room. Nevertheless it was found that the larger the available section of the decay curve used to extrapolate $T_x$ to $T_{60}$ ($x < 60$), the more $T_x$ approaches $T_{60}$. Therefore, the maximum available decay range is used to estimate $T_{60}$ in the $INR$ calculations rather than using a fixed interval like $T_{20}$ or $T_{30}$. Similar to the results in Figure 7, Figure 5a shows the $INR$ error scatter plot over all impulse responses mentioned as measurement type 1 in Table II (798 $INR$ deviation values obtained from far field room impulse response measurements using an omnidirectional microphone). Figure 5b shows the $INR$ error scatter plot over all impulse responses mentioned as measurement type 2 in Table II (380 $INR$ deviation values obtained from near field room impulse response measurements using an omnidirectional microphone). The lower the decay range, the more the $INR$ tends to overestimate it. Discarding the extreme 5% of all values and taking the gliding average over 5 dB of the decay range, Figure 5a and 5b are converted to curve $IR_{\text{type1}}$ and $IR_{\text{type2}}$ in Figure 6. It can be concluded that in general the $INR$ deviates less than 2 dB from decay ranges exceeding 25 dB. For lower decay ranges, the deviation becomes significant, which should be taken into account and needs further investigation.

Figure 8 shows the measured ISO 3382-1 parameter value errors in steps of the just noticeable difference (JND) as a function of the decay range $INR_{\max} - \Delta L_{\text{noise}}$ (left) and as a function of the estimated decay range $INR$ (right). The depicted curves are obtained in a way similar to Figure 6, i.e. after discarding the extreme 5% of all values and taking the gliding average over 5 dB of the decay range.

With increasing decay range all room acoustic parameter values converge to the minimum noise values. At a decay ranges below 20 dB some parameters (in particular the $IACC_{0-80}$) show an irregular error curve, mainly caused at the lowest frequencies. Table III shows the derived minimum required decay range $INR_{\max} - \Delta L_{\text{noise}}$ and its estimator $INR$ for different accuracy requirements shown as a fraction of the JND. It should be noted that a decay range < 20 dB may be unrealistic as it is still difficult to find the impulse response starting point [22].

## 5. Conclusions

Using the crosspoint of the decay line and the noise level as an approximation of infinite time in parameter calculations, using the *INR* as an estimator for the decay range, and assuming the same JND for each octave band, the following is found for 95% of all octave band measurements:

- With increasing decay range all room acoustic parameter values converge to no noise values.
- To determine the reverberation time with a maximum error of 5% (= JND), the minimum *INR* should be 37 dB for $T_{20}$ and 43 dB for $T_{30}$. This is in line with the requirements of the ISO 3382-1 standard, being 35 and 45 dB respectively.
- Calculating the Sound Strength *G* from an impulse response, using the ISO 3382 requirement *INR* of at least 30 dB results in a measurement error less than 0.1 dB (= 0.1 JND).
- Using a minimum *INR* value of 35 dB (the decay range for $T_{20}$ calculations in accordance with ISO 3382-1), all measured room acoustic parameter errors are less than 0.5 JND except the parameter values related to the energy decay rate ($T_{30}$ and $T_{20}$).
- Using a minimum *INR* of 45 dB (the decay range for $T_{30}$ calculations in accordance with ISO 3382-1), all measured room acoustic parameter errors are less than 0.1 JND except the parameter values related to the energy decay rate ($T_{30}$ and $T_{20}$).
- To determine the reverberation time with a maximum error of 0.5% (= 0.1 JND), the minimum decay range or *INR* for $T_{20}$ or $T_{30}$ calculations should be at least 57 dB.

Finally, it can be concluded that the room Impulse response to Noise Ratio *INR* is a useful quality parameter in practical situations, where the decay range exceeds 25 dB.

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