Calibration and Uncertainty Estimation for The Reference Sound Source in Reverberation Room

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Abstract: - Since the determination of room acoustic parameters are requesting the sound power of the sound source. Few trials to publish the way of calibration and uncertainty estimation in details for the reference sound source were performed. So, it is very interesting to find a way to calibrate the reference sound source that can be used in different acoustic measurements. Also, there is a need to find the value uncertainty of due to the calibration of reference sound source. Sound power level of any sound source can be determined by means of sound pressure level measurements performed in accordance to relevant ISO standards. The calibration of reference sound source according to ISO 6926 may be implemented in a hemi-anechoic or reverberation room. The method and way of sound power calculations which may depend on number of microphones, their positions and place of measurements stated. Measurements of sound pressure level, reverberation time and background noise level were performed using traceable instruments by direct method in ISO3741. Then the calculation of sound power level in 1/3 octave band frequency was carried out for the reference sound source side by side with uncertainty contributions resulting from measurements. The values of uncertainty σ_{R0} σ_{omc} respectively are in order of magnitude of 0.4 and 0.07 dB. The total uncertainty lies within the range of 0.7-1.0dB in the 1/3 octave band frequency from 125Hz to 10000Hz.

Keywords: - RSS, reverberation room, microphones, sound power, uncertainty

1. INTRODUCTION

Reference sound sources (RSS) can be used in various kind of acoustics measurement, particularly for the determination of sound power levels of machinery or for measuring equivalent sound absorption areas in room and building acoustics. Sound power measurements can be performed in diffuse or in free sound fields. The sound power level is used for quantitative evaluation of sound energy radiated from electrical and mechanical apparatus. Procedures for measuring the sound power level are categorized into the standard[1] on the basis of measurement principle, environment, and accuracy. Among them, the practical procedures involve the use of a reference sound source (RSS) with a predetermined sound power level, and an apparatus under test can be easily calibrated in comparison with RSS. The RSS has stable and broad-band sound power output. Requirements for its performance and calibration procedure are prescribed in the standard [2].

Thus precise calibration of the RSS is essential for end-users to establish reliable sound power measurements. In [2], the RSS is calibrated in hemi-anechoic rooms or in reverberation room. From the accuracy viewpoint and facilities, we decided to use reverberation room which is the accurate method. The sound power levels in the reverberation room require the determination of the average sound pressure levels in the reverberant field. Several studies were conducted with the goal of developing a calibration procedure for reference sound sources. In one of these, a series of 60 measurements was performed in the National Bureau of Standards reverberation room.

These measurements emphasized the importance of source position and demonstrated that by averaging over three source positions, a transfer calibration can be performed with a precision of about 0.1 dB, for certain stable sources. In another series of tests, measurements performed in a free field over a reflecting plane were compared with reverberation room measurements.

The free-field data are about 1 dB higher than the reverberation room data over the entire audible frequency spectrum. In 1979, P.A.Mansbach[3] developed calibration procedures for calibration of a RSS. He recommended that the measurements to be done at reverberation room. The environmental condition controlled and the precision was within more than 0.1dB. But there were higher deviations at low frequencies and many details about the uncertainty still absent. In 1995 , M.Vorländer and G.Raabe [4] performed the calibration of a RSS through an intercomparison among eight laboratories. The project was performed by Physikalisch Technische Bundesanstalt (PTB) institute and Brüel and Kjar (B&K) company where in the study, the RSS was calibrated while standing on a reflecting plane far away from the other reflecting surfaces. Also, the measurements compared with that obtained in hemi-anechoic room. No detailed description has been found of the surface density of the floor and the influence of the surface density on the sound power level. In the present work, the calibration of RSS at a qualified reverberation room using the standards [1] and [2] with traceable calibration system and high stability was implemented. Calculations of sound power and uncertainty budget, where the uncertainty sources and contributions were identified in details. The obtained uncertainty is considered as smallest value and this is challenge. Thus precise calibration of the RSS is essential for end-users to establish reliable sound power measurement.

2. MATERIALS AND METHOD

2.1. Calculation of sound pressure level and sound power level

For the level in each frequency band of interest, the average sound pressure level over the measurement surface given by equation (1)

$$\overline{L_p^i} = 10\log\left[\frac{1}{N}\sum_{i=1}^{N} 10^{0.1L_{pi}^i}\right] dB, \qquad (1)$$

$\overline{L_p^i}$ is the sound pressure level averaged over the measurement, in dB (This is calculated parameter_ logarithmic average);

L_{pi}^i is the sound pressure level at the ith microphone position, in dB (This is measured parameter for each microphone position);

N is the number of microphone positions

2.1.1. Calculate one-third-octave band sound power levels using the equivalent absorption area of the room in accordance with the direct method of ISO 3741

The sound power level of the noise source under test in each one-third-octave band, L_W, under reference meteorological conditions, shall be calculated using Equation (2)

$$L_W = \overline{L_{p(ST)}} + \left\{10log\frac{A}{A_0}dB + 4.34\frac{A}{S}dB + 10\log\left(1+\frac{S\,c}{8V\,f}dB\right) + C_1 + C_2 - 6dB \right., \qquad (2)$$

$\overline{L_{p(ST)}}$ is the mean corrected one-third-octave band time-averaged sound pressure level in the test room with the noise source under test in operation in dB;

A is the equivalent absorption area of the room in m^2. The equivalent sound absorption area A is obtained from application of the Sabine equation and a measurement of reverberation time (s) in the room using equation (3)

$$\mathrm{A} = \frac{55.26}{\mathrm{c}}\left(\frac{\mathrm{V}}{\mathrm{T}_{60}}\right), \qquad (3)$$

where V is the internal volume of the room (m^3) and the dimensional constant of 55.26 has the unit (s/m). T_{60} is the reverberation time of the reverberation test room at the mid band frequency of the measurement(s) in seconds; A_0 =1m^2. S is the total surface area, of the reverberation test room in m^2. c is the speed of sound in m/s at the temperature θ of the air in the reverberation test room at the time of test in ^{o}C,

$$\mathrm{c} = 20.05\sqrt{273+\theta}, \qquad (4)$$

V is the volume of the reverberation test room in m^3. f is the mid-band frequency of the measurements in Hz.

C_1 (dB) is the reference quantity emendation to account for the different reference quantities utilized to calculate decibel SPL and decibel sound power level.

$$C_1 = -10log\frac{p_s}{p_{s,0}}dB + 5\log\left(\frac{273.15+\theta}{\theta_0}\right)dB, \qquad (5)$$

C_2 (dB) is the radiation impedance emendation to modify the real sound power relevant for the meteorological conditions, the following equation is valid for a monopole source and is a mean value for other sources [5]

$$\mathrm{C}_2 = \text{-}10\log\frac{\mathrm{p_s}}{\mathrm{p_{s,0}}}\mathrm{dB} + 15\log\left(\frac{273.15+\theta}{\theta_1}\right)\mathrm{dB}, \qquad (6)$$

p_s is the static pressure in the test room at the time of test in kPa. $p_{s,0}$ is the reference static pressure=101,325 kPa. θ (^{o}C) is the air temperature in the test room at the time of test. θ_0=314 K, θ_1=296 K.

The value given for θ_0 leads to a characteristic impedance of air of 400 Ns/m3 at the reference static pressure 101,325 kPa[6]. This value is not related to any real environmental condition; it is a consequence of the decibel reference values used for sound pressure and for sound power.

$$\theta_0 = 273.15K * \left(\frac{331.45\frac{m}{s} * 1.292\frac{kg^3}{m} * 1pW}{(20\mu Pa)^2 * 1m^2}\right. \sim 314\mathrm{K}, \qquad (7)$$

2.2. Instrumentation and measurement system

Sound pressure levels (SPL) measurements were accomplished in Rev.room with volume of 157.16m^3 and total superficial area of 177.77 m^2. The reverberation chamber is almost a rectangle room. The room is built as a box and it has been isolated from the surrounding building. Access to the room is provided by double access doors made from wood. Figure 1 below shows the schematic section drawing/photo of the reverberation chamber. Before the experiment begins, the qualification of the room performed. Where, as mention in ISO 3741 for frequencies below f, the average sound absorption coefficient, α, of all the surfaces of the reverberation test room should not exceed 0,16 for frequencies above f or equal to f, the average sound absorption coefficient should not exceed 0,06.

The volume of the sound source is less than 1 % of the total volume of the reverberation room. Also, according to ISO 3741, the room with the smallest dimension greater than 4m. In table 1, present details about the instruments used.

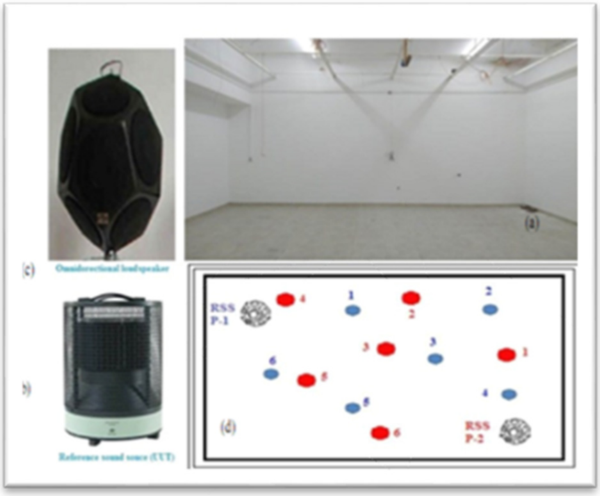


Figure 1. a) room of measurements at NIS; b) sound source photo (RSS)under test of type B&K 4204; c) omnidirectional loud speaker B&K 4292used in the calibration d) Schematic diagram for measurement illustrating places of sound source and microphone positions

$$f = \frac{2000}{V^{1/3}}, \tag{8}$$

2.3. Measurements method and specified conditions

The SPL inside the room was executed with six microphone position(N_m=6) , all of them more than λ/2 apart from each other, from (ceiling, floor, RSS and walls). The source was also moved in two different locations (N_s=2) inside the space SPL was executed in 1/3 octave band frequency domain from 125 Hz to 10000Hz. Five repeated measurements of the time-average SPL of the RSS shall be taken at one fixed microphone in conformance with this International Standard with a pause of at least 5 minutes between measurements. To every group of the spatially distributed SPL measurements, the energy-based mean and spatial standard deviation (s_e) for all the octave bands considered were deliberate using eq. (9),

$$s_e = \sqrt{\frac{1}{(N_m-1)}\sum_{i=1}^{N_m}(\overline{L_p} - L_{pi})^2}, \tag{9}$$

where, N_m is the No. of microphone placed inside the rev.room , L_{pi} is the average SPL for each microphone position , and $\overline{L_p}$ is the energy-base average sound pressure level for all the microphone position. Measurements of the reverberation time were in performed in three different locations within the octave band frequencies with 5 times of decay. The background noise was executed before every group of mensuration. A correction was not applied as for any octave bands where the background noise values within the octave bands was found to be in the accepted limit shown in table 1.

As a portion of the particular condition, all equipment was switched off and on between each measuring series, and the same operator conducted all measurements. For each 1/3 octave band , the average standard deviations ($\overline{s_r}$) were computed for all measurements in the research.
The formula used to compute the average standard deviation presented in equation (10)

$$\overline{s_r} = \frac{\sum_{i=1}^{N_{source}} s_{ri}}{N_{source}}, \tag{10}$$

2.4. Atmospheric temperature, humidity and pressure

The atmospheric conditions were recorded with data logger and barometer (see table2) Environmental conditions during the measurements were recorded on a data sheet and compared with the limits in table 1.

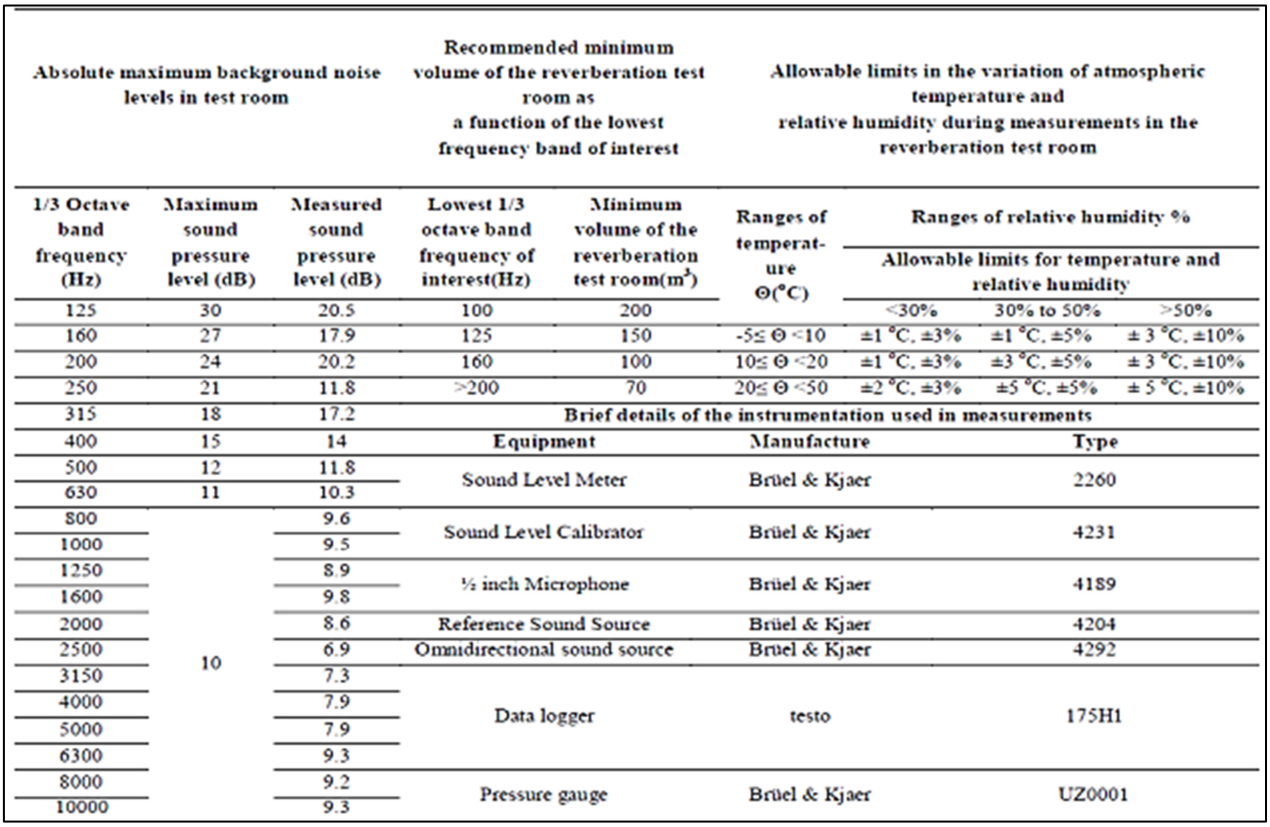
The instruments set-up was calibrated before and after the measurement. All instruments are calibrated regularly and traceable to DFM and NIS. All the equipment used had been calibrated. It was preferable that before the first measurement, all the devices were left for 10 minute for electrical and room conditioning. It was important and useful to assess if the temp. and humid. variations during the experiment. It is recommended that during single mensuration the deviation were lower than 5ºC in temp., 5% in rel. humid. and 1mbar in static pressure (see table 1).

2.5. Estimation of uncertainty

The uncertainty in statement of the sound power level emerges from sundry factors which influence the results, some correlated with environmental conditions in the measurement laboratory and others with experimental techniques. ISO/IEC Guide 98-3 shall be used to determine the measurement uncertainty. The uncertainty of sound power levels, $u(L_W)$ is estimated by the total standard deviation (eq. 11):

$$u(L_W) = \sigma_{tot.}, \qquad (11)$$

Table 1. 1-maximum and measured background noise, 2-recommended minimum volume of reverberation room, 3-limits in atmospheric variations, 4-instrumentation used in measurements



Absolute maximum background noise levels in test room

1/3 Octave band frequency (Hz)	Maximum sound pressure level (dB)	Measured sound pressure level (dB)
125	30	20.5
160	27	17.9
200	24	20.2
250	21	11.8
315	18	17.2
400	15	14
500	12	11.8
630	11	10.3
800	10	9.6
1000		9.5
1250		8.9
1600		9.8
2000		8.6
2500		6.9
3150		7.3
4000		7.9
5000		7.9
6300		9.3
8000		9.2
10000		9.3

Recommended minimum volume of the reverberation test room as a function of the lowest frequency band of interest

Lowest 1/3 octave band frequency of interest(Hz)	Minimum volume of the reverberation test room(m^3)
100	200
125	150
160	100
>200	70

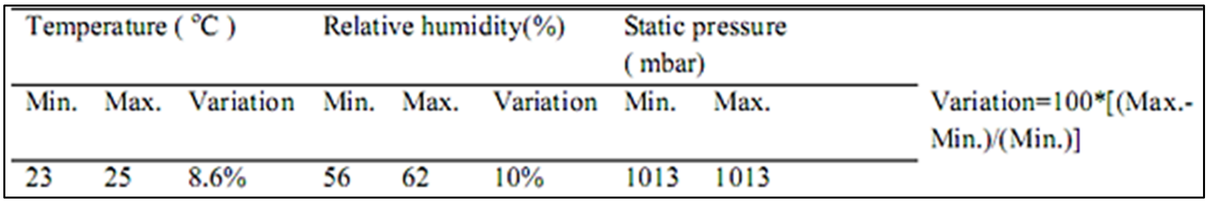
Allowable limits in the variation of atmospheric temperature and relative humidity during measurements in the reverberation test room

Ranges of temperat-ure Θ(°C)	Ranges of relative humidity % Allowable limits for temperature and relative humidity		
	<30%	30% to 50%	>50%
-5≤ Θ <10	±1 °C, ±3%	±1 °C, ±5%	± 3 °C, ±10%
10≤ Θ <20	±1 °C, ±3%	±3 °C, ±5%	± 3 °C, ±10%
20≤ Θ <50	±2 °C, ±3%	±5 °C, ±5%	± 5 °C, ±10%

Brief details of the instrumentation used in measurements

Equipment	Manufacture	Type
Sound Level Meter	Brüel & Kjaer	2260
Sound Level Calibrator	Brüel & Kjaer	4231
½ inch Microphone	Brüel & Kjaer	4189
Reference Sound Source	Brüel & Kjaer	4204
Omnidirectional sound source	Brüel & Kjaer	4292
Data logger	testo	175H1
Pressure gauge	Brüel & Kjaer	UZ0001

Table 2. Measurement environmental conditions in five measurements



Temperature (°C)			Relative humidity(%)			Static pressure (mbar)		
Min.	Max.	Variation	Min.	Max.	Variation	Min.	Max.	Variation=100*[(Max.-Min.)/(Min.)]
23	25	8.6%	56	62	10%	1013	1013	

This total standard deviation is obtained using the modeling approach described in ISO/IEC Guide 98-3[7]. This standard deviation is explicit by the standard deviation of reproducibility of the method (σ_{R0}) and the standard deviation (σ_{omc}) depict the uncertainty due to the instability of the operating and mounting conditions (omc) of the source under test in accordance with eq. (12):

$$\sigma_{tot.} = \sqrt{\sigma_{R_0}^2 + \sigma_{OMC.}^2}, \qquad (12)$$

Derived from $\sigma_{tot.}$ the expanded measurement uncertainty, U, in dB, shall be enumerated from equation (13)

$$U = k\sigma_{tot.}, \qquad (13)$$

With respect to the main uncertainty quantity $\sigma_{tot.}$, investigations on σ_{omc} have a higher priority compared to those on the other uncertainty components leading to σ_{R0}. This is because σ_{omc} may be significantly larger in practice than, for example, σ_{R0} = 0,5 dB for accuracy grade 1 measurements (ISO 3741). The expanded measurement uncertainty depends on the degree of confidence that is desired. For a normal distribution of measured values, there is 95 % confidence that the true value lies within the range ($L_W - U$) to ($L_W + U$). This corresponds to a coverage factor of $k = 2$.

2.5.1. Determination of σ_{omc}

The standard deviation (σ_{omc}) which describes the uncertainty associated with the instability of the operating and mounting conditions for the particular source can be determined separately from repeated measurements carried out on the same source at the same location by the same persons, using the same measuring instruments and the same measurement position(s).

$$\sigma_{omc} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(L_{p,i}\text{-}L_{p,av.})^2}\,dB, \qquad (14)$$

Where, $L_{p,i}$ is the sound pressure level measured at a prescribed position and corrected for background noise for the i_{th} repetition of the prescribed operating and mounting conditions(N=5).
$L_{p,av.}$ is its arithmetic mean level calculated for all these repetitions. When the measurements averaged over all measurement positions $L_{p,i}$, $L_{p,av.}$, are replaced in equation (14), by $\overline{L_{p,i}}, \overline{L_{p,av.}}$ respectively.

2.5.1.1. Determination of σ_{R0}

The standard deviation σ_{R0} includes all uncertainty due to conditions and situations allowed by this international Standard (different radiation characteristics of the source under test, different instrumentation, different implementations of the measurement procedure), except that due to instability of the RSS. In the round robin test the round robin test for determining σ_{R0} shall be carried out in accordance with ISO 5725, where the sound power level of the source under test is determined under reproducibility conditions, i.e. different persons carrying out measurements at different testing locations with different measuring instruments. This total standard deviation σ_{tot} , in decibels, of all results obtained with a round robin test includes the standard deviation σ_{omc} and allows σ_{R0} to be determined by using (eq. 15)

$$\sigma_{R_0} = \sqrt{\sigma^2_{tot.}\text{-}\sigma^2_{omc}}, \qquad (15)$$

If no round robin test has been carried out, the existing knowledge about the noise emission from a particular family of machines may be used to estimate realistic values of σ_{R0}.The determination of σ_{R0} using equation (16) is imprecise if σ tot is only slightly higher than σ_{omc}. In this case, equation (16) gives a small value of σ_{R0}, but with a low accuracy. To limit this inaccuracy, σ_{omc} should not exceed $\sigma_{tot} / \sqrt{2}$.

2.6. Modeling approach for σ_{R0}

Generally, σ_{R0} is dependent upon several partial uncertainty components, c_i u_i (c_i is the sensitivity coefficient &u_i is stand. uncertainty) that associated with the different measurement parameters such as uncertainties of instruments, environmental corrections, and microphone positions. If these contributions are assumed to be uncorrelated, σ_{R0} can be described by the modeling approach presented in ISO/IEC Guide 98-3, as follows:

$$\sigma_{R_0} = \sqrt{(c_1u_1)^2 + (c_2u_2)^2 + \cdots \ldots \ldots \ldots + (c_nu_n)^2}, \quad (16)$$

2.6.1. Contributions to the uncertainty σ_{R0}

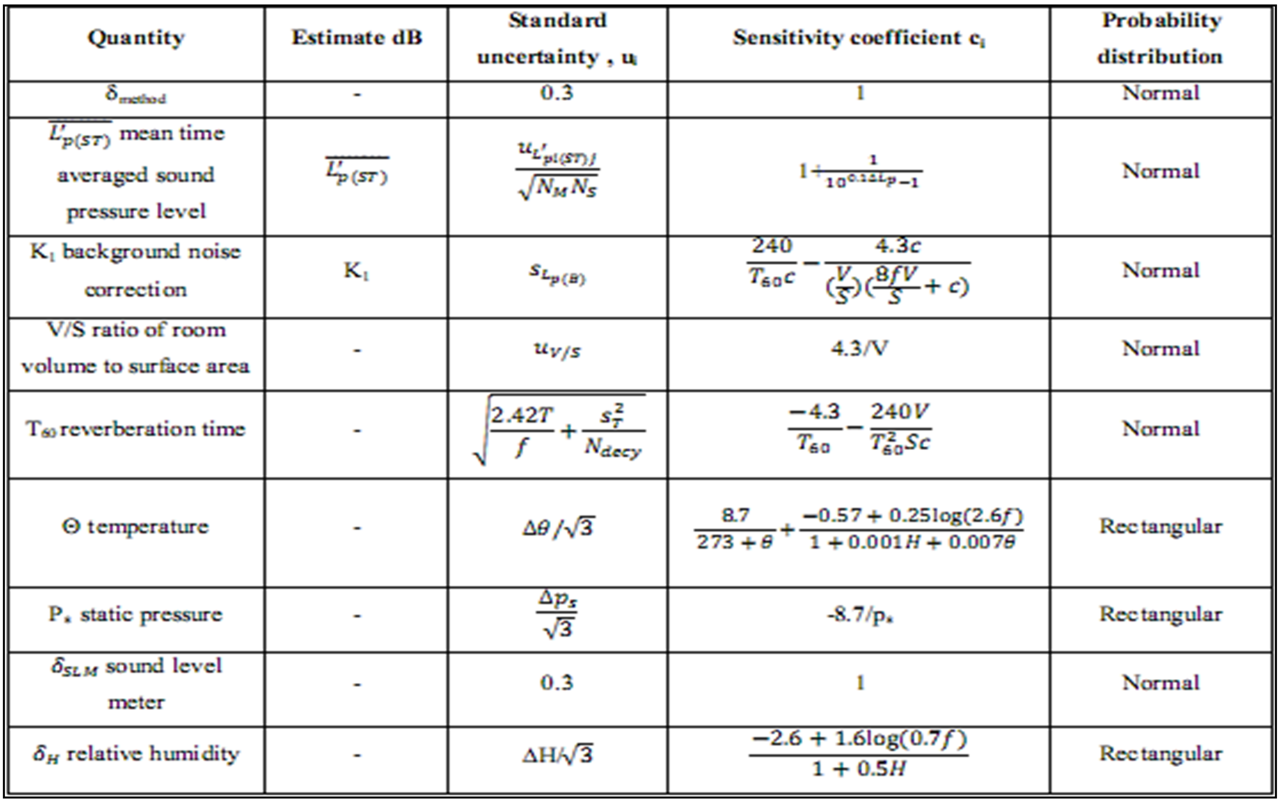
The sound power level, L_W, is a function of a number of parameters, indicated by the following equation, obtained with appropriate substitution in equation (2):

$$L_W = \delta_{method} + \delta_{omc} + \overline{L'_{p(ST)}} + 10\log\frac{A}{A_0}dB + 4.34\log\frac{A}{S}dB + 10\log\left(1 + \frac{S\,c}{8V\,f}\right)dB\text{-}K_1 + C_1 + C_2\text{-}6dB + \delta_{slm} + \delta_H\,, \qquad (17)$$

Where δ_{method} is an input quantity to allow for any uncertainty due to the measurement method applied including the derivation of results and associated uncertainties δ_{omc} is an input quantity to allow for any uncertainty due to operating and mounting conditions, — this quantity is not included in the calculation of σ_{R0} (see eq. 15). $\overline{L'_{p(ST)}}$ is the mean one-third-octave band time-averaged sound pressure level of the noise source under test. A is the equivalent absorption area of the room(m^2), A_0=1 m^2 S is the total surface area(m^2) of the reverberation test room, V is the volume (m^3) of the reverberation test room. In which T_{60} (sec)is the reverberation time of the reverberation test room at the mid-band frequency of the measurement(s) , f is the mid-band frequency(Hz) of the measurement band, c is the speed(m/s) of sound at the temperature, θ (°C) of the air in the reverberation test room at the time of test(see eq.4).K_1 is the background noise correction (dB), C_1 (see eq.5)is the reference quantity emendation (dB) to account for the different reference quantities used to count decibel SPL and dB sound power level, and is a duty of the distinctive impedance of the air under the meteorological conditions at the time and place of the measurements. C_2(see eq.6) (dB) is the radiation impedance correction to change the actual sound power relevant for the meteorological conditions at the time and place of the measurement into the sound power, the value shall be gained from the convenient noise test code, but in the obscurity of a noise test code, the following equation is valid for a monopole source, and is a mean value for other sources [6].

Table 3 provides some information about current expectations concerning the values for the components, c_i, u_i, that are necessary to calculate $\sigma_{R0} = \sqrt{\sum_{i=1}(c_i u_i)^2}$.

Table 3. Uncertainty budget for determinations of σ_{R0} for sound power level and sound energy level using direct method, valid for A-weighted measurements of a source with a relatively flat frequency spectrum



Quantity	Estimate dB	Standard uncertainty , u_i	Sensitivity coefficient c_i	Probability distribution
δ_{method}	-	0.3	1	Normal
$\overline{L'_{p(ST)}}$ mean time averaged sound pressure level	$\overline{L'_{p(ST)}}$	$\frac{u_{L'_{pi(ST)j}}}{\sqrt{N_M N_S}}$	$1+\frac{1}{10^{0.1\Delta L_p}-1}$	Normal
K_1 background noise correction	K_1	$s_{L_{p(B)}}$	$\frac{240}{T_{60}c}-\frac{4.3c}{(\frac{V}{S})(\frac{8fV}{S}+c)}$	Normal
V/S ratio of room volume to surface area	-	$u_{V/S}$	4.3/V	Normal
T_{60} reverberation time	-	$\sqrt{\frac{2.42T}{f}+\frac{s_T^2}{N_{decy}}}$	$\frac{-4.3}{T_{60}}-\frac{240V}{T_{60}^2 Sc}$	Normal
Θ temperature	-	$\Delta\theta/\sqrt{3}$	$\frac{8.7}{273+\theta}+\frac{-0.57+0.25\log(2.6f)}{1+0.001H+0.007\theta}$	Rectangular
P_s static pressure	-	$\frac{\Delta p_s}{\sqrt{3}}$	$-8.7/p_s$	Rectangular
δ_{SLM} sound level meter	-	0.3	1	Normal
δ_H relative humidity	-	$\Delta H/\sqrt{3}$	$\frac{-2.6+1.6\log(0.7f)}{1+0.5H}$	Rectangular

1-Measurement method, δ_{method}: The uncertainty due to the measurement method applied, u_{method}, uncertainties. For frequencies above 100Hz, experience has shown that the approximate value of uncertainty due to the measurement method applied is u_{method} = 0,3 dB. Below 100 Hz, the wavelength reduces both the effective number of possible microphone positions and the number of room modes. This increases this parameter to u_{method} = 3 dB below 100 Hz. The measurement method has a direct effect on the measurement result so the sensitivity coefficient, c_{method} = 1. For measurements above 100 Hz, the uncertainty contribution is 0,3 dB.

2-Sound pressure level repeatability $\overline{L'_{p(ST)}}$: The uncertainty due to measurement repeatability, $u_{L'p(ST)}$ is the nearness of consent between results of consecutive mensuration; it may be obtained from the standard deviation of measured levels using the following equation:

$$u_{L'p(ST)} = \frac{u_{L'p(ST)j}}{\sqrt{N_M N_S}} = \frac{1}{\sqrt{N_M N_S}}\sqrt{\sum_{j=1}^{N_S}\sum_{i=1}^{N_M}\frac{\{[\overline{L'_{pi(ST)}}]_j - L'_{pm(ST)}\}^2}{N_M N_S - 1}} \qquad (18)$$

where $L'_{pm(ST)}$ is the arithmetic mean value of the uncorrected time-averaged sound pressure levels with the noise source under test in operation, in decibels. The sensitivity coefficient, $c_{L'p(ST)}$ is influenced by background noise levels. It is obtained from the derivative of L_W with respect to $\overline{L'_{p(ST)}}$. Using a derivation similar to that for c_{K1}, the sensitivity coefficient due to repeatability is:

$$c_{L'p(ST)} = 1 + \frac{1}{10^{0.1\Delta L_p}{}_{-1}} \qquad (19)$$

This may be further simplified to $c_{L'p(ST)} = 1 + c_{K1}$ (when $c_{L'p(ST)} = 1.1$)

For the A-weighted value, the summation across multiple frequency bands tends to make an uncertainty contribution of 0,2 dB more typical. The uncertainty contribution can be reduced by increasing the reverberation time, reducing the variability of measurements in the room using diffusors, or increasing the number of source and microphone positions.

3-Background noise correction K_1: The uncertainty (u_{K1}) due to the background noise correction K_1 can be obtained from the standard deviation (sLp(B)) of the decibel values from of repeated measurements of background noise at a single microphone position. The sensitivity coefficient (c_{K1}) due to the background noise $\overline{L_{p(B)}}$ is obtained from the derivative of L_W with respect to $\overline{L_{p(B)}}$.

$$K_{1i} = -10\log\left(1 - 10^{-0.1\Delta L_{pi}}\right) dB \qquad (20)$$

$$L_{pi(ST)} = L'_{pi(ST)} - K_{1i} \qquad (21)$$

Using equations a and b , $\overline{L_{p(ST)}}$ is given by $\overline{L_{p(ST)}} = \overline{L'_{p(ST)}} + 10\log\left(1 - 10^{-0.1\Delta L_p}\right) dB,$ where $\Delta L_p = \overline{L'_{p(ST)}} - \overline{L_{p(B)}}$. The sign of the sensitivity coefficient is unimportant, and reduces to:

$$|c_{K1}| = \frac{1}{10^{0.1\Delta L_p}-1} \ , \qquad (22)$$

For $\Delta L_p \leq 10$ dB this may be further simplified to$|c_{K1}| = \frac{3.6}{\Delta L_p} - 0.24$. In an extreme scenario low noise sources are assumed with background noise standard deviation of 3 dB. Lowering the fluctuations in background noise can reduce this uncertainty component. Significant reductions in the sensitivity coefficient are obtained by reducing background noise by systematically tracking down and blocking and/or absorbing noise from unwanted sources (through proper grounding, lead wrapping, vibration isolation, adding mass, adding absorptive materials, etc., as appropriate). Furthermore, the uncertainty, uK1, is typically halved each time the averaging time is increased by a factor of four. The worst case $\overline{L'_{pA}} - \overline{L'_{pA(B)}}$ is 10 dB. This results in a sensitivity coefficient of $c_{K1} = 0{,}11$ and a total contribution to uncertainty of 0,3 dB. Typically, this contribution is 0,03 dB due to better control of the background noise.

4-Room volume to surface area ratio V/S: The uncertainty ($u_{V/S}$) related to the estimate of the ratio of room volume to surface area is a ratio the two measured quantities are correlated. For a right cuboid room, the uncertainty (Δl) in the measurement of each room dimension (lx, ly, lz) should typically be less than 1 % of that dimension. The uncertainty in the resulting ratio V/S is then:

$$u_{V/S} = 2\Delta l(\tfrac{V}{S})^2\sqrt{(l_x^{-4} + l_y^{-4} + l_z^{-4})/3} \qquad (23)$$

The sensitivity coefficient($c_{V/S}$) is obtained from the derivative of the sound power level L_W Equation (17) with respect to V/S:

$$c_{V/S} = \frac{240}{T_{60}c} - \frac{4.3c}{(\frac{V}{S})(8f\frac{V}{S}+c)} \qquad (24)$$

The sensitivity coefficient is largest at low frequencies. Assuming a small room with V/ S ≈0,66 and T_{60} = 1 s at 200 Hz the sensitivity coefficient is −0,9 and with a 0,4 % uncertainty in V/S the associated total uncertainty is −0,003 dB The sensitivity coefficient increases to 0,7 at 8 kHz.

5-Room volume, V: The uncertainty related to the estimation of the room volume is (u_V) For a right cuboid room, the uncertainty (Δl)in the measurement of each room dimension, lx, ly, lz, should typically be less than 1 % of that dimension with a rectangular distribution giving a standard deviation of (Δl/√3). The room volume then has a standard uncertainty of:

$$u_V = \Delta l V\sqrt{(l_x^{-2} + l_y^{-2} + l_z^{-2}/3} \qquad (25)$$

The sensitivity coefficient (c_V)is obtained by ignoring the V/S terms, which are accounted for separately and taking the derivative of the remaining terms in L_W, equation 17 with respect to V: C_V=4.3/V, assuming 1 % uncertainty for the room volume, the combined uncertainty would be 0,04 dB.

6-Reverberation time T_{60}: The uncertainty in the determination of the reverberation time of the room(u_T) is gained from the standard deviation(s_T) of decay mensuration of the rev. time T_{60} and the following formula which is loosely based on ISO 354-2003[8]

$$u_T = \sqrt{\frac{2.42T_{60}}{f} + \frac{s_T^2}{N_{decays}}}, \qquad (26)$$

where N_{decays} is the overall number of rev. time decay measurements. The sensitivity coefficient(c_T) due to reverberation time is obtained from the derivative of L_W with respect to reverberation time. For terms containing A, the equivalent absorption area of the room, derivatives were taken with respect to reverberation time after substitution for A:

$$c_T = \frac{-4.3}{T_{60}} - \frac{240\,V}{T_{60}^2\,S\,c}, \qquad (27)$$

assuming a standard deviation s_T = 0,2 s at 500 Hz (T_{60}=1s), the sensitivity coefficient is −5dB/s and the worst case uncertainty contribution $u_T\ c_T$ = 1 dB.

7-Temperature θ: The uncertainty due to changes in temperature (u_θ) , assume that the temperature in degrees Celsius θ falls within a range ± Δθ, with a rectangular distribution: $u_\theta = \Delta\theta / \sqrt{3}$

The sensitivity coefficient due to the temperature (c_θ) is obtained from a rough curve fit to the derivative of L_W with respect to temperature. The C_1 and C_2 terms were differentiated with respect to temperature. For terms containing A, the equivalent absorption area of the room, derivatives were taken with respect to a after substitution of A = a S. The required ∂a/∂θ was estimated from ISO 9613-1[9]. The amplitude of the pressure absorbed with each wall reflection a was estimated from the room absorption a room the absorption per meter in air, adBm, and the Sabine estimate (4 V/S) of the mean free path (approximately 3,3 m for 70 m3 < V < 200 m^3).

$$c_\theta = \frac{8.7}{273+\theta} + 17.4\frac{V}{S}\left[1 + \frac{1}{a_{room}+4\left(\frac{V}{S}\right)a_{dBm}}\right]\frac{\partial a_{dBm}}{\partial\theta} \sim \frac{8.7}{273+\theta} + \frac{-0.57+0.25\log(2.6f)}{1+0.0011H+0.007\theta}, \quad (28)$$

Where H is the rel. humid., explicit as a %; f is the highest frequency significantly affecting levels Better control of temperature, allowing the room to come to temperature equilibrium, or shorter measurement times can reduce this uncertainty. Higher temperature and humidity are typically associated with a lower sensitivity coefficient per degree change in temperature.

8-Static pressure p_s: The uncertainty due to changes in static pressure (u_{ps})in this example, assumes that the static pressure(p_s) falls within a range, $\Delta p_s = \pm$ 4kPa, with a rectangular distribution and is given by:

$$u_{ps} = \frac{\Delta p_s}{\sqrt{3}} \quad (29)$$

The sensitivity coefficient due to the static pressure (c_{ps}) is obtained from the derivative of L_W with respect to static pressure ps. The C_1 and C_2 terms were differentiated with respect to static pressure

$$c_{ps} = \frac{-8.7}{p_s} \quad (30)$$

The uncertainty contribution is usually small ups $c_{ps} \approx 0{,}05$ dB

9-Sound level meter δ_{slm}: For sound power measurements the uncertainty in the measuring instrumentation(u_{slm})for a class 1 instrument is u_{slm} = 0,3 dB [10]. Uncertainties in the sound level meter directly affect measured levels, so that c_{slm} = 1, and the uncertainty contribution is 0.3 dB.

10-Relative humidity δ_H: The uncertainty due to changes in relative humidity(u_H) assume that the relative humidity H falls within a range ± ΔH, with a rectangular distribution; it is given by

$$u_H = \frac{\Delta H}{\sqrt{3}}, \quad (31)$$

The sensitivity coefficient due to the relative humidity (c_H) is obtained from a rough curve fit of the derivative of L_W with respect to relative humidity in a similar manner to that used for c_θ.

$$c_H = \frac{-2.6+1.6\log(0.7f)}{1+0.5H} \text{ if H>10\%}$$

Combined standard uncertainty: the combined standard uncertainty of the determination of the sound power level, $u(L_W)$ in decibels, is given by Equation:

$$u(L_W) = \sigma_{tot.} = \sqrt{\sigma_{R_0}^2 + \sigma_{omc}^2 dB} \quad (32)$$

3. RESULTS AND DISCUSSION

Measurement precision assessment, as internationally defined [11] is a needful stride towards a full uncertainty reporting. Naturally, it relies on different factors, including instrumentation and operator's and experience. Though, the results stated hither could be hired for any 2ndry lab. as a proof when they are civilizing their uncertainty budget. Of course, it is not the eventual result regarding the topic, but a productive source of information, instead.

3.1. Sound pressure level & sound power level

The results of averaged SPL are presented in the frequency range from 125 to 10000 Hz, because the frequency range below 125 Hz not presented due to the room volume. The values of the (average SPL and T_{60}) are presented in figure (2-a, b).

The measurements were performed in the frequency range from 125Hz up to 10000Hz due to the room volume. It is clear from the figure that the sound pressure level increases up to the frequency of 1600Hz then decreases gradually up to 10000Hz. The standard deviation in the specified conditions for the RSS was approximately around 0.1dB for all the octave bands. From figure (2-b) we found that the values of the average reverberation time of all the measured positions lies in the range between 0.9-2.9 sec, the higher values were at the lower frequencies.

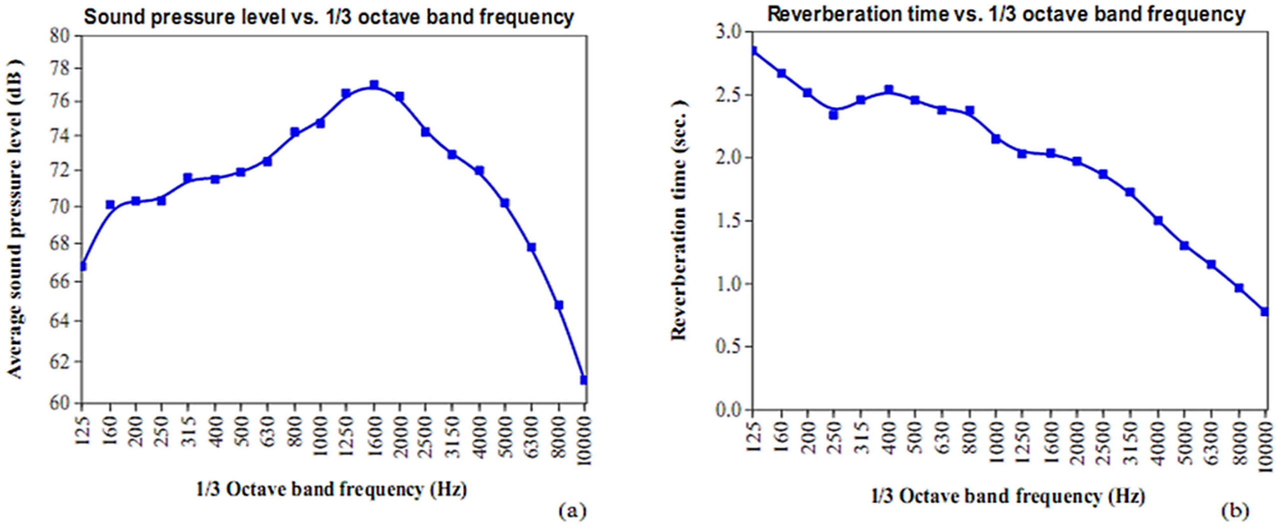


Figure 2. a) Average sound pressure level versus 1/3 octave band frequency and b) reverberation time versus 1/3 octave band frequency

It is clear from the figure (3) that the calculated values of the sound power levels lie within 72.9-83.6dB and the higher values obtained in the middle of the frequency bands (1250-2000 Hz) while at the lower and higher frequencies the sound power levels have lower values than the middle frequencies. It is worth mention that the microphones have higher variations at the lower and higher frequencies.

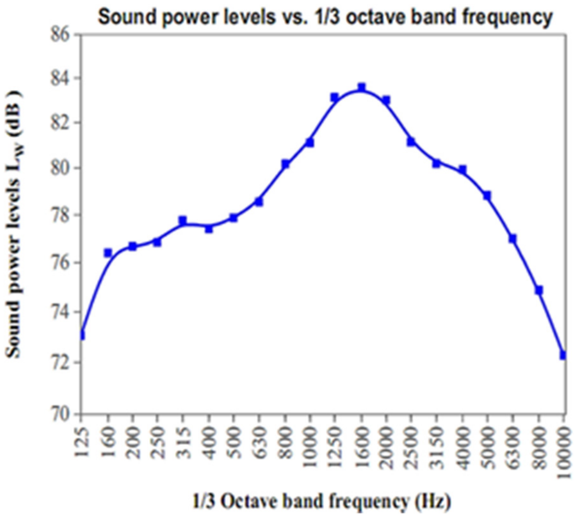


Figure 3. Sound power levels determined for each frequency band for the RSS at the reverberation room.

The total absorption area (S) deduced from the formula S=2*(L*W+L*H+W*H).

In Table 4 we totalize the uncertainties implicated and that we have used for the calculations. It is clear from the table that the values of $u(L_W)$ lies within 0.757 to1.0dB. Where at the low frequency range from 125Hz up to 160 Hz, the uncertainty values are 1.00 and 0.959dB respectively and this is due to the instabilities in the calibration of microphone especially to very low frequencies region. Also, the reverberation time values at low frequencies are higher than that at high frequencies due to the room conditions. It is worth mention that during the measurements we avoided the fluctuations that may occurs. This is the reason for the small value of uncertainty u_{omc} ~0.074dB. Also the environmental conditions are well controlled in order to reduce the uncertainty. I t is important to concentrate that the rev. room utilized was qualified according to the international standards. The values of uncertainty $u\boldsymbol{\sigma}_{\boldsymbol{R_0}}$ which are the sum of different standard uncertainties.

4. CONCLUSIONS

In this article discussion of calibration method and uncertainty evaluation was studied in details. Due to the importance of RSS in many acoustic measurements, so it is necessary to give the readers information about the way of how the sound power determined and how to estimate the uncertainty of this type of calibration. From the results, advices for the measurements were discussed to avoid the errors that may appear during the measurements. The sound power of RSS B&K 4204 was ranging from 72 up to approximately 83 dB within the frequency range of interest. The qualification of our reverberation room is very important to perform this type of measurements. Also, it is recommended to carry out the measurements in a large reverberation room in the direct method. Due to the errors appears in calibration of microphones even at very low or very high frequencies, the uncertainty values may be higher in both very high and very low frequencies. In the calculations of uncertainty, it was found that controlling the environmental conditions and fluctuations during the measurement may reduce the value of uncertainty. σ_{R0} is dependent upon several partial uncertainty components that illustrated very well as well as σ_{omc} depict the uncertainty related to the instability of the operating and mounting conditions. The total uncertainty lies within 0.7-1.0 dB in the frequency range of interest.

Table 4. The determined expanded uncertainty for sound power levels using direct method in 1/3 octave bands from 125Hz to 10000Hz

Frequency(Hz)	**Uncertainty $\|c_i u(x_i)\|$**										**Uncertainty $\sigma_{R0} = \sqrt{(c_1u_1)^2 + (c_2u_2)^2 + \cdots (c_nu_n)^2}$**
	u_{method}	$u_{L'p(ST)}$	u_{K1}	$u_{V/S}$	u_V	u_T	u_θ	u_{ps}	u_{slm}	u_H	
125	0.30	0.071	0.04	0.062	0.066	0.372	0.008	0.049	0.30	0.022	0.497
160	0.30	0.071	0.04	0.062	0.066	0.341	0.004	0.049	0.30	0.029	0.474
200	0.30	0.071	0.04	0.062	0.066	0.315	0.005	0.049	0.30	0.036	0.456
250	0.30	0.071	0.04	0.062	0.066	0.293	0.007	0.049	0.30	0.042	0.442
315	0.30	0.071	0.04	0.062	0.066	0.254	0.008	0.049	0.30	0.049	0.418
400	0.30	0.071	0.04	0.062	0.066	0.222	0.010	0.049	0.30	0.057	0.400
500	0.30	0.071	0.04	0.062	0.066	0.202	0.011	0.049	0.30	0.063	0.390
630	0.30	0.071	0.04	0.062	0.066	0.183	0.012	0.049	0.30	0.070	0.382
800	0.30	0.071	0.04	0.062	0.066	0.163	0.014	0.049	0.30	0.078	0.374
1000	0.30	0.071	0.04	0.062	0.066	0.154	0.015	0.049	0.30	0.084	0.372
1250	0.30	0.071	0.04	0.062	0.066	0.142	0.016	0.049	0.30	0.091	0.369
1600	0.30	0.071	0.04	0.062	0.066	0.125	0.018	0.049	0.30	0.099	0.365
2000	0.30	0.071	0.04	0.062	0.066	0.114	0.019	0.049	0.30	0.105	0.363
3150	0.30	0.071	0.04	0.062	0.066	0.105	0.020	0.049	0.30	0.112	0.363
4000	0.30	0.071	0.04	0.062	0.066	0.098	0.022	0.049	0.30	0.119	0.363
5000	0.30	0.071	0.04	0.062	0.066	0.095	0.023	0.049	0.30	0.126	0.365
6300	0.30	0.071	0.04	0.062	0.066	0.093	0.024	0.049	0.30	0.133	0.367
8000	0.30	0.071	0.04	0.062	0.066	0.089	0.026	0.049	0.30	0.140	0.368
10000	0.30	0.071	0.04	0.062	0.066	0.092	0.027	0.049	0.30	0.100	0.371

Frequency(Hz)	**Uncertainty σ_{omc}**	**Total Combined uncertainty U(L_W)=$\sqrt{(\sigma_{R_0})^2 + (\sigma_{Omc})^2}$**	**u (L_W)Expanded uncertainty (±dB) @ k=2**
125	0.074	0.502	1.004
160	0.074	0.479	0.959
200	0.074	0.462	0.924
250	0.074	0.448	0.896
315	0.074	0.424	0.848
400	0.074	0.406	0.813
500	0.074	0.397	0.794
630	0.074	0.389	0.778
800	0.074	0.381	0.763
1000	0.074	0.379	0.758
1250	0.074	0.376	0.752
1600	0.074	0.372	0.744
2000	0.074	0.370	0.741
3150	0.074	0.370	0.740
4000	0.074	0.370	0.740
5000	0.074	0.372	0.744
6300	0.074	0.373	0.747
8000	0.074	0.375	0.751
10000	0.074	0.378	0.757

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