ODEON APPLICATION NOTE

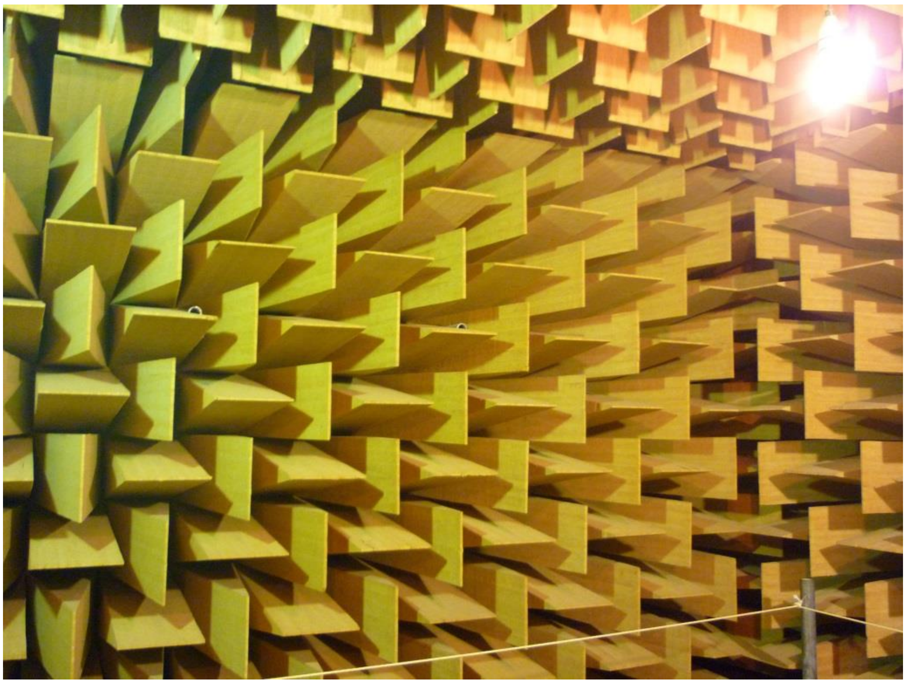
Calibration of Impulse Response Measurements

Part 2 – Free Field Method

GK, CLC - May 2015

Scope

In this application note we explain how to use the *Free-field* calibration tool in ODEON in order to derive level-depending room acoustic parameters, such as Sound Strength (G) or STI_{male} / STI_{female}. It should be emphasized that all other parameters provided by ODEON do not require calibration since they depend only on the shape of impulse response and the relative energy decay (see more about the measuring system and calibration in the ODEON 13 manual[1]).



The calibration in this application note was done using the **small anechoic room** at the Technical University of Denmark. The volume of the room is about 60 m^3. Although the method theoretically requires an ideal anechoic room (no reflections), the implementation in ODEON allows the user to use even an ordinary room, but as dry as possible. The main process in a free field calibration is to derive the energy of the direct sound from the source to the receiver. ODEON applies an algorithm which excludes the reflections coming after the direct sound. However, the algorithm works better as these reflections become weaker.

Equipment

A very dry room is needed for the calibration. Ideally an anechoic room must be used which provides a reflection-free sound field. If such a room is not available, a small room full of furniture, carpets and curtains can be used, since ODEON is able to isolate the direct sound from the subsequent reflections with high success at medium and high frequencies. At low frequencies the isolation is less successful because sound reflections overlap, due to the large wavelengths. A good room for the free-field calibration should have a reverberation time of less than 0.3 sec. Apart from the room requirement, the hardware needed is what it is going to be used during the normal sweep-signal measurements and it is the same as for the diffuse-field calibration (see application note Part 1 – Diffuse Field Method):

1) An omni-directional loudspeaker.
2) An omni-directional microphone.
3) Amplifiers for the speaker (if not an active one is used) and microphone.
4) Audio interface.
5) Lap-top PC.
6) ODEON 13, any edition.
7) Ear protectors (not as necessary as for the diffuse-field calibration, since levels are much lower here).

Theory

The free field calibration is explained in the ISO standard 3382-1, for performance spaces[2]. By definition the sound strength G of an omni-directional source, for a specific frequency, is given as the logarithmic ratio of the sound energy (squared and integrated sound pressure) of the measured impulse response to that of the impulse response measured in a free field at 10 m distance from the source:

$$G = 10\log_{10}\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10}^2(t)dt} \quad \text{dB} \tag{1}$$

or

$$G = L_{pE} - L_{pE,10} \quad \text{dB} \tag{2}$$

where $L_{pE} = 10\log_{10}\left[\frac{1}{T_0}\int_0^\infty \frac{p^2(t)dt}{p_0^2}\right]$ and $L_{pE,10} = 10\log_{10}\left[\frac{1}{T_0}\int_0^\infty \frac{p_{10}^2(t)dt}{p_0^2}\right]$ is the sound pressure exposure level of $p(t)$ and $p_{10}(t)$ respectively.

The variables in these equations are as follows:

- $p(t)$: Instantaneous sound pressure of the impulse response at the receiver's position.
- $p_{10}(t)$: Instantaneous sound pressure of the impulse response at 10 meters distance from the source in free field.
- p_0: Reference sound pressure, 20µPa.
- T_0: 1 sec.

The value of $L_{pE,10}$ can be evaluated inside an anechoic room, where only the direct sound arrives at the receiver as in free field:

$$L_{pE,10} = 20\log_{10}\frac{d}{10} + L_{pE}^{Anech} \quad \text{dB} = L_{pE}^{Anech} + 20\log_{10}(d) - 20 \quad \text{dB} \tag{3}$$

Where d is the distance from the source (preferably $\geq$ 3m) and L_{pE}^{Anech} is the spatial- averaged sound pressure exposure level at every 12.5° around the source.

If we subtract both sides of the equation from the term L_{pE} we get:

$$L_{pE} - L_{pE,10} = L_{pE} - L_{pE}^{Anech} - 20\log_{10} + 20 \quad \text{dB}$$

which is equivalent to

$$G = L_{pE} - L_{pE}^{Anech} - 20\log_{10}(d) + 20 \quad \text{dB} \tag{4}$$

So G can be calculated just by knowing the relative sound pressure levels at the anechoic room L_{pE}^{Anech} and the room under measurement, L_{pE}. The term *relative* is used to emphasise that no absolute sound pressure levels are needed. In other words, no calibration with a reference dB level is required, since our equipment cannot replace the need of a calibrated sound level meter if absolute sound pressure measurements are needed.

Equation (3) is derived under the assumption that the power level L_w of an unknown source at a specific frequency can be calculated from the spherical propagation law in free field measured average sound pressure level L_{pE}^{RevCh} inside a reverberation chamber:

$$\begin{aligned} L_w &= L_{pE}^{Anech} + 10\log_{10}(4\pi) + 10\log_{10}(d^2) \quad \text{dB(re } 10^{-12} \text{ Watt)} \\ &= L_{pE}^{Anech} + 11 + 10\log_{10}(d^2) \quad \text{dB(re } 10^{-12} \text{ Watt)} \end{aligned} \tag{5}$$

The sound pressure level 10 meters away from this unknown source in free field conditions is calculated according to the spherical spread law:

$$\begin{aligned} L_{pE,10} &= L_w - 11 - 10\log_{10}(10m)^2 \\ &= L_w - 31 \quad \text{dB} \end{aligned} \tag{6}$$

Substituting equation (5) to (6) leads to equation (3). If the sound source had a known power level of 31 dB then the sound pressure level at 10 m would be 0 dB. By choosing the G- ISO 3382-1 spectrum in the measurement setup (see next section) ODEON derives the sound pressure level for a receiver as if the source was an omni-directional source of power level 31 dB/Octave band.

NOTE: ODEON does not display the G value explicitly in measured or simulated results. It displays the SPL (Sound Pressure Level) of a source. The value of SPL becomes equal to the value of G only when an omni-directional source type and a power of 31 dB/Octave band is selected in the Measurement Setup (for measurements) or in the Point Source Editor (for simulations).

Alternatively a Speech ISO 3382-3 spectrum can be chosen in the measurement setup. In this case ODEON derives the sound pressure level as if the power spectrum of the source was equivalent to a human speaker. For derivation of STI this type of source should be chosen.

Method

We start ODEON 13 and then open the Options>Program Setup>Measurement Setup window (Figure 1). In this window we should specify:

1) The type of sweep signal to be used - the default *Exponential Sweep* setting is recommended for calibration.
2) Audio devices – we should select the input (eg. microphone or line in) and output (speaker) devices used for the measurement.
3) Receiver model – keep the default 1 channel: Omni.
4) The source power spectrum can be specified there for used when loading the impulse response after measurement. For calibration of G the G- ISO 3382-1 spectrum should be chosen, while for STI_{male} / STI_{female} calibration the Speech ISO 3382-3 spectrum should be used.

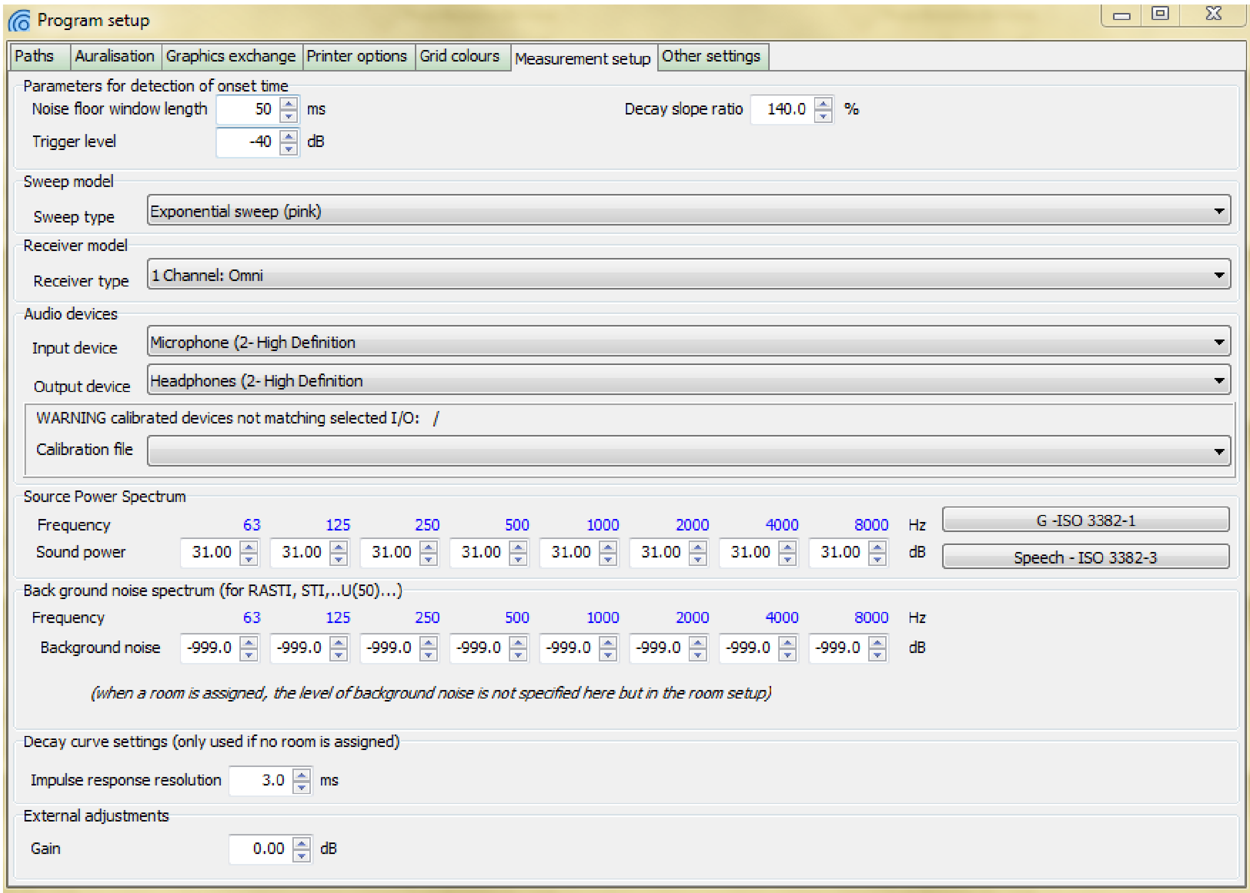


Figure 1: In the measurement setup important settings, like input-output devices can be performed.

Once all connections have been fixed we can test the measuring signal by choosing Tools>Measure IR (Sinusoidal Sweep) or by clicking on the button (Figure 2). A message like: "*WARNING! Calibration file not consistent with selected audio devices. No calibration applied*" may be displayed at the bottom of the window but it can be ignored at this phase. In this window the sweep length and the estimated length of the impulse response can be adjusted. The longer is the sweep the higher is the suppression of the background noise in the room. A 3 dB suppression is achieved for a doubling of the sweep length. The Play Test Signal button plays the sweep signal without recording any measurement. The slider in the middle of the screen adjusts the **internal gain**. Any other gain adjustments in the measuring equipment (windows mixer, audio interface, amplifiers) belong to **external gains**.

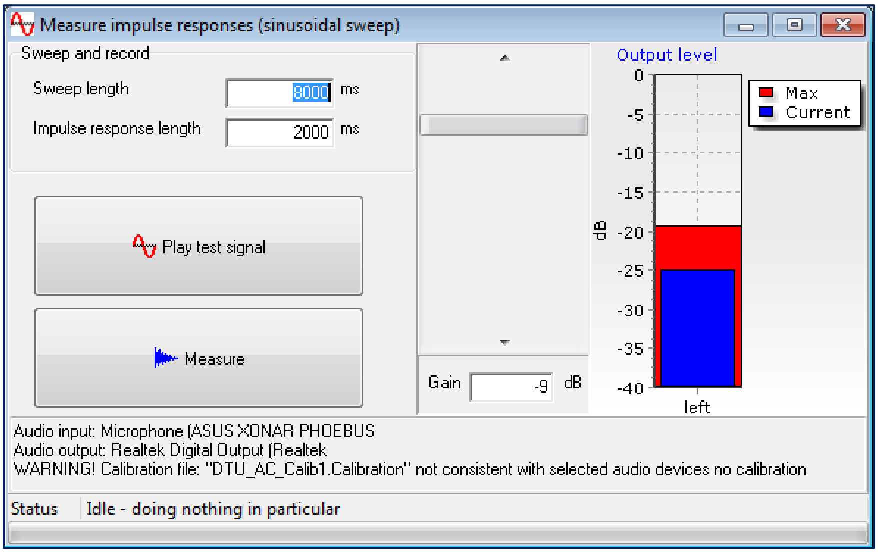


Figure 2: Details for the sweep signal can be set in the *Measure Impulse Response* window.

Adjusting the levels

The most important requirement for a calibrated measurement is that all external level/gain adjustments must be set to fixed values during the calibration and the measurement. Only the internal gain can be freely changed between recordings for calibration or measurement, since ODEON itself compensates for the adjustment. Apparently all gains – even the internal one - should remain unchanged during a recording.

It is crucial at this point to decide which should be the value of the external gains during the measurement in order to drive the room with an adequate signal to noise ratio without overloading. When overloading occurs ODEON automatically cancels the measurement. The best practice is to maximize the internal gain for most recordings, so that if a few of them lead to overloading, you can freely reduce the internal gain without harming the calibration settings.

The most straightforward way of adjusting the external gains is to maximize all values: Windows volume can be set to 100% and amplifier knobs can be turned to the maximum value (Figure 3). Then all settings are easy to remember/replicate during the measurement). <u>However, one should be careful not to overload and damage the speaker</u>! High output gains are also likely to cause distortion. In addition, the gain of the microphone should be set to a level where the internal noise does not become very high.

<u>Often the amplifiers used are rather powerful for the speakers used so that a much lower gain is sufficient.</u> The corresponding value must then be clearly noted down for reference. Apart from that, no extreme sound power output is needed if the equipment is able to derive a sufficient signal to noise ratio (SPL/Noise parameter inside ODEON) or decay range, in normal room conditions (with moderate ambient noise).

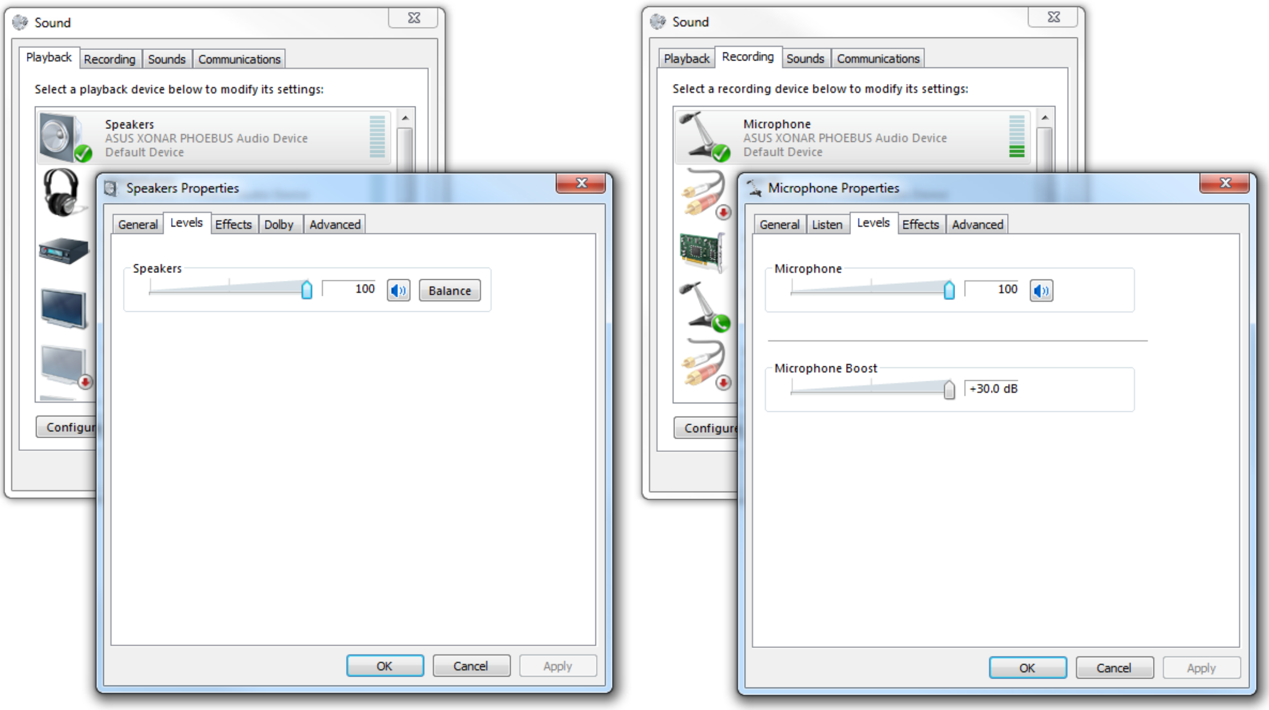


Figure 3: Levels and gains in the windows mixer are considered external adjustments and should remain fixed during calibration and measurements. A straightforward recommendation is to set all parameters at their maximum value.

Recording

After fixing the external level adjustments, recordings of impulse responses in the anechoic/dry room can be performed by clicking the Measure button in the Measure Impulse Response window. An introductory video on how to obtain measurements in room can be found at [4]. The recordings are saved as .WAV files. Some trial measurements should be performed initially by varying the internal gain until an adequate signal to noise ratio is achieved. It can be desirable to make the measurement with the highest possible SNR, achievable without overload, but this is not required. <u>NOTE</u>: Use ear protectors to prevent hearing damage! An indication of the quality of the signal to noise ratio can be obtained by loading the recording on the Load impulse response tool, (under the Tools menu) and checking whether all SPL values at octave bands have been derived. A "*" character means that ODEON was unable to derive the corresponding value from the impulse response (eg. due to insufficient signal to noise ratio/ decay range). In contrast to a diffuse-field calibration, "*" characters are expected here for most parameters, except SPL, because any impulse response is truncated at the direct sound –too short length to provide sufficient information for most of the parameters. An example of a successful impulse response in the anechoic/dry room is given in Figure 4, where all SPL values have been derived. The sound strength parameter (G value) is denoted as SPL (dB) and is not calibrated yet. Hence it is expected that SPL can be very awkward (even negative, meaning much lower sound pressure than the reference 20 μPa).

Source – Receiver positions in the anechoic/dry room

The source should be placed at a stable location almost at the center of the room and far away from walls and furniture (if any). The microphone should be placed ideally at positions every 12,5^{o} around the source, preferably at a radius greater than 3m[2]. This gives roughly 28 spots. However to our experience even half spots (14) can be a good compromise between accuracy and speed. The distance of the microphone from the source should be as precise as possible, because the measured sound pressure level can vary significantly with slight changes (figure 5). A good tip is to use a piece of rope with nooses at the end, tied at the source and microphones stands. Stretching the piece of rope every time you move the microphone around the source will ensure a fixed distance from it. Figure 6 shows illustrates the geometry for a free-field calibration.

Unable to derive decay parameters for : 125, 250, 500, 1000, 2000, 4000, Hz bands - Measured response - D:\...\MAY_1st_CalibrationTest\AnechoicChamber\S1R5.wav

Raw Impulse response at 1000Hz | Raw decay curve at 1000Hz | Decay curves at 1000Hz T(30) = 0.03 seconds | Decay curves (all bands) | Energy parameters | Parameter curves | Freque

Band (Hz)		63	125	250	500	1000	2000	4000	8000
EDT	(s)	0.12	0.09	0.07	0.03	0.01	0.01	0.01	0.01
EDTNew		*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
T(15)	(s)	*.**	0.04	0.05	0.02	0.01	0.01	0.01	0.01
T(20)	(s)	*.**	0.04	0.05	0.02	0.01	0.01	0.01	0.01
XI(T(20))	(‰)	*.*	21.3	11.1	8.1	4.5	3.4	2.5	26.4
T(30)	(s)	*.**	*.**	*.**	0.02	0.03	0.03	0.02	0.02
XI(T(30))	(‰)	*.*	*.*	*.*	5.1	164.9	142.0	161.9	170.1
Curvature(C)	(%)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
Ts	(ms)	*	*	*	*	*	*	*	*
SPL	(dB)	-55.0	-37.9	-33.7	-37.0	-36.3	-35.9	-33.7	-33.2
SPL(Af)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
D(50)		*.**	*.**	*.**	*.**	*.**	*.**	*.**	*.**
C(7)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
C(50)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
C(80)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
U(50)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
U(80)	(dB)	*.*	*.*	*.*	*.*	*.*	*.*	*.*	*.*
Echo(Dietsch)		*.**	*.**	*.**	*.**	*.**	*.**	*.**	*.**
Source power	(dB)	31.00	31.00	31.00	31.00	31.00	31.00	31.00	31.00
Background noise	(dB)	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00
SPL/Noise	(dB)	*.**	*.**	*.**	*.**	*.**	*.**	*.**	*.**
Peak/Noise	(dB)	*.**	*.**	*.**	*.**	*.**	*.**	*.**	*.**
Decay range	(dB)	*.**	*.**	*.**	*.**	*.**	*.**	*.**	*.**
Distortion/Noise	(dB)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SPL(A)	*.*	dB
SPL(Lin)	*.*	dB
SPL(C)	*.*	dB
STI	*.**	
STI(Female)	*.**	
STI(Male)	*.**	
RASTI	*.**	
STI(expected)	*.**	
T(30_Average)	*.*	s

Figure 4: Room acoustic parameters from a healthy impulse response recording inside the anechoic/dry room. Since only the direct sound is taken into account, it should not be expected to obtain all acoustic parameters. The only relevant parameter is SPL.

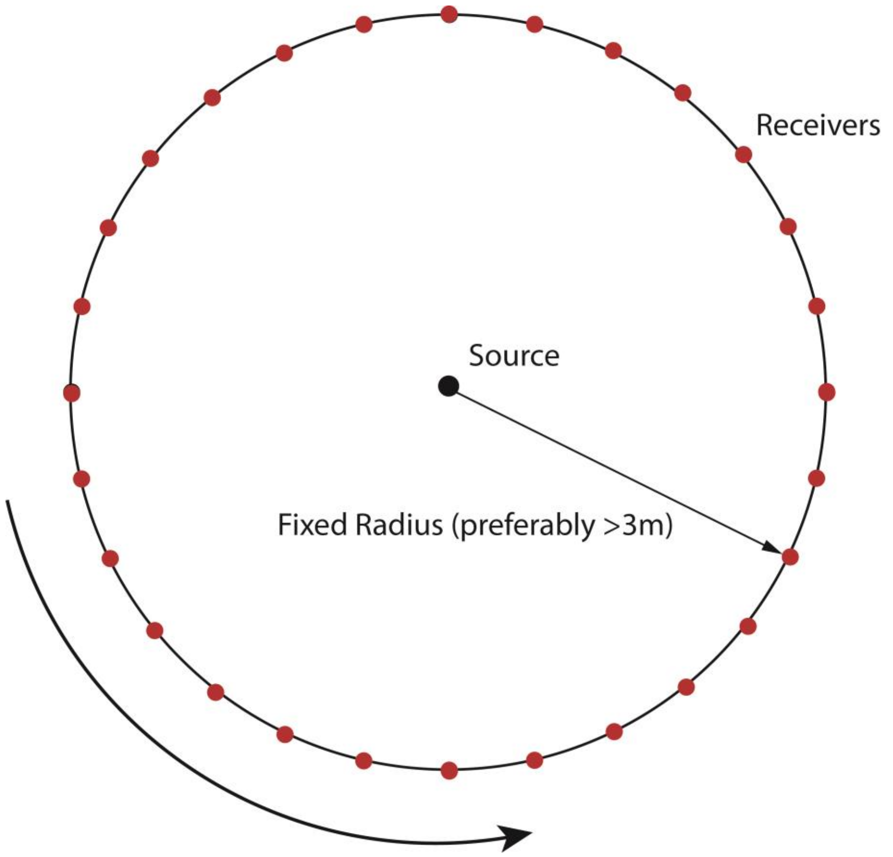


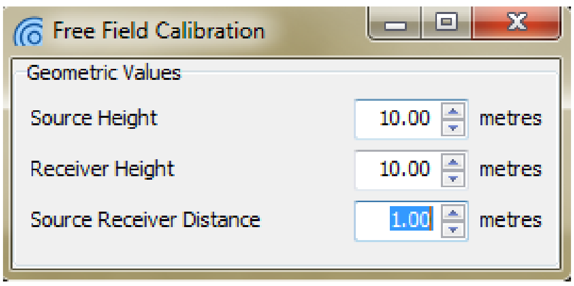
Figure 5: Diagram of measurement positions for free-field calibration. The source should be fixed roughly at the center of the room and the microphone should be placed at a fixed radius around the source. Ideally 28 positions are required (red spots) but 14 is also an acceptable number.

Deriving the Calibration File

Having a series of impulse responses in the room we can derive the calibration file to be used with the actual measurement by clicking on Tools>Measurement Calibration>Free-field>One step (requires fixed signal chain). Two stages are required now:

1st Stage

ODEON asks for the geometry of the source-receiver configuration, in order to estimate the arrival time of the first reflection after the direct sound and truncate the impulse response just before this reflection.



If calibration is done in an ordinary dry room the precise heights and distances should be entered in the boxes. Figure 6 shows a typical geometry, where the floor is the closest surface and creates the 1st reflection. All heights and distances should be measured from the centres.

However, when the recordings are performed in a purely anechoic room there is no need for truncating the impulse response as there are virtually no reflections. In this case it is advisable to set a high value for the heights (around 10 m) in order to ensure that the whole energy associated with the direct sound is included. Besides, an anechoic room usually has a phantom floor: Source, microphone, people and equipment stand on a metal grid far above the absorptive wedges in the bottom of the anechoic chamber. So practically there is no floor to create reflections.

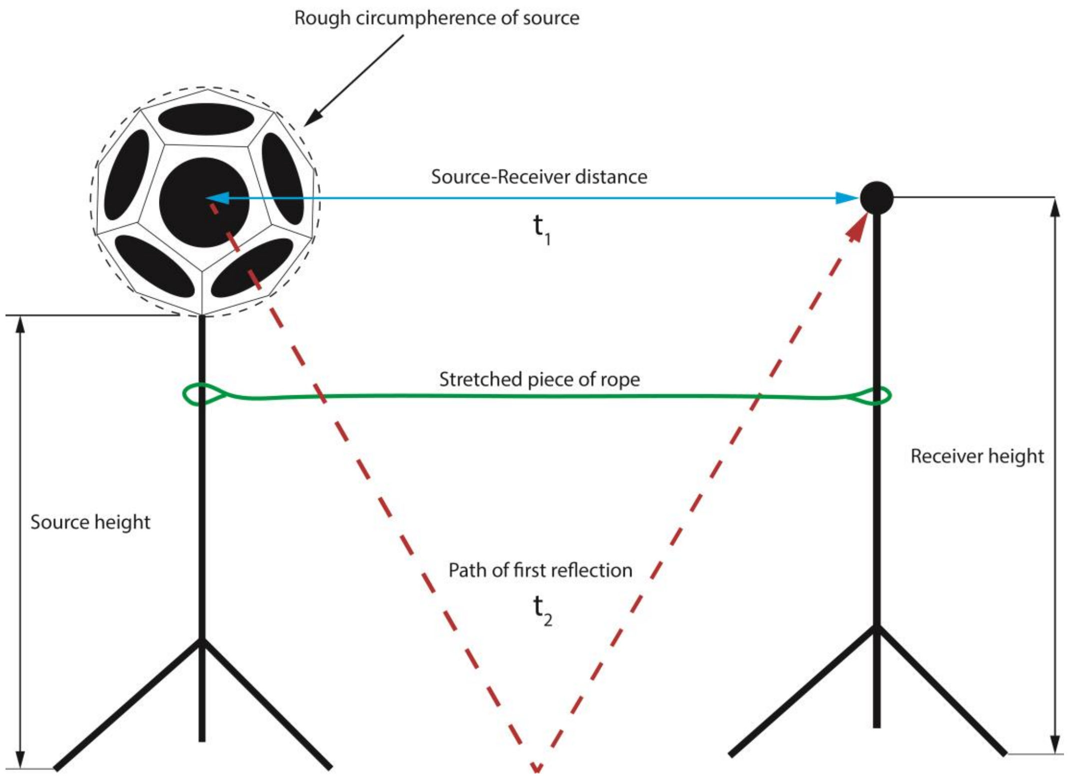
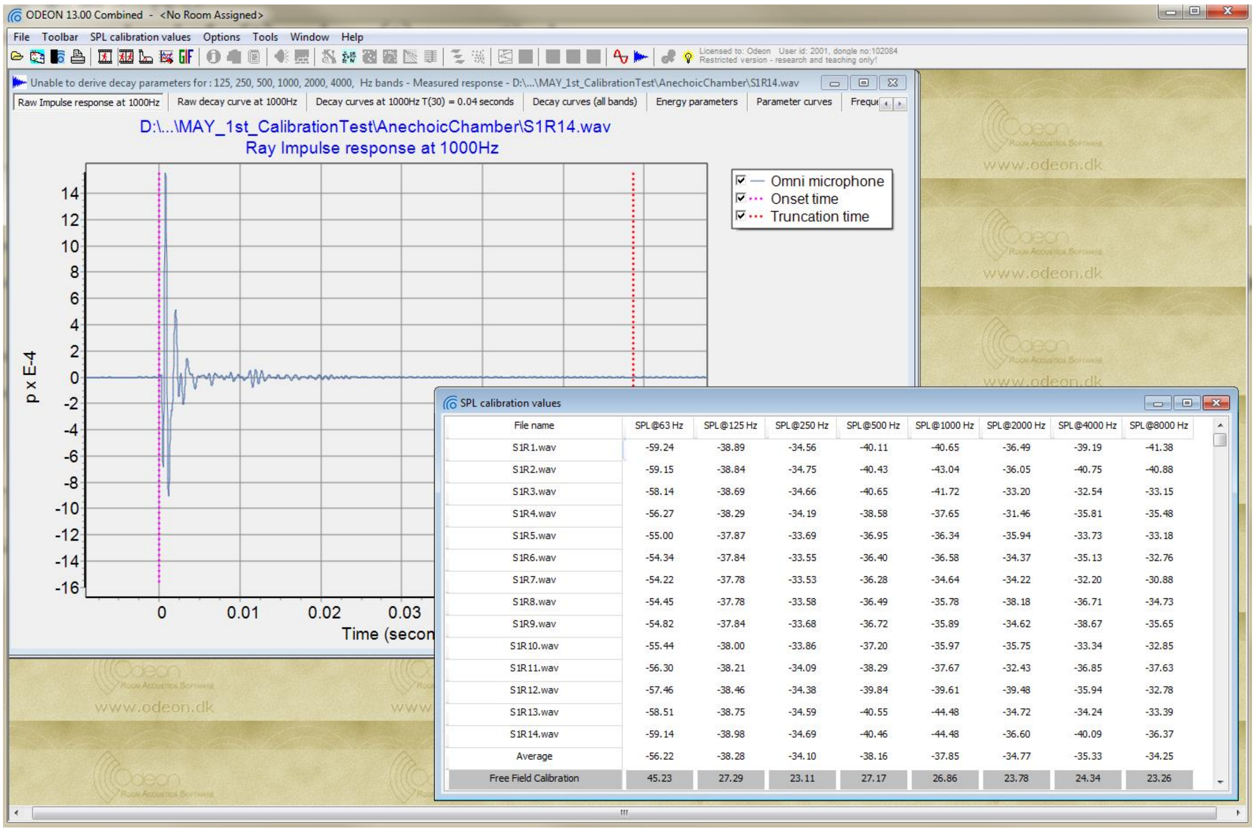


Figure 6: Geometry for impulse response recording in the anechoic/dry room. It is advisable to use a piece of stretched rope with loops to ensure constant distance between source-receiver (preferably <3m). ODEON needs to know the time difference between the arrival of the 1st reflection and the direct sound (t_2-t_1). This is calculated by entering the source and receiver heights, as well as the source-receiver distance.

2nd stage

All recordings (.WAV files) measured at the receiver positions according to figure 5 should be selected together using the SHIFT or CTRL key and opened at once. ODEON then derives the free field calibration values (adjustments) for the eight octave bands between 63 Hz and 8000 Hz as an average of the different positions (Figure 5) and asks for a name of the calibration file. The user is prompted to set the file as the active calibration file in the Measurement Setup, which is going to be used with future measurements. It is also possible to change the active calibration file afterwards in the Measurement Setup in the Calibration File menu. However, if the input and output devices are different from those used during the generation of the calibration file ODEON gives a warning for device mismatch, meaning that all level depended parameters will not be calibrated in future measurements. You can now launch the Measurement Setup window to check whether the active calibration file is the correct one.



File name	SPL@63 Hz	SPL@125 Hz	SPL@250 Hz	SPL@500 Hz	SPL@1000 Hz	SPL@2000 Hz	SPL@4000 Hz	SPL@8000 Hz
S1R1.wav	-59.24	-38.89	-34.56	-40.11	-40.65	-36.49	-39.19	-41.38
S1R2.wav	-59.15	-38.84	-34.75	-40.43	-43.04	-36.05	-40.75	-40.88
S1R3.wav	-58.14	-38.69	-34.66	-40.65	-41.72	-33.20	-32.54	-33.15
S1R4.wav	-56.27	-38.29	-34.19	-38.58	-37.65	-31.46	-35.81	-35.48
S1R5.wav	-55.00	-37.87	-33.69	-36.95	-36.34	-35.94	-33.73	-33.18
S1R6.wav	-54.34	-37.84	-33.55	-36.40	-36.58	-34.37	-35.13	-32.76
S1R7.wav	-54.22	-37.78	-33.53	-36.28	-34.64	-34.22	-32.20	-30.88
S1R8.wav	-54.45	-37.78	-33.58	-36.49	-35.78	-38.18	-36.71	-34.73
S1R9.wav	-54.82	-37.84	-33.68	-36.72	-35.89	-34.62	-38.67	-35.65
S1R10.wav	-55.44	-38.00	-33.86	-37.20	-35.97	-35.75	-33.34	-32.85
S1R11.wav	-56.30	-38.21	-34.09	-38.29	-37.67	-32.43	-36.85	-37.63
S1R12.wav	-57.46	-38.46	-34.38	-39.84	-39.61	-39.48	-35.94	-32.78
S1R13.wav	-58.51	-38.75	-34.59	-40.55	-44.48	-34.72	-34.24	-33.39
S1R14.wav	-59.14	-38.98	-34.69	-40.46	-44.48	-36.60	-40.09	-36.37
Average	-56.22	-38.28	-34.10	-38.16	-37.85	-34.77	-35.33	-34.25
Free Field Calibration	45.23	27.29	23.11	27.17	26.86	23.78	24.34	23.26

Figure 7: Fourteen impulse responses and calibration values derived by ODEON. For each impulse response the SPL values recorded in ODEON are reported. At the bottom of the table the average SPL is shown and the free field calibration values are derived.

Calibrated Measurements

Actual measurements can be carried out with the Measure IR (Sinusoidal Sweep) tool using the active calibration file in the Measurement Setup. Calibration will be applied on the recorded .WAV files during processing at the Load impulse response tool, (under the Tools menu). If there is a mismatch between the input/output devices used for the calibration file and the ones used for the measurement, a warning is displayed by ODEON and no calibration is applied.

In the ODEON measuring system the chain of calibration and measurement can be reversed: Someone could measure first and calibrate the equipment afterwards as long as the external gains are fixed. When the measurement is finished a calibration file can by assigned by clicking Tools>Measurement Calibration>Assign Calibration to Existing Measurements.

An example of calibrated measurement is shown in figure 8. The calibration file from figure 7 was used in this case. The SPL values correspond to the sound strength of the source, since a G-ISO 3382-1 source power spectrum has been chosen in the Measurement Setup, as shown in figure 1.

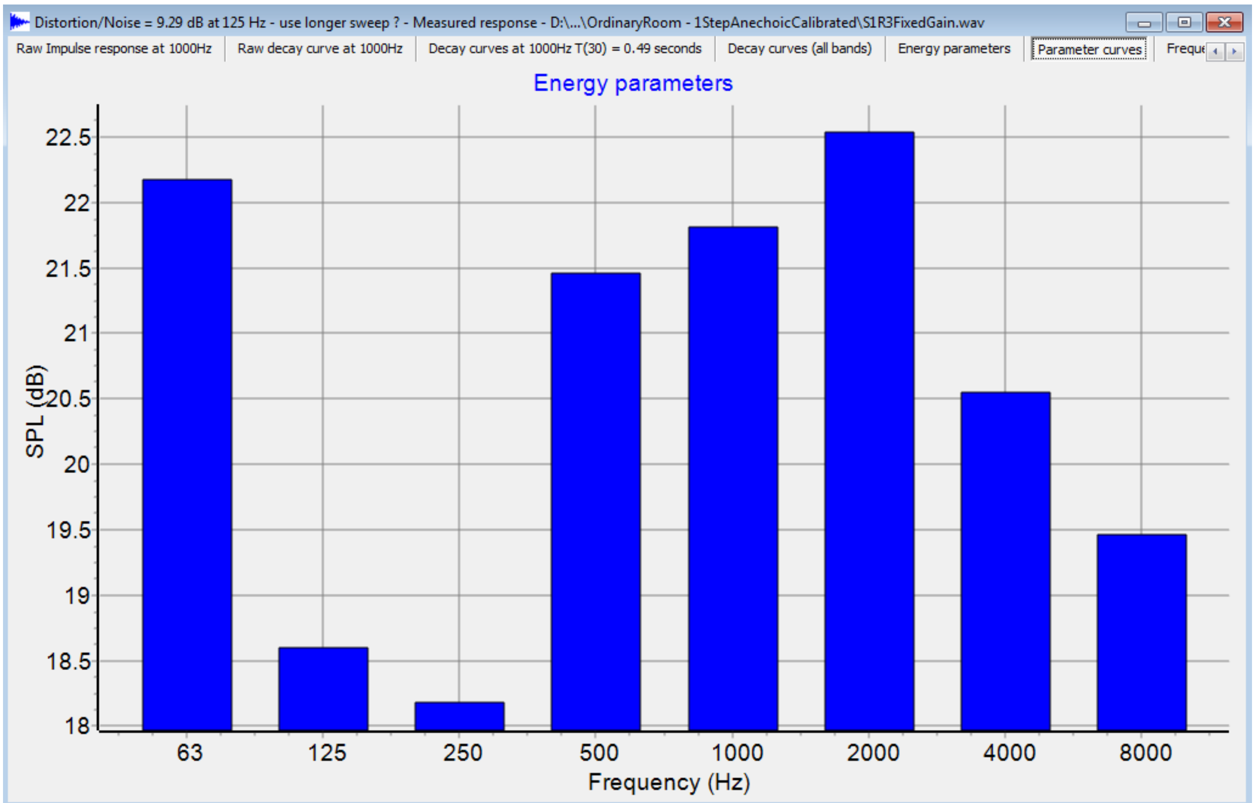


Figure 8: SPL measurement calibrated with the calibration file derived in figure 7. These SPL values correspond to the sound strength G of the source, since a G-ISO 3382-1 sound power spectrum has been chosen in the Measurement Setup (see figure 1).

Conclusion

The note describes the steps required for a calibrated measurement of G and STI using an anechoic (free-field) room. Another way for calibration is utilizing a reverberation chamber – performing a so called diffuse field calibration. The sound field for both environments is considered to be fully known, as long as specific assumptions hold (free field respectively and diffuse field). For this reason the sound power of an unknown source can be specified from analytic expressions like eq.(5) and calibration of the equipment towards a known source like G-ISO 3382-1 and Speech-ISO 3382-3 can be done.

The basic steps described in this note hold for a diffuse-field calibration as well and the main difference is the way the power of the unknown source is derived. For that matter, one could follow the same process for such a calibration just by selecting Tools>Calibrate Measurements>Diffuse field>One step (requires fixed signal chain).

References

1. C.L. Christensen & G. Koutsouris. ODEON Room Acoustics Software, manual, version 12, Odeon A/S, Denmark 2013 (http://www.odeon.dk/download/Version13/ODEONManual.pdf).
2. ISO standard 3382-1, Acoustics - Measurement of Room Acoustic Parameters – Part 1: Performance Places.
3. ISO standard 3382-2, Acoustics – Measurement of Room Acoustic Parameters – Part 2: Reverberation Time in Ordinary Rooms.
4. Claus Lynge Christensen. Impulse Response Measurements, ODEON video tutorials: http://www.odeon.dk/impulse-response-measurements.