Prediction of Sound Levels in Offices and Corridors

(This document is preliminary)

1. Abstract:

Sound system designers often use simulation programs to predict the performance of their loudspeaker designs. This article has been written because many programs only give satisfactory results in cubical[1] rooms. This is often said to be due to the use of incorrect absorption data, but the results are still inaccurate when actual reverberation measurements are used.

Therefore the focus of this article is the calculation of sound propagation in rooms that are not cubical. This will allow more precise loudspeaker placement, increased loudspeaker spacing, and improved homogeneity of the sound field, improved intelligibility and significant cost savings.

Most methods for predicting sound propagation are based on the Hopkins-Stryker[2] Equation. However, in tests it turns out that this works well for cubical rooms, but gives incorrect results for non-cubical rooms, which is most of them (!). The reason for this is that the Hopkins-Stryker method relies on a statistically homogenous "diffuse" reverberation sound field that does not occur in most cases. Studies in non-cubical rooms have shown that the reverberation time between 250 Hz to 8 kHz[3] is 500 ms or less, and consists only of early and single reflections and (sometimes) room modes. Therefore it does not have a statistically homogenous reverberation sound field. In consequence the measurement of the reverberation time RT_{60} is a misleading action.

Note that the calculation of reverberation time RT_{60} according to Sabine[4], Eyring[5] or Fitzroy[6] also relies on a statistically homogenous "diffuse" reverberation field.

Investigation into a better method for predicting the propagation of sound in non-cubical rooms shows that an equation developed by Theodore J. Schultz, a Boston acoustician, represents reality better than the Hopkins-Stryker method.

The following analysis compares measured data against different possible equations.

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[1] Cubical rooms have a length to width to height ratio of L x W x H of up to approx. >1<3:1:1. e.g. 3 metres wide, 3 metres high and between three and nine metres long

[2] see 3.2.2 Hopkins-Stryker equation

[3] The range 250 Hz to 8 kHz contains most of the information that gives intelligible speech.

[4] Wallace Clement Sabine (1889 to 1919)

[5] Norris Eyring (about 1930), see also: J. Acoust. Soc. Am. Vol. 58 No. 3 pp 643-655, September 1975 and Don Davis & Eugene Patronis Jr. Sound System Engineering 3rd ed. page 156

[6] Dariel Fitzroy (1898 to 1977)

2. Conclusion:

2.1. Distribution of the sound field

In order to plan the loudspeaker design for non-cubical rooms it is essential to have:

- for rooms up to 3 m high, where differences in sound level of up to 6 dB are acceptable, a ceiling grid pattern of between 5 m and 7 m.
  Condition: the minimum sound level directly under the loudspeaker must be at least 6 dB higher than the minimum requested sound level.
  For example: The minimum requested sound level in a room is 85 dBA. In this case are 91 dB (85 dB + 6 dB) directly under the loudspeaker necessary.
  If less variation is necessary, the distances between the loudspeakers must be less than 5 m.

  EXAMPLE: In a room up to 3 m high of 15 m by 8 m no more than three loudspeakers are needed. If the specification calls for dual circuits and no more than 10 dB loss of sound level when one loudspeaker line is lost, this can be achieved with only one loudspeaker, even when the loudspeaker isn't in the middle of the room, but is asymmetrically in one third of the room

- speech intelligibility isn't decreased under the normally specified minimum[7] STI of 0,5 as long as the ceiling grid pattern is less than 7 m.

2.2. Obstacles in the sound path

In the course of analysis we investigated how obstacles or fittings (in German, "Streukörper"[8]) in the path of sound influence sound propagation.
In the test "Non-cubical room Office 2" we investigated the effect of a solid heavy obstacle 4.8 m long, 0.45 m deep and 2.3 m high in a room of 2,9 m high and a 7,8 m wide. This obstacle is 48% of the room cross section and reduces the pressure flow in direct line of the sound path by 79%. Sound level is reduced by approximately 5 dB without affecting the speech intelligibility. It can be clearly demonstrated that such obstacles in the sound path which don't separate rooms completely only partly obstruct the propagation of sound. This is an advantage for intelligibility as no additional loudspeakers need to be installed but it is a disadvantage for sound insulation in rooms, because these obstructions only slightly reduce sound levels.

[7] this minimum requirement of STI >0,5 equivalent a CIS >0,7 is requested for example of the TRVB S 158 in Austria, the VDE 0833-4 in Germany, the BS 5839-8 in UK and the ISO 7240-19.
[8] VDI 3760 Berechnung und Messung der Schallausbreitung in Arbeitsräumen
ISO 14257 Measurement and parametric description of spatial sound distribution curves in workrooms for evaluation of their acoustical performance

Analysis:

2.3. Non-cubical room "Office 1"

The diagram Figure 2-1 shows the decrease of sound level calculated according to different methods. Figure 2-2 shows the measured vales. The dimensions of the room are: 10 m x 5 m x 2,5 m and the RT_{60} is approximately 0,46 s. Speech intelligibility was measured and is shown in the diagram in Figure 2-3 below.

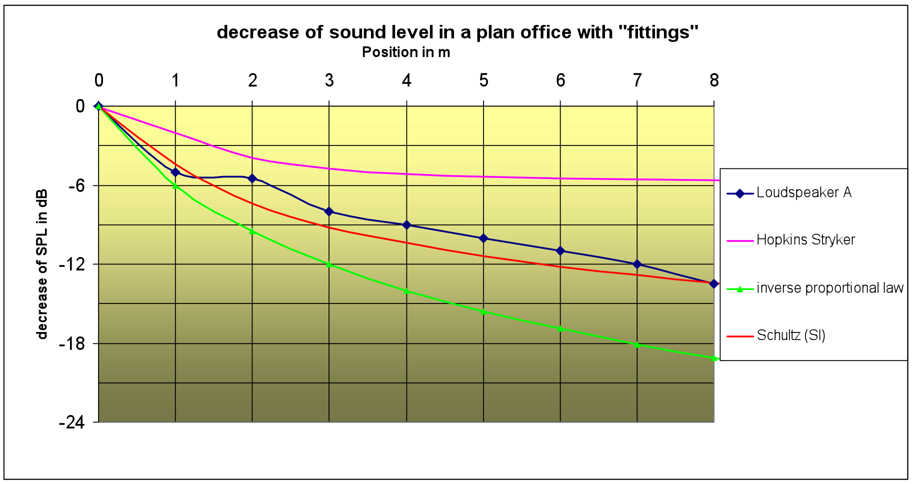

Figure 2-1

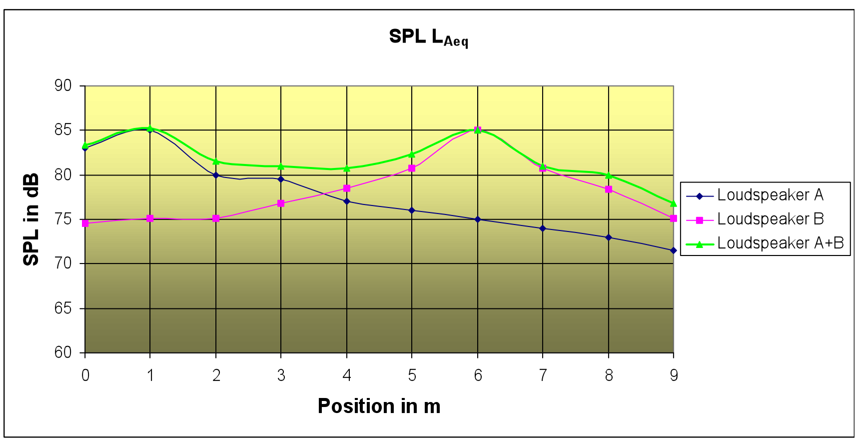

Figure 2-2

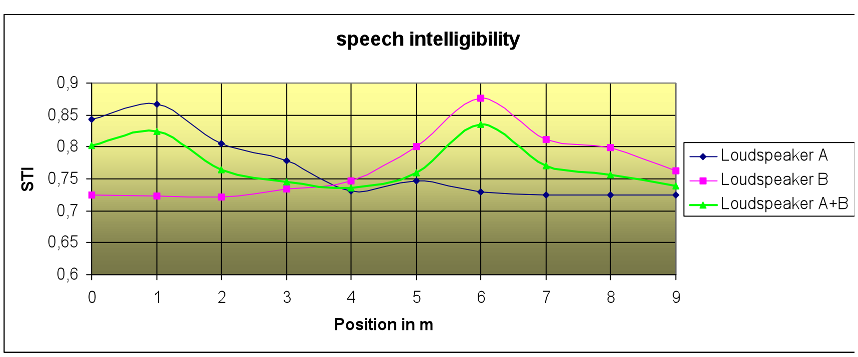

Figure 2-3

Diagram shows Figure 2-4 the impulse response of the room
Diagram shows Figure 2-5 the reverberation times in the octave bands from 250 Hz to 8 kHz.

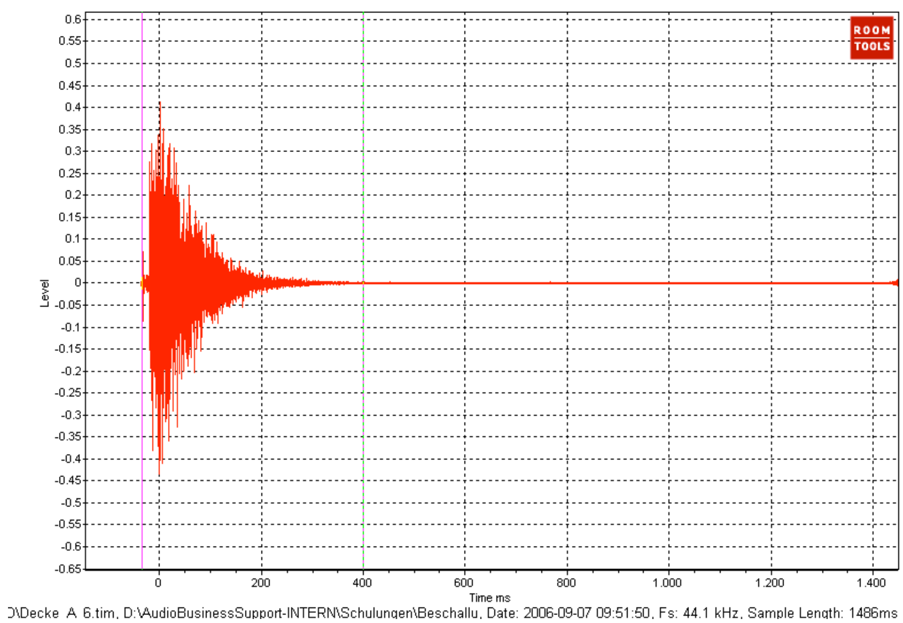

Figure 2-4

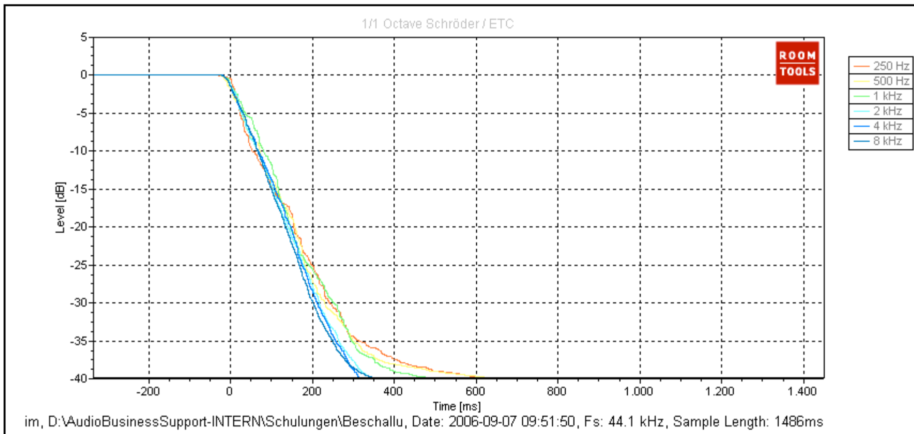

Figure 2-5

2.4. Non-cubical room "Office 2"

This diagram Figure 2-6 shows the decrease of sound level calculated according to different methods. Figure 2-7 shows the measured vales. The dimensions of the room are: 15 m x 8 m x 2,9 m and the RT_{60} is approximately 0,42 s.
Speech intelligibility was measured and is shown in the diagram in Figure 2-8 below.

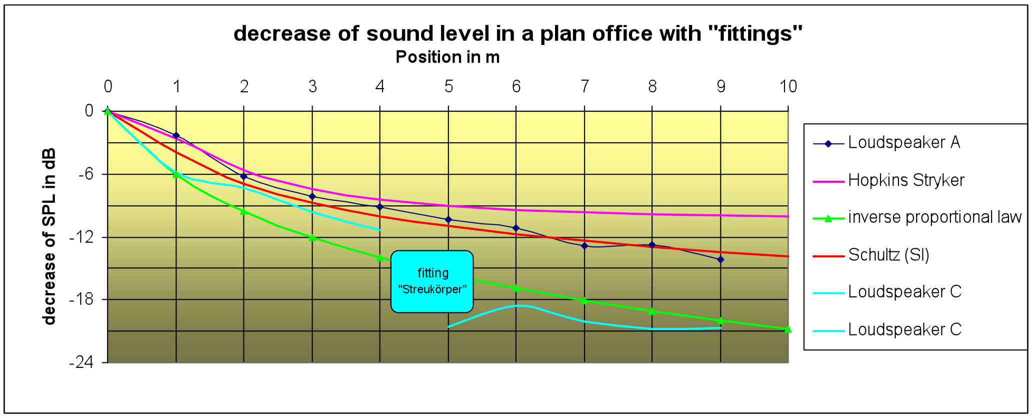

Figure 2-6

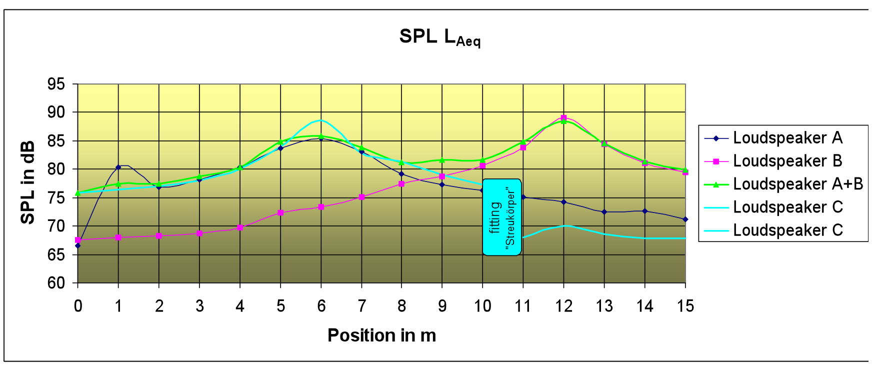

Figure 2-7

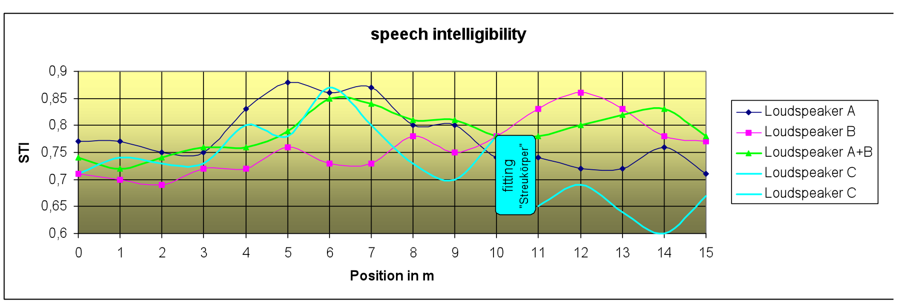

Figure 2-8

Diagram shows Figure 2-9 the impulse response of the room
Diagram shows Figure 2-10 the reverberation times in the octave bands from 250 Hz to 8 kHz.

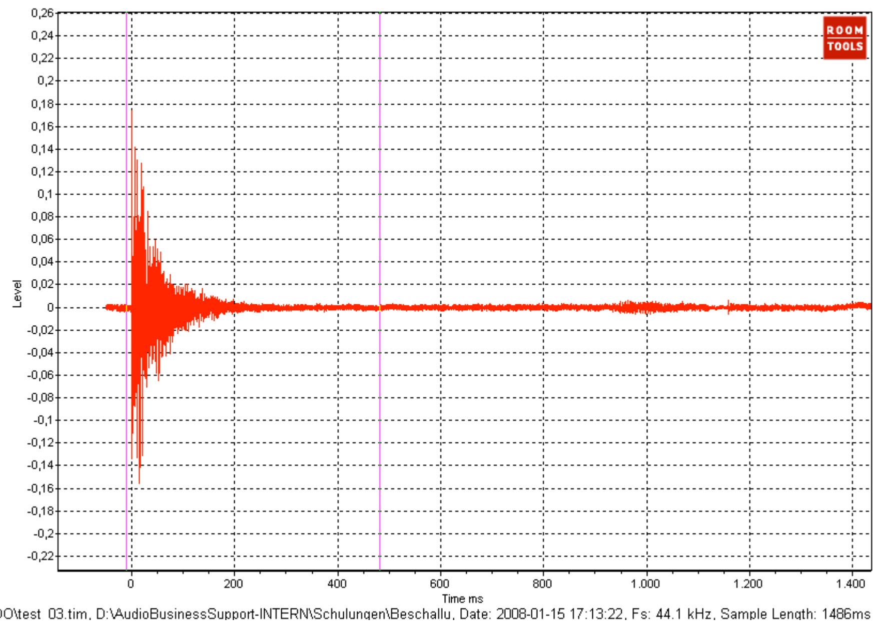

Figure 2-9

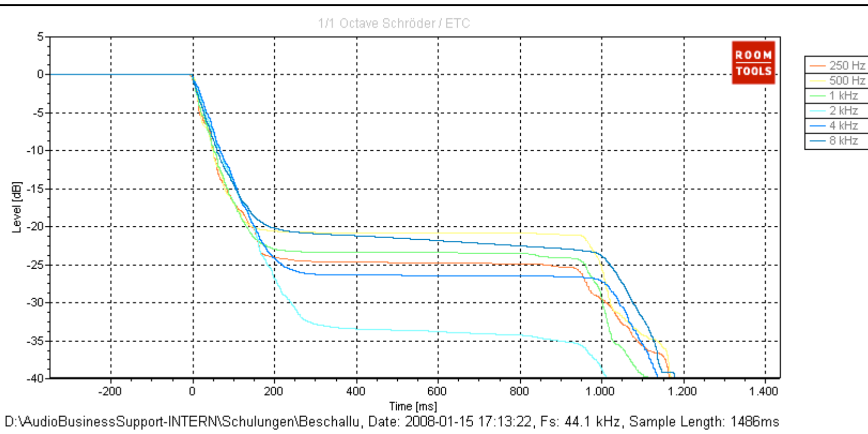

Figure 2-10

2.5. Non-cubical room "Corridor"

This diagram Figure 2-11 shows the decrease of sound level calculated according to different methods. Figure 2-12 shows the measured values. The dimensions of the room are: 18 m x 1,5 m x 2,9 m and the RT_{60} is approximately 0,66 s
The speech intelligibility was measured and is shown in the diagram in Figure 2-13 below.

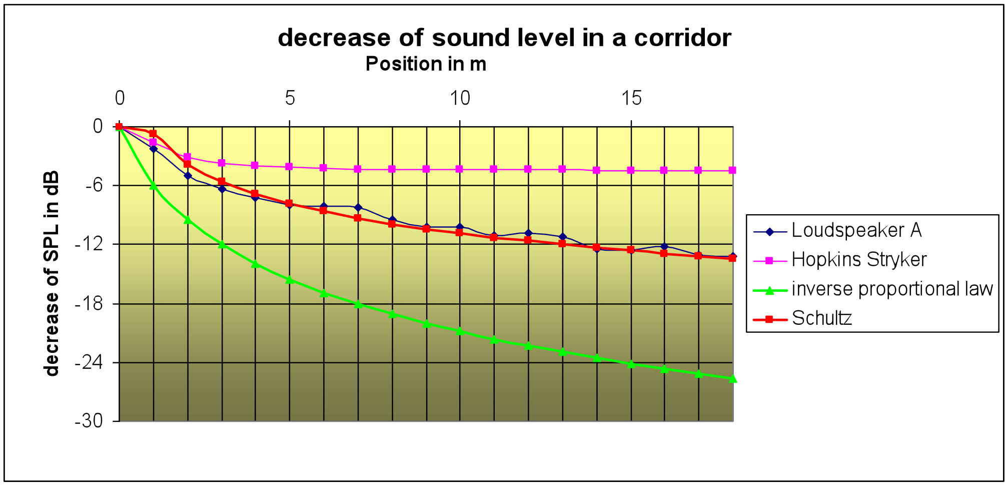

Figure 2-11

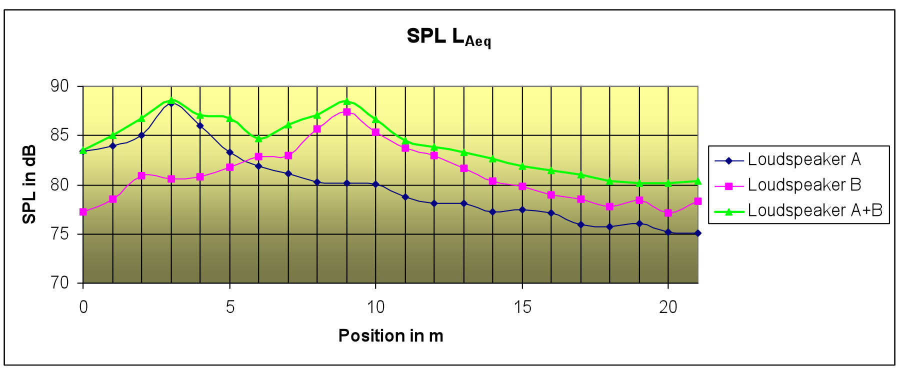

Figure 2-12

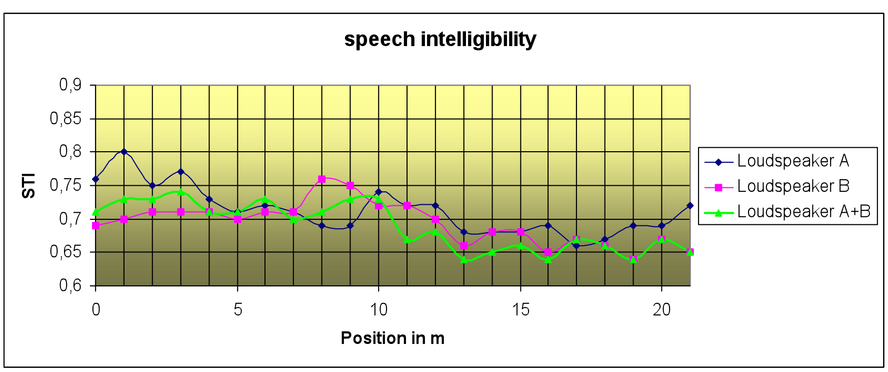

Figure 2-13

Diagram Figure 2-14 shows the impulse response of the room
Diagram Figure 2-15 shows the reverberation times in the octave bands from 250 Hz to 8 kHz.

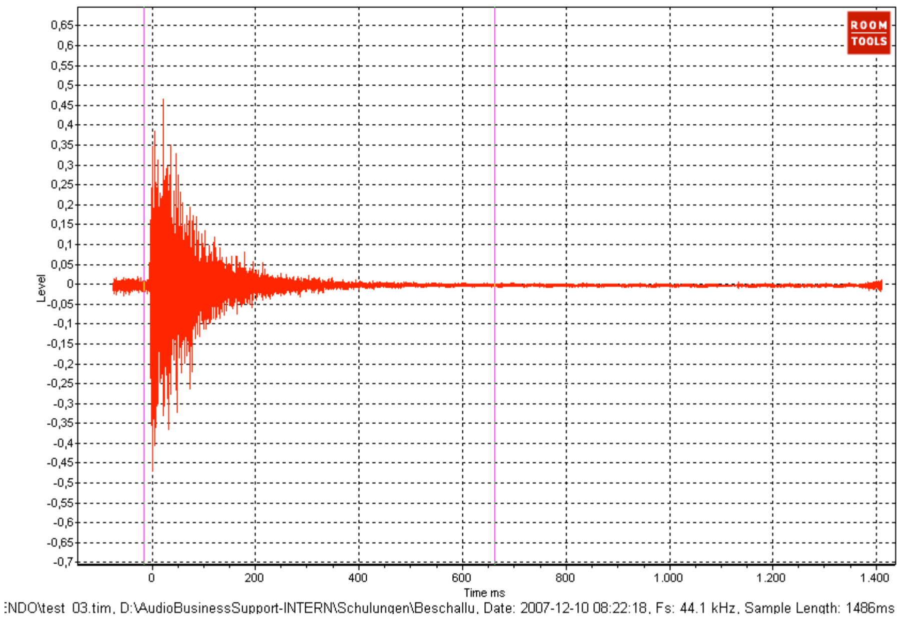

Figure 2-14

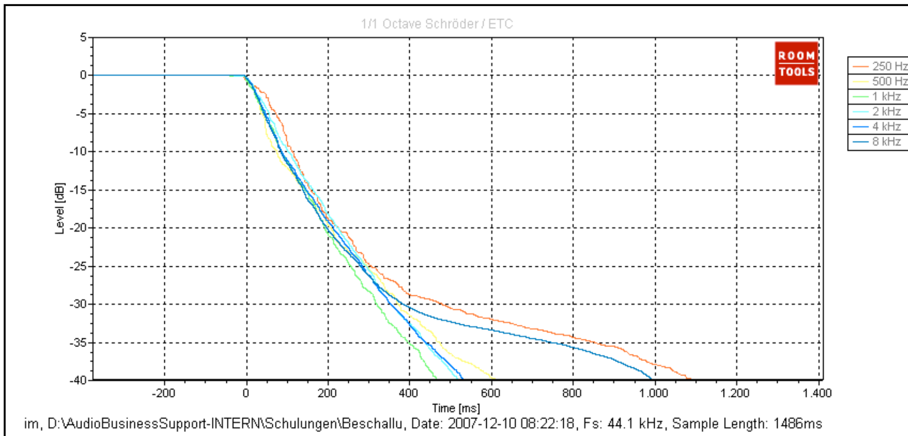

Figure 2-15

3. Calculation methods:

3.1. Calculation of the reverberation time

3.1.1. Sabine's reverberation equation

Sabine's empirical equation (Equation 3-1) is used especially for long reverberation times with the disadvantage, that the reverberation time is for a given total absorption (a=1) not zero.

$$RT_{60} = K \cdot \frac{V}{S \cdot \bar{a}}$$

RT_{60} = reverberation time in s

V = volumen in m^3 or ft^3

S= total boundary surface of a room

$\bar{a}$ = average absorption coeeficient

K=correction factor: 0,161=SI; 0,049=imperial

Equation 3-1

3.1.2. Eyring's reverberation equation

Eyring's empirical equation (Equation 3-2) is used especially for medium long reverberation times. This equation is a development of Sabine's equation.

$$RT_{60} = \frac{K \cdot V}{-S \cdot \ln(1-\bar{a})}$$

RT_{60} = reverberation time in s

V = volumen m^3 or ft^3

S= total boundary surface of a room in m^2 oder ft^2

$\bar{a}$ = average absorption coeficient

K=correction factor: 0,161=SI; 0,049=imperial

Equation 3-2

3.1.3. Fitzroy's reverberation equation

Fitzroy's equation Equation 3-3 calculates the RT_{60} for the x, y and z room surfaces with different absorption coefficients.
The Equation 3-3 below also includes the air absorption surface Sa_{air}

$$RT_{60} = \frac{s_x}{S}\left(\frac{K_1 \cdot V}{(S \cdot a_x + Sa_{air})}\right) + \frac{s_y}{S}\left(\frac{K_1 \cdot V}{(S \cdot a_y + Sa_{air})}\right) + \frac{s_z}{S}\left(\frac{K_1 \cdot V}{(S \cdot a_z + Sa_{air})}\right)$$

$$Sa_{air} = 4 \cdot V \cdot m$$

RT_{60} = reverberation time in s

V = volumen m^3 or ft^3

S= total boundary surface of a room in m^2 or ft^2

$s_{x,y,z}$= room surface of x, y or z in m^2 oder ft^2

$a_{x,y,z}$ = absorption coefficient

Sa_{air} = equivalent absorption surface of air in m^2

K_1 = correction factor: 0,161=SI; 0,049=imperial

m = constant of energy damping [$10^{-3} m^{-1}$]

Table 3-1 shows the sound propagation in free field and rooms with the influence of the energy damping of air

	centre octave frequency in Hz						
	125	250	500	1 kHz	2 kHz	4 kHz	8 kHz
free field sound propagation	sound absorption coefficient in [dB/km]						
temperature 10°C relative humidity 70%	0,5	1	2	4	8	20	50
Sound propagation in rooms	constant of energy damping m [10^{-3} m^{-1}]						
temperature 20°C relative humidity 50%	0	0,075	0,25	0,75	2,5	7,5	25
example	equivalent absorption surface Sa_{air} 4.V.m						
V=1000 m^3	0	0,3	1	3	10	30	100

source: W. Fasold / E. Veres „Schallschutz+Raumakustik in der Praxis“ table 4.10 page 102

3.2. Calculated decrease of sound level

3.2.1. Calculation 1/r - inverse proportional law

In this context we are talking about the decrease of sound pressure. The sound pressure of a spherical wavefront radiated from a point source decreases by a factor of ½ as the distance is doubled. This is the so called 1/r inverse proportional law.
For the calculation of the sound propagation expressed in dB see to Equation 3-4
In acoustics this calculation is valid only for free field spaces or anechoic rooms.

$$L_{decr} = 20 \cdot \log r$$

L_{decr} = decrease of sound level in dB

r distance from sound source to listener in m

Equation 3-4

3.2.2. Hopkins-Stryker equation

The condition for correct calculation using this method is that a homogenous statistical reverberation field exists, which is seldom the case for non cubical rooms.
This Hopkins-Stryker equation (see to Equation 3-5) for the decrease of sound level uses the parameter of volume and active surface (boundary surface of the room and absorption)

$$L_{decr} = 10 \log\left(\frac{Q}{4 \cdot \pi \cdot r^2} + \frac{4}{S \cdot \bar{a}}\right) + corr$$

L_{decr} = decrease of sound level in dB

Q = Directivity (1=360°; 2=180°; 4=90°)

r = distance of sound source to listener in m

S = total boundary surface of a room in m^2

$\bar{a}$ = average absorption coefficient

corr = correction value

For a calculation it is necessary to know the directivity of a loudspeaker, the surface and the absorption.
In particular, because the acoustical quality of materials in a room are not known the absorption in a room is quite often not defined.

3.2.3. Schultz's equation

The calculation of the decrease of the sound level in the Schultz equation is solely dependent on the distance between the sound source and the listener, the volume of the room and the relevant octave band.
All these parameters are easily definable. The decisive frequency is the centre octave frequency, where the speech intelligibility is most essential, therefore preferably the 2 kHz octave band.
The calculation is made according an approximation[9] see to Schultz's Equation 3-6:

$$L_{decr} = 120 - 10 \cdot \log r - 5 \cdot \log V - 3 \cdot \log f + corr$$

L_{decr} = decrease of sound level in dB

r = distance of sound source to listener in m

V = volumen in m^3

f = frequency in Hz e. g. 2 kHz

corr = correction value: e. g. -101=SI; -88=imperial

Equation 3-6

For experts: The Equation 3-7 below gives the explanation why there is a constant difference of "13" in the approximation of Schultz between SI and imperial units.

1 m = 3,2804 ft

$$L_{decr}(\rightarrow SI) = 120 - 10 \cdot \log r - 5 \cdot \log V - 3 \cdot \log f + korr$$
$$L_{decr}(\rightarrow imperial) = 120 - 10 \cdot \log r \cdot conv_{m \rightarrow ft} - 5 \cdot \log V \cdot conv_{m \rightarrow ft}{}^3 - 3 \cdot \log f + korr$$
$$L_{decr}(\rightarrow imperial) = 120 - (10 \cdot \log r + 10 \cdot \log[conv_{m \rightarrow ft}]) - (5 \cdot \log V + 5 \cdot 3 \log[conv_{m \rightarrow ft}]) - 3 \cdot \log f + korr$$
$$SI_{diff} = L_{decr}(\rightarrow SI) - L_{decr}(\rightarrow imperial)$$
$$SI_{diff} = -10 \cdot \log[conv_{m \rightarrow ft}] - 5 \cdot 3 \log[conv_{m \rightarrow ft}]$$
$$SI_{diff} = --10 \cdot \log[3{,}2804] - 5 \cdot 3 \log[3{,}2804]$$
$$SI_{diff} = \approx -5{,}16 - 7{,}74$$
$$SI_{diff} = \approx 12{,}89 \approx 13$$

Equation 3-7

[9] Don Davis & Carolyn Davis Sound system Engineering 2nd edition page 212

3.2.4. Practical procedure of the Schultz equation:

In daily practice it is recommended to use the diagram **Fehler! Verweisquelle konnte nicht gefunden werden.** below instead of using the equation.

What is the procedure?

The drawing Figure 3-2 shows on the x-axis the distance between the perpendicular of the loudspeaker and the listener.
IMPORTANT: the distances are calculated at the listener's level and are NOT the shortest diagonal distance between loudspeaker and listener

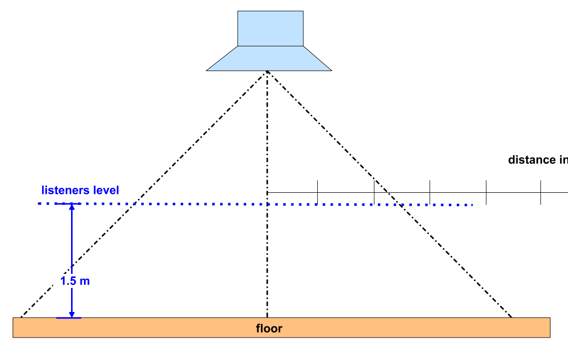

Figure 3-2

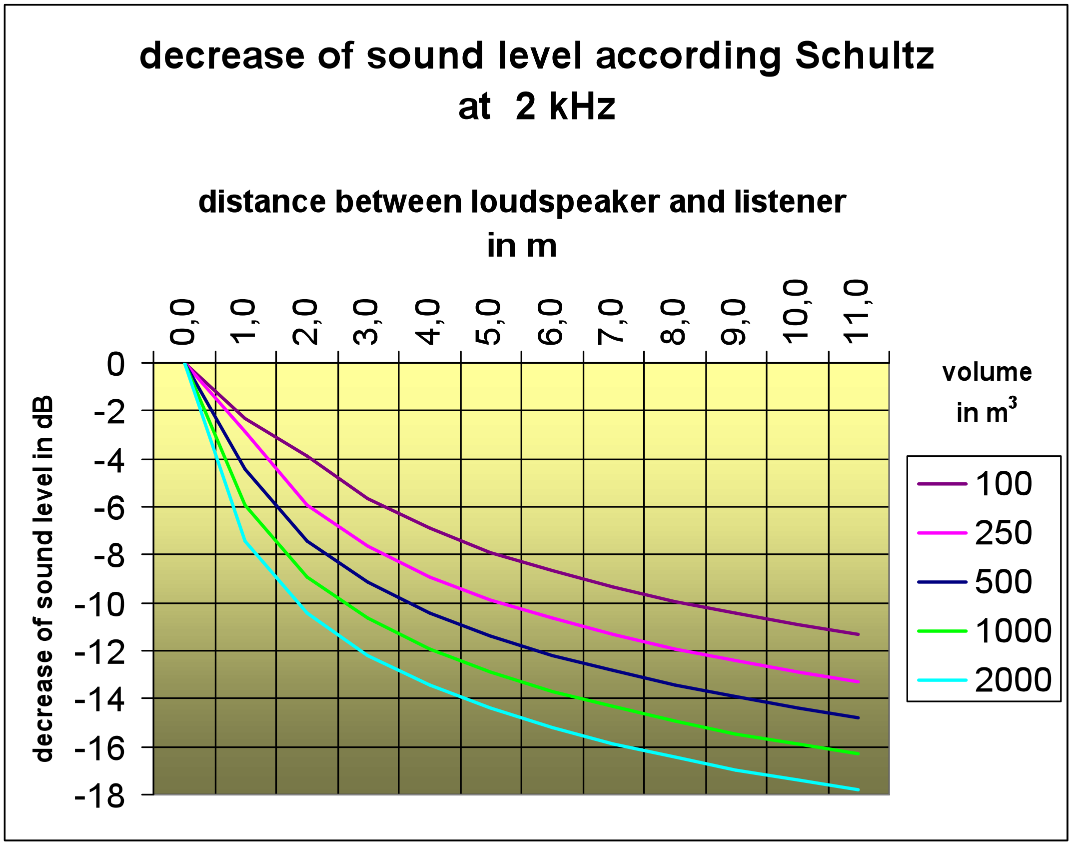

Figure 3-1