ACOUSTICS
part – 4
Sound Engineering Course

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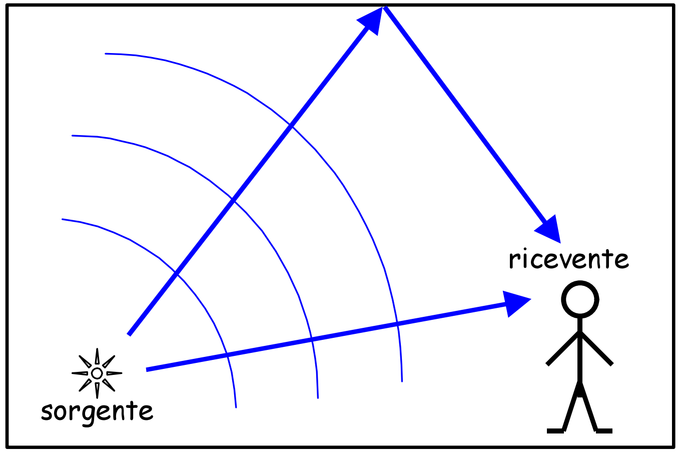
Indoors acoustics

A sound generated in a closed room produces an acoustic field that results from the superposition of **direct waves** and **reflected waves.**

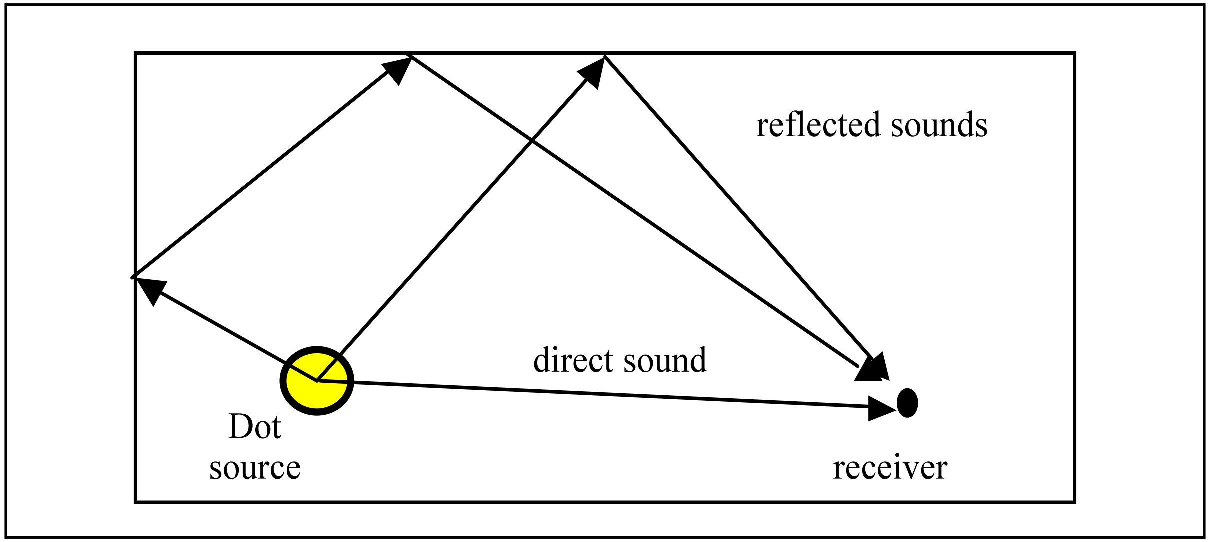


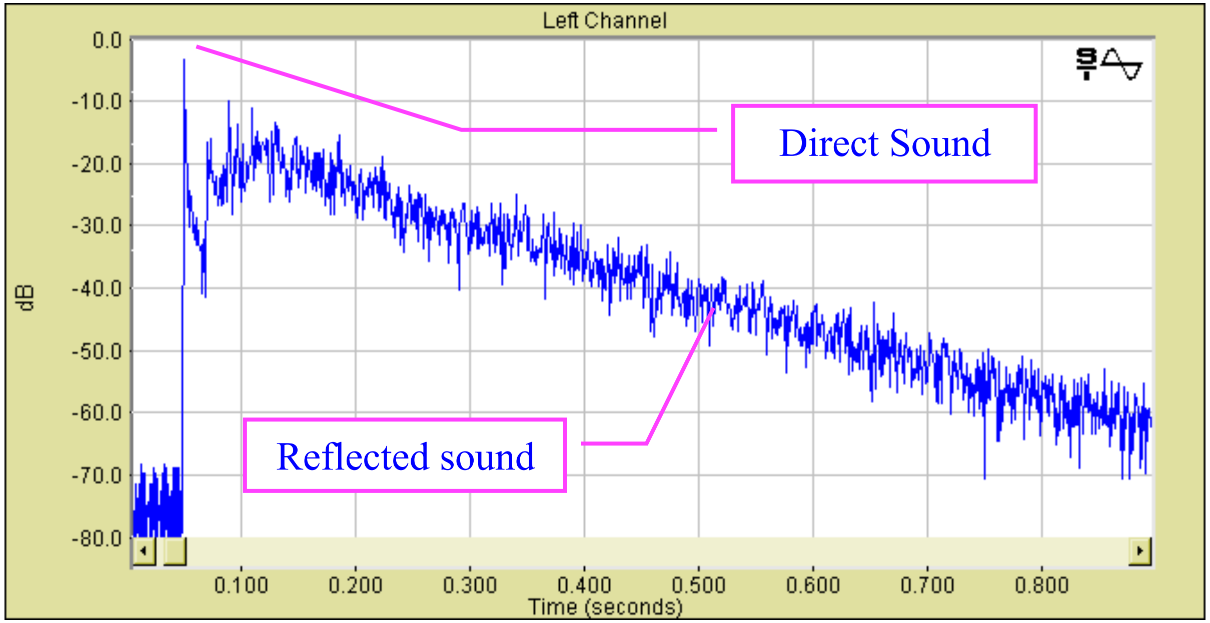
Direct waves come directly from the source to the listener, as in an open field.

Reflected Waves are produced by all the reflections on the walls of the room.

The amount of energy reflected by the boundary surfaces is dependent on their acoustic behavior, described by their coefficients of absorption, reflection and transmission (a,r and t).

Indoors sound propagation methods



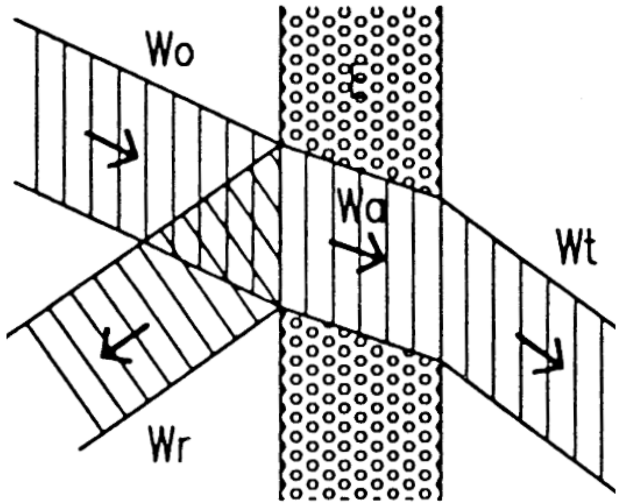


Reflection, absorption and transmission coefficients

The energy balance equation for a wave reflected on a wall is:

- $W_o = W_r + W_a + W_t$

dove W_o is the power of the incoming wave, W_r is the reflected power, W_a is the power absorbed and converted into heat and W_t is the power going through the wall.



Dividing by W_o we obtain: $1 = r + a + t$

where $r = W_r / W_o$, $a = W_a / W_o$ and $t = W_t / W_o$ are, respectively, the *reflection, absorption and transmission coefficients* of the wall relative to the incoming acoustic energy.

The value of coefficients *r, a, t* varies between 0 and 1 $0 \leq r,a,t \leq 1$

And depents on the material of the wall as well as on frequency and angle of the sound pressure wave.

We can define the **apparent acoustic absorption coefficient** as

$\alpha = 1 - r$

Apparent indicates that the acoustic energy going into the wall is only partly absorbed, but does not return in the originating room.

Free field, reverberant field, semi-reverberant field

In a closed environment the acoustic field can be of three different kinds:

- **Free field**
- **Reverberant field**
- **Semi-reverberant field**

Free Field

A field is defined as *free* when we are close to the source, where the direct energy component prevails, compared to which the contribution of all the reflections becomes negligible.

In this case, the field is the same as outdoors, and only depends on source distance and directivity, **Q.**

The **sound pressure level** is:

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi d^2}\right)$$

In which $\mathbf{L_W}$ is the level of source sound power, **Q** its directivity, and **d** is the distance between source and receiver. In a free field, the sound level decreases by 6 dB each time distance **d** *doubles*.

Reverberant field

A field is said to be *reverberant* if the number of side wall reflections is so elevated that it creates a uniform acoustic field (even near the source).

The **equivalent acoustic absorption area** is defined as:

$$A = \alpha S = \sum_i \alpha_i \cdot S_i \quad (m^2)$$

where α is the average absorption coefficient and S is the total interior surface area (floor, walls, ceiling, etc.)

The **sound pressure level** is:

$$L_p = L_w + 10\log\left(\frac{4}{A}\right)$$

A reverberant field may be obtained in so called *reverberant chambers,* where the absorption coefficients of different materials are also measured.

Semi-reverberant field (1)

A field is said to be *semi-reverberant* when it contains both free field zones (near the source, where the direct sound prevails) and reverberant field zones (near the walls, where the reflected field prevails). In normally sized rooms, we can suppose that the acoustic field is *semi-reverberant.*

The **sound pressure level** is:

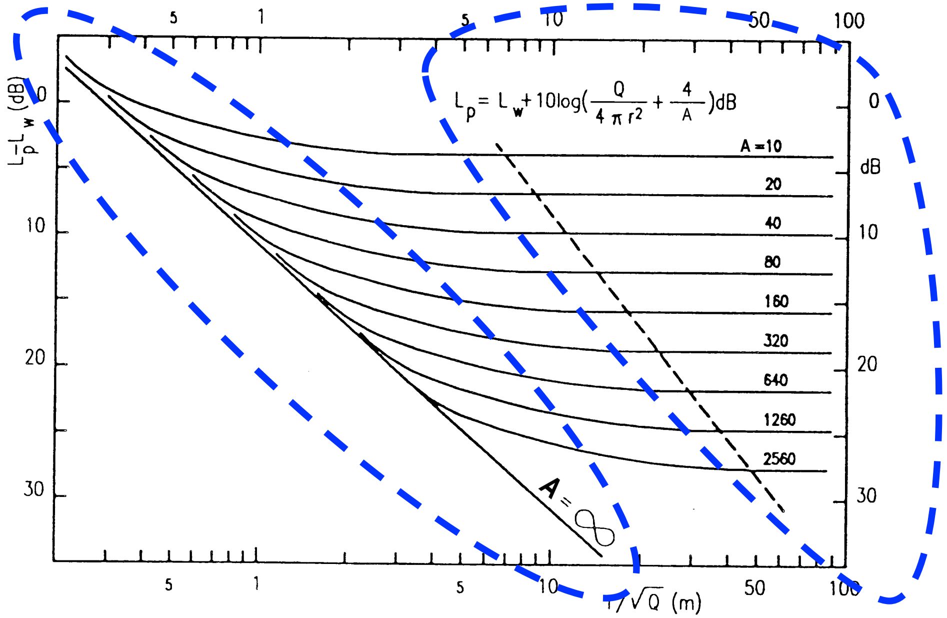
$$L_p = L_w + 10\log\left(\frac{Q}{4\pi d^2} + \frac{4}{A}\right)$$

In a semi-reverberant acoustic field, the density of sound energy in a point is therefore given by the sum of the direct and indirect acoustic fields.

$$L_{ptot} = 10 \cdot \log\left[10^{Lp,dir/10} + 10^{Lp,rev/10}\right]$$

- the straight line ($A = \infty$) represents the limit case for a free field (6dB for each doubling of distance d).

- the dotted and shaded line marks a zone on whose right the acoustic field is practically reverberant.



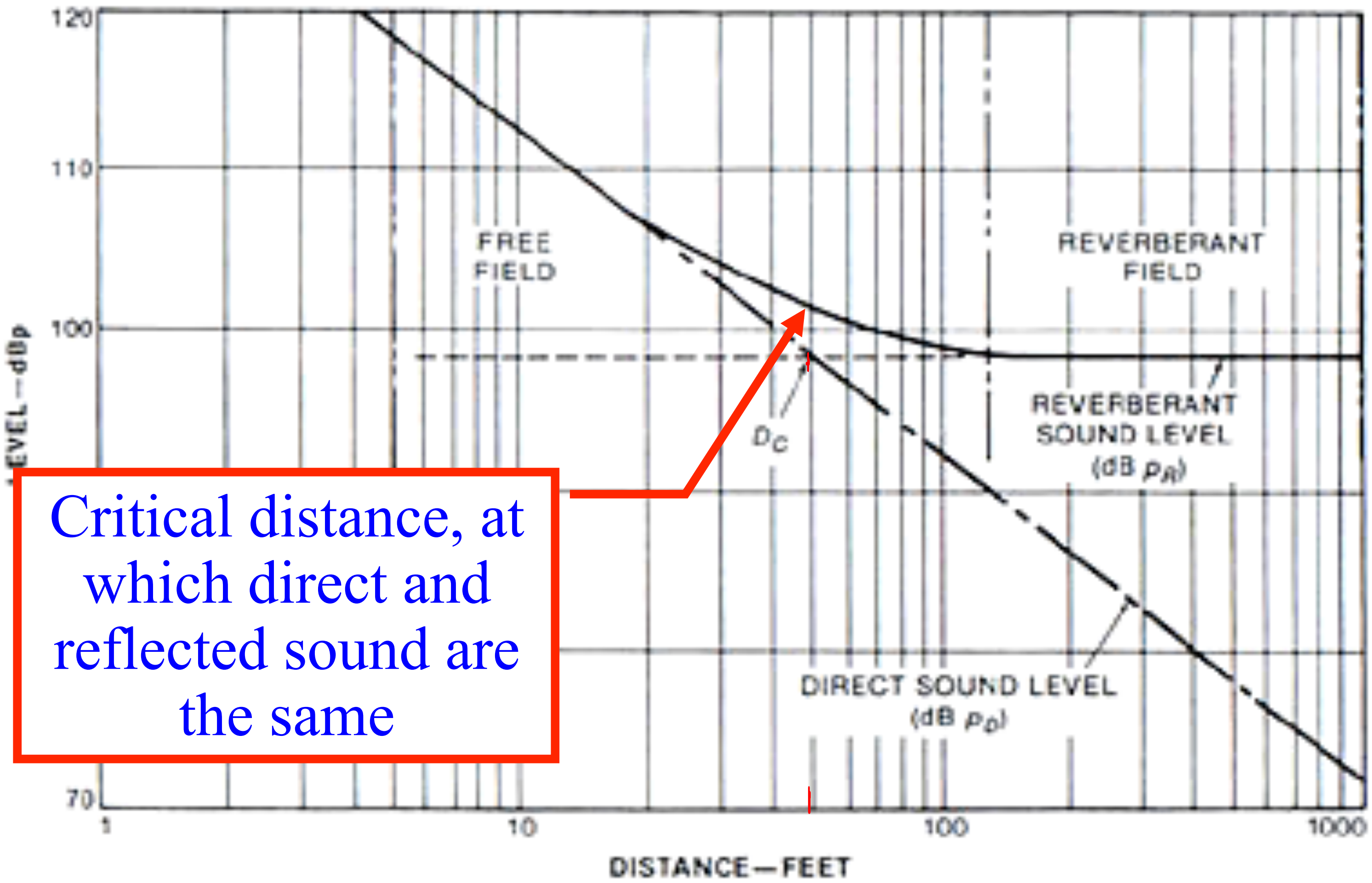
Reduction of the sound level in the environment via an acoustic treatment of the walls:

- *close to the source*, the attenuation will be very small, even if the value of R is increased considerably;

- *far from the source*, (mainly reverberant acoustic field) the sound level reduction can be quite noticeable.

Critical Distance

Sound level as a function of source distance



Critical Distance

$$L_p(d) = L_W + 10 \cdot \lg\left[\frac{Q}{4 \cdot \pi \cdot d^2} + \frac{4}{\sum \alpha_i \cdot S_i}\right]$$

Direct sound

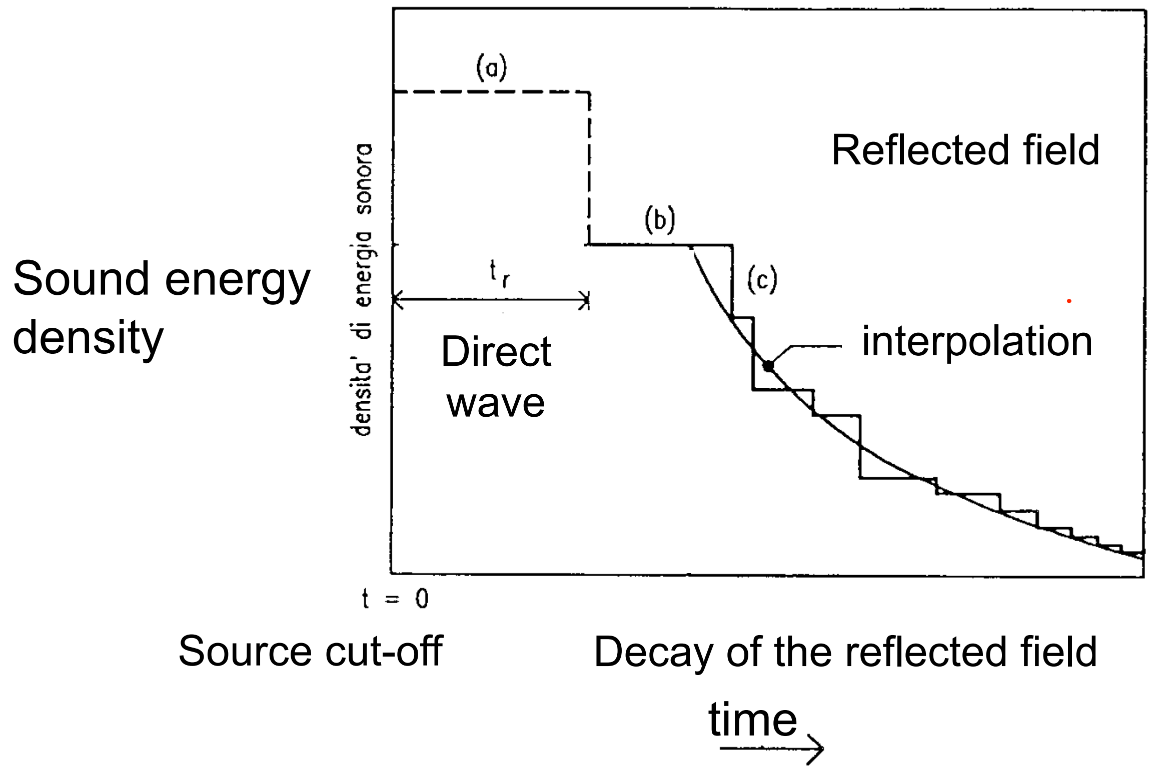
Reflected sound

$$\frac{Q}{4\pi d^2} = \frac{4}{\alpha \cdot S} \qquad d_{cr} = \sqrt{\frac{Q \cdot \alpha \cdot S}{16 \cdot \pi}}$$

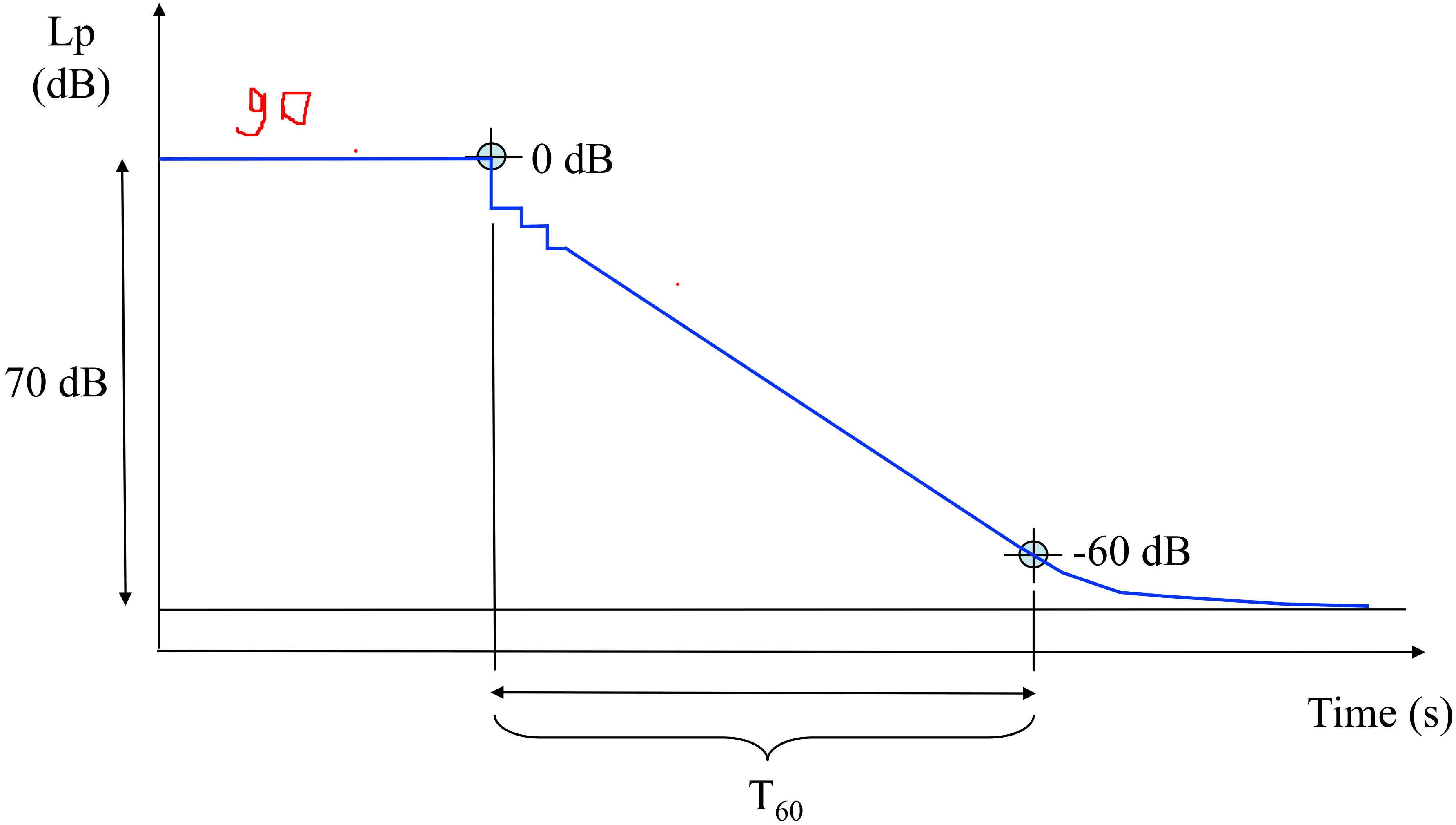
Reverberation time

Reverberation time (1)

Let's consider a room containing an active sound source, and let's abruptly interrupt the emission of sound energy. We define as **reverberation** time RT (s) of an environment, the time necessary for the sound energy density to decrease to a millionth (60 dB) of the value it had before the source was switched off.



Reverberation time T_{60}



Sabine's Formula (3)

If the environment is perfectly reverberant the value of the reverberation time is the same in all points and is

- $$T_{60} = 0.16 \cdot \frac{V}{\sum_i (\alpha_i \cdot S_i)} \quad \text{(s)}$$

where V is the volume of the environment. This relation is known as "**Sabine's formula**".

By measuring the reverberation time, it is possible to determine:

- $A = \sum_i (\alpha_i \cdot S_i) = \overline{\alpha} \cdot S_{tot}$ **equivalent area of acoustic absorption**

Sabine's Formula

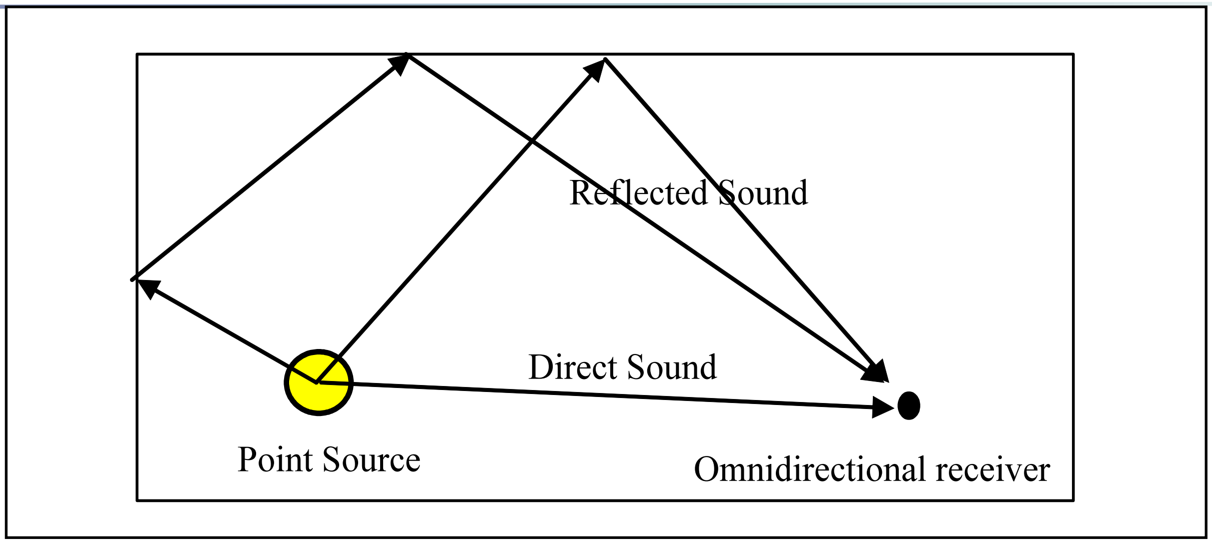
$$T_{60} = T_{20} = \frac{0.16 \cdot V}{\sum \alpha_i \cdot S_i} \quad \Rightarrow \quad A = \frac{0.16 \cdot V}{T_{60}}$$

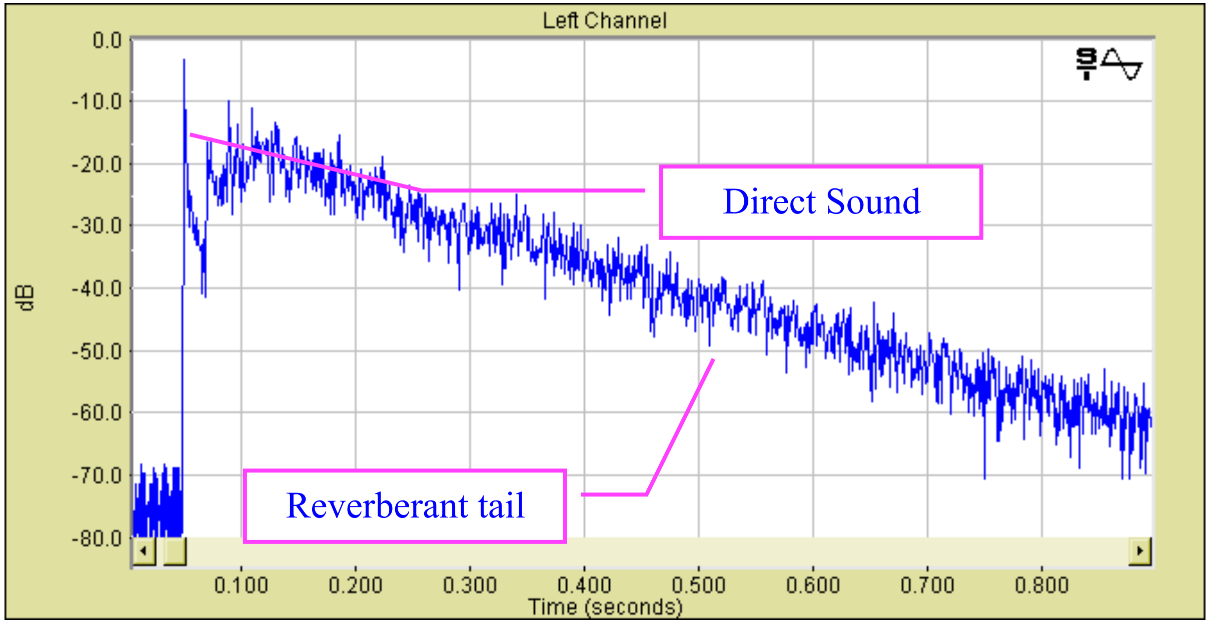
Substituting in the critical distance formula:

$$d_{cr} = \sqrt{\frac{Q}{16 \cdot \pi} \cdot \frac{0.16 \cdot V}{T_{60}}} = \sqrt{\frac{Q}{100 \cdot \pi} \cdot \frac{V}{T_{60}}}$$

Acoustical Parameters from Impulse Response

Basic sound propagation scheme





ISO 3382 acoustical parameters

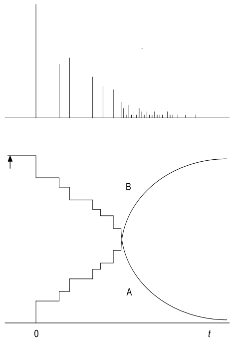
Tabella 15.2 Definizione dei descrittori acustici oggettivi utilizzati nelle comparazioni

Descrittori acustici oggettivi	**Simboli, unità**	**Definizione o espressione matematica**	**Proposto da**	**Attributi soggettivi in letteratura**
Tempo di riverberazione	RT_{60} (s)	Pendenza della linea best fit del decadimento del livello sonoro tra −5 e −25 dB o a −30 dB, estrapolato a −60 dB	Sabine 1923	Riverberazione - Vivezza
Early Decay Time	*EDT* (s)	Pendenza della lnea di best fit del decadimento del livello sonoro da 0 a −10 dB, estrapolato a −06 dB.	Jordan 1975	Riverberazione - Vivezza
Chiarezza	*C80* (dB)	$C80 = 10 \log \frac{\int_0^{80ms} p^2(t)dt}{\int_{80ms}^{\infty} p^2(t)dt}$	Reichardt 1975	Chiarezza musicale
Definizione	*D-50* (%)	$D = \frac{\int_0^{50ms} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$	Thiele 1953	Speech intelligibility & sound definition
Rapporto segnale/rumore	*S/N* (dB)	$S/N = 10 \log \frac{\int_0^{95ms} \alpha(t)p^2(t)dt}{\int_{95ms}^{\infty} p^2(t)dt}$	Lochner e Burger 1964	Speech intelligibility
Rapid Speech Transmission Index	*RASTI* (ratio)	RASTI = [(S/N)media + 15]/30	Steeneken e Houtgast 1980	Speech intelligibility

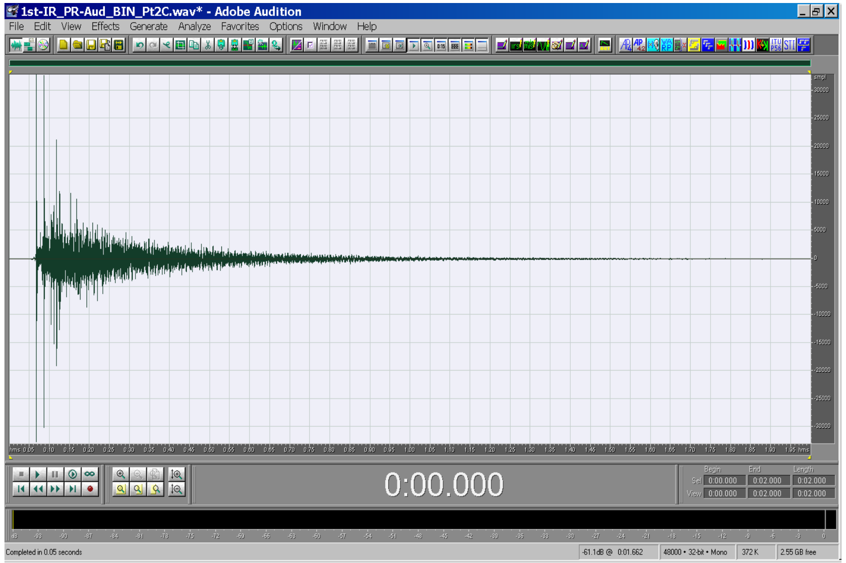
From Impulse Response to Sound Decay

- Schroeder's backward integral

- Makes it possible to reconstruct the decay of a stationary source by backward integration of the measured impulse response



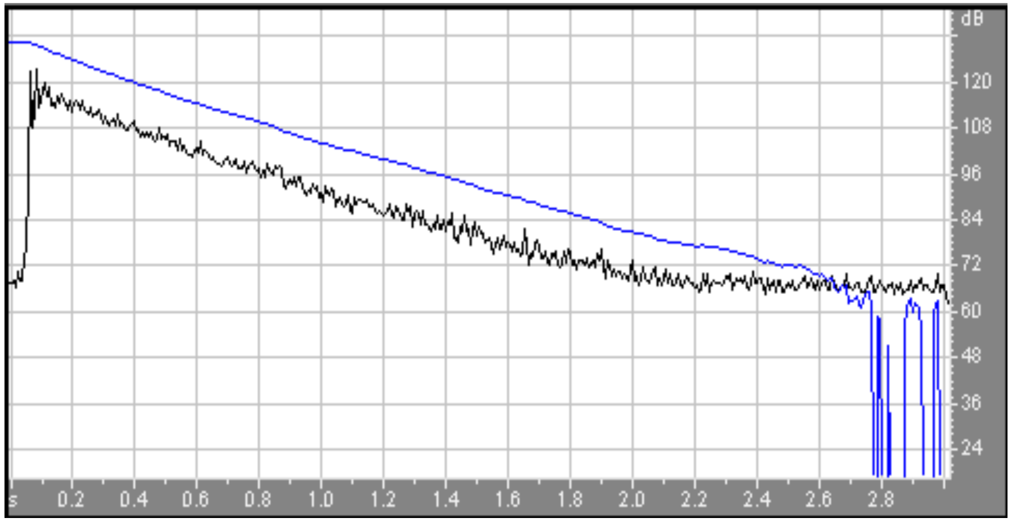
Schroeder's BW Integration



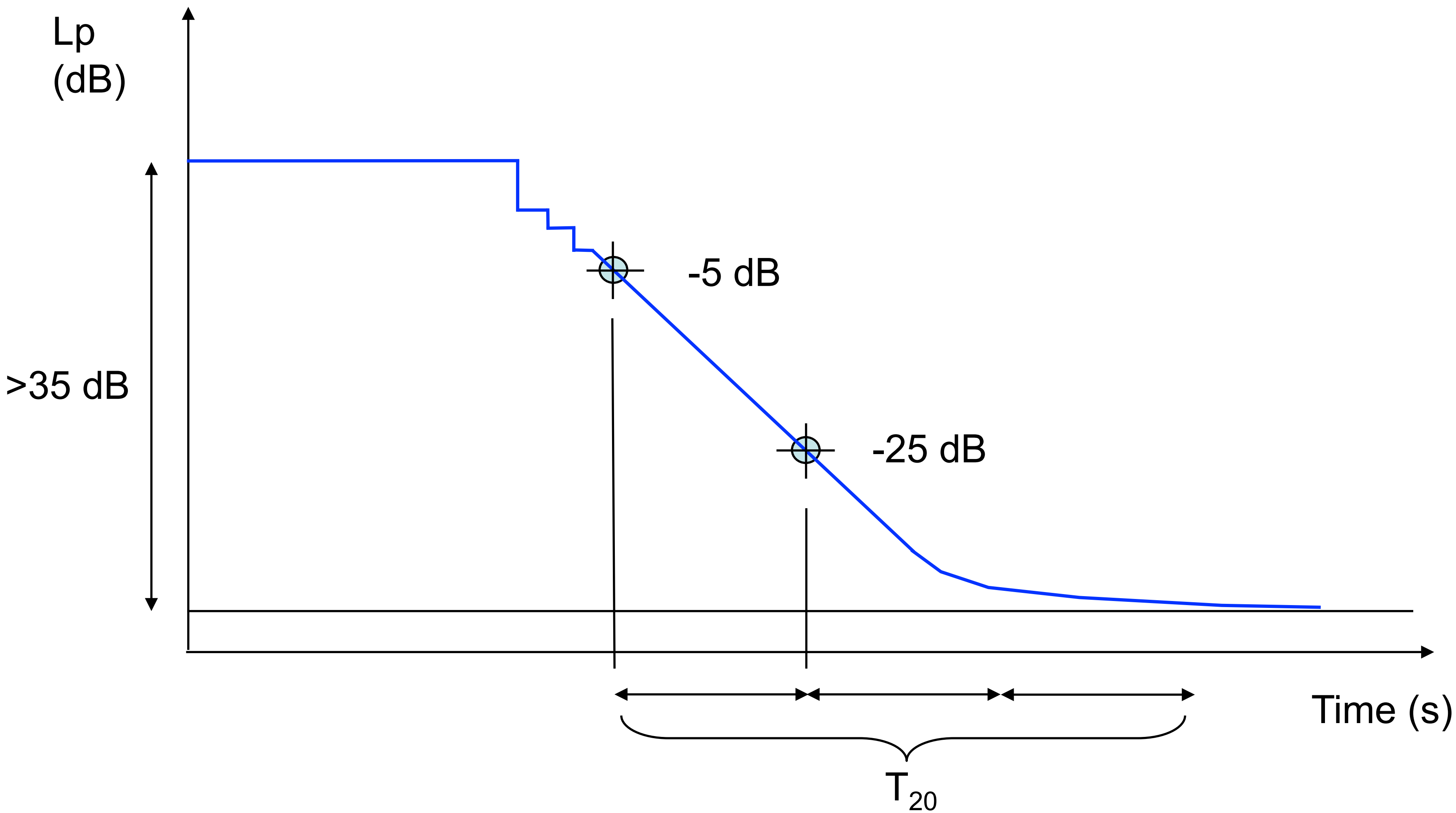
Pressure Impulse Response

Stationary Sound Decay (in dB)

Energetic Impulse Response (in dB)

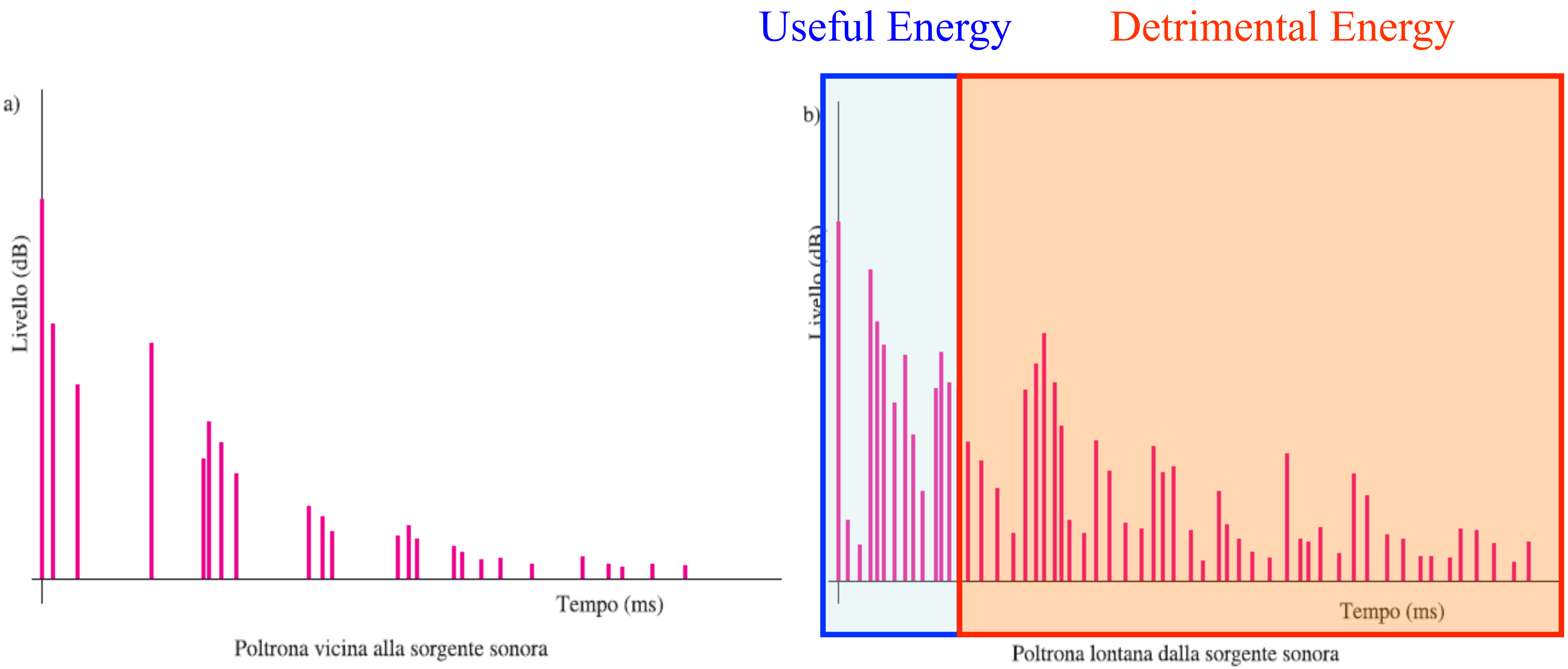


Reverberation time T20



ISO 3382 Reverberation Time(s)

- Early Decay Time (EDT):
  extrapolated from 0 to -10 dB
- Reverberation Time T_{10}:
  extrapolated from -5 to -15 dB
- Reverberation Time T_{20}:
  extrapolated from -5 to -25 dB
- Reverberation Time T_{30}:
  extrapolated from -5 to -35 dB


Useful Energy
Detrimental Energy
a)
Livello (dB)
Tempo (ms)
Poltrona vicina alla sorgente sonora
b)
Tempo (ms)
Poltrona lontana dalla sorgente sonora

Early-Late parameters

- Clarity Index C_{80} (symphonic music):

$$C_{80} = 10 \cdot \lg \left[\frac{\int_0^{80ms} p^2(\tau) \cdot d\tau}{\int_{80ms}^{\infty} p^2(\tau) \cdot d\tau} \right]$$

Optimal Value = +/- 1 dB

- Clarity Index C_{50} (speech):

$$C_{50} = 10 \cdot \lg \left[\frac{\int_0^{50ms} p^2(\tau) \cdot d\tau}{\int_{80ms}^{\infty} p^2(\tau) \cdot d\tau} \right]$$

Optimal Value = +/- 1 dB

Early-Late parameters

- Definition Index D:

$$D = \frac{\int_0^{50ms} p^2(\tau)\cdot d\tau}{\int_0^{\infty} p^2(\tau)\cdot d\tau}\cdot 100$$

- Center Time t_S:

$$t_s = \frac{\int_0^{\infty} \tau \cdot p^2(\tau)\cdot d\tau}{\int_0^{\infty} p^2(\tau)\cdot d\tau}$$

Other acoustical parameters

SPL at 10 m

- Strenght: $$G = SPL - L_W + 31 \quad dB$$

- IACC: $$\rho(t) = \frac{\int_{-\infty}^{\infty} h_d(\tau) \cdot h_s(\tau + t) \cdot d\tau}{\sqrt{\int_{-\infty}^{\infty} h_d^2(\tau) \cdot d\tau \cdot \int_{-\infty}^{\infty} h_s^2(\tau + t) \cdot d\tau}}$$

Other acoustical parameters

- Lateral Fraction:

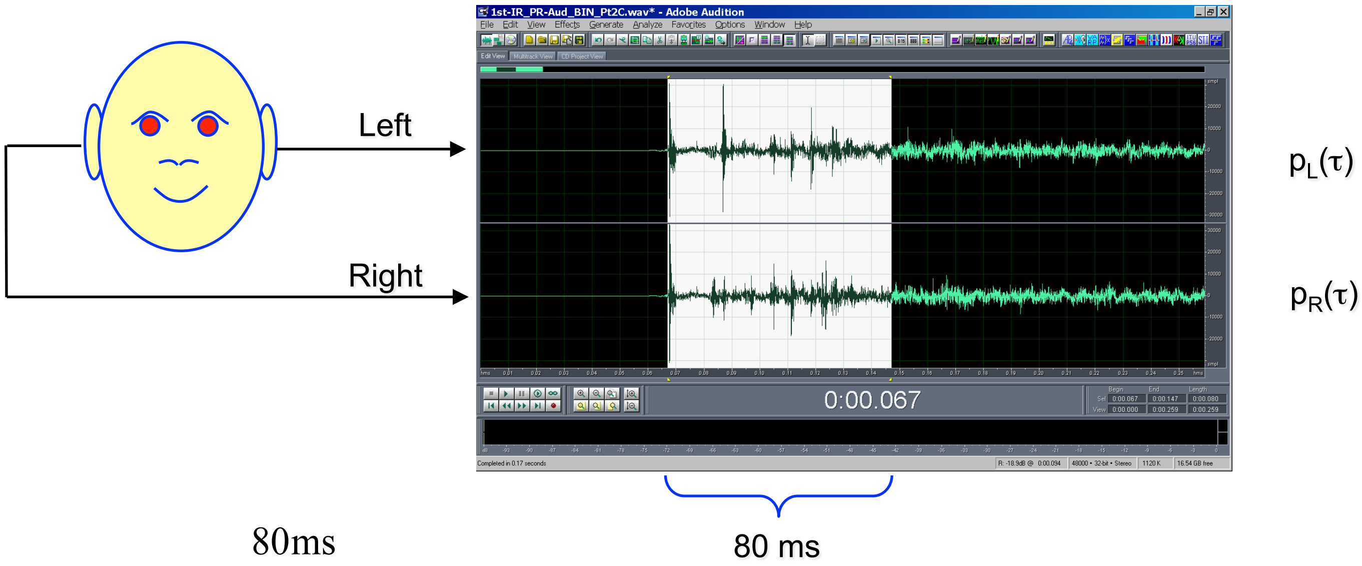
$$J_{LF} = \frac{\int_{5ms}^{80ms} h_Y^{2}(\tau) \cdot d\tau}{\int_{0ms}^{80ms} h_W^{2}(\tau) \cdot d\tau}$$

- LFC:

$$J_{LFC} = \frac{\int_{5ms}^{80ms} h_Y(\tau) \cdot h_W(\tau) \cdot d\tau}{\int_{0ms}^{80ms} h_W^{2}(\tau) \cdot d\tau}$$

IACC "objective" spatial parameter

- It was attempted to "quantify" the "spatiality" of a room by means of "objective" parameters, based on 2-channels impulse responses measured with directive microphones
- The most famous "spatial" parameter is IACC (Inter Aural Cross Correlation), based on binaural IR measurements

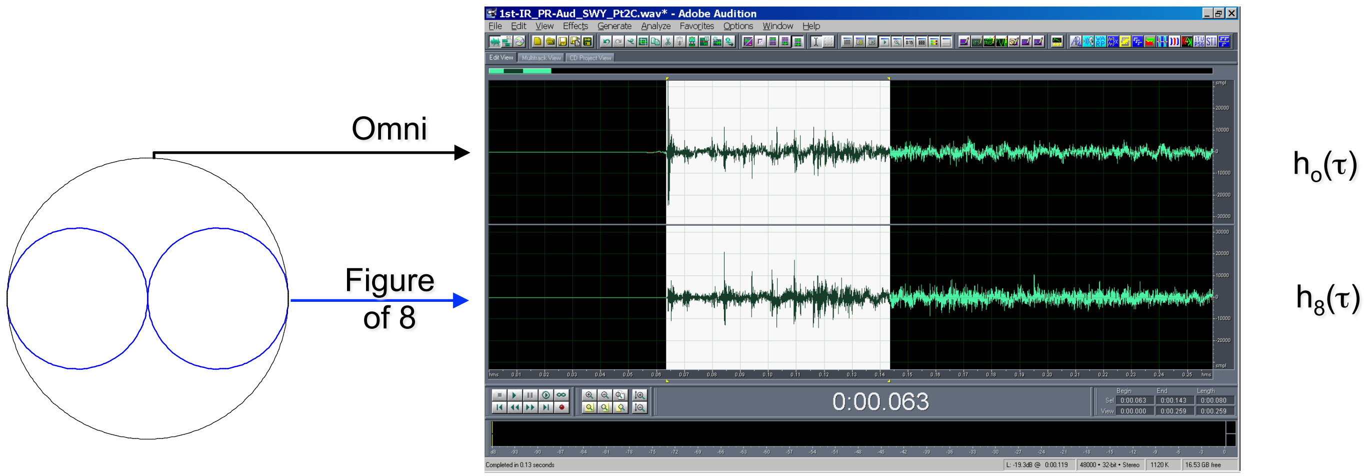


$$\rho(t) = \frac{\int_0^{80ms} p_L(\tau)\cdot p_R(\tau + t)\cdot d\tau}{\sqrt{\int_0^{80ms} p_L^2(\tau)\cdot d\tau \cdot \int_0^{80ms} p_R^2(\tau + t)\cdot d\tau}}$$

$$IACC_E = Max[\rho(t)] \quad t \in [-1ms \ldots +1ms]$$

LF "objective" spatial parameter

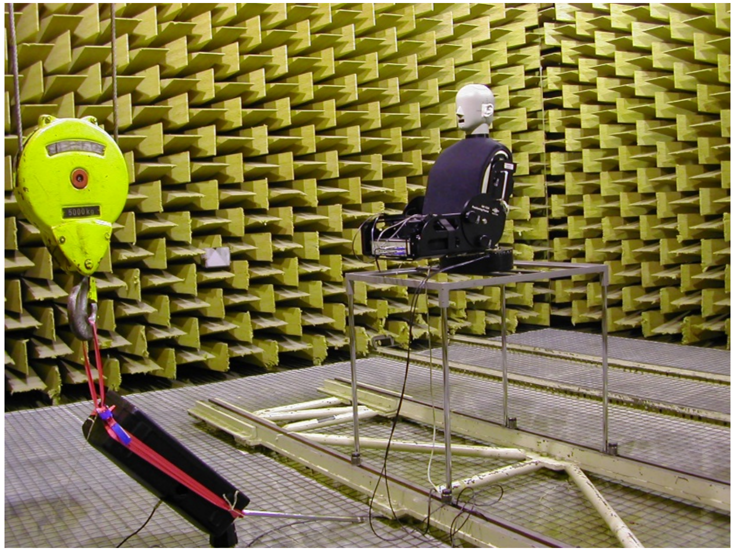
- Another "spatial" parameter is the Lateral Energy ratio LF
- This is defined from a 2-channels impulse response, the first channel is a standard omni microphone, the second channel is a "figure-of-eight" microphone:

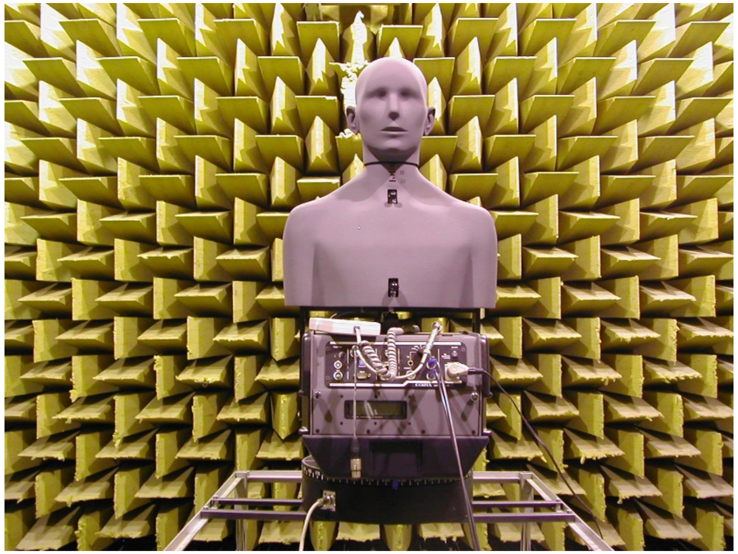


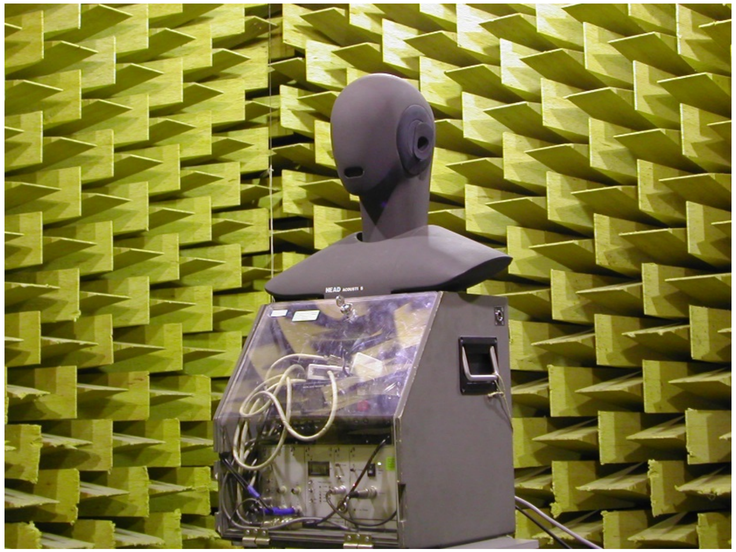
$$LF = \frac{\int_{5ms}^{80ms} h_8^2(\tau) \cdot d\tau}{\int_{0ms}^{80ms} h_o^2(\tau) \cdot d\tau}$$

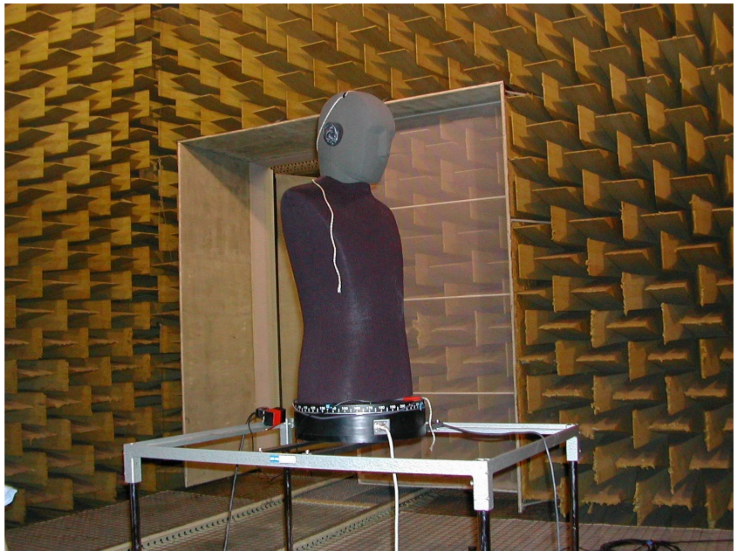
Are IACC measurents reproducible?

- Experiment performed in anechoic room - same loudspeaker, same source and receiver positions, 5 binaural dummy heads



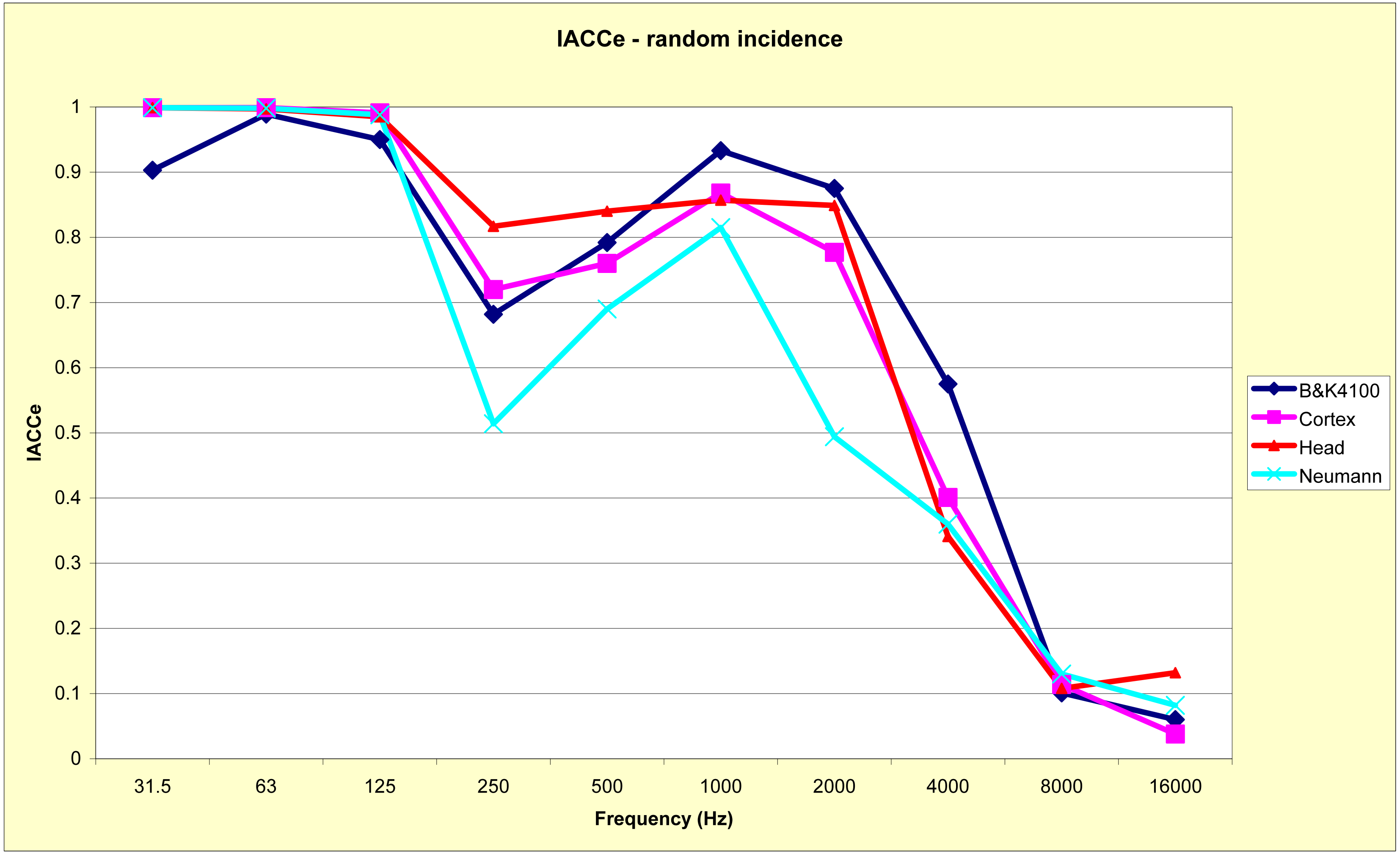






Are IACC measurents reproducible?

- Diffuse field - huge difference among the 4 dummy heads

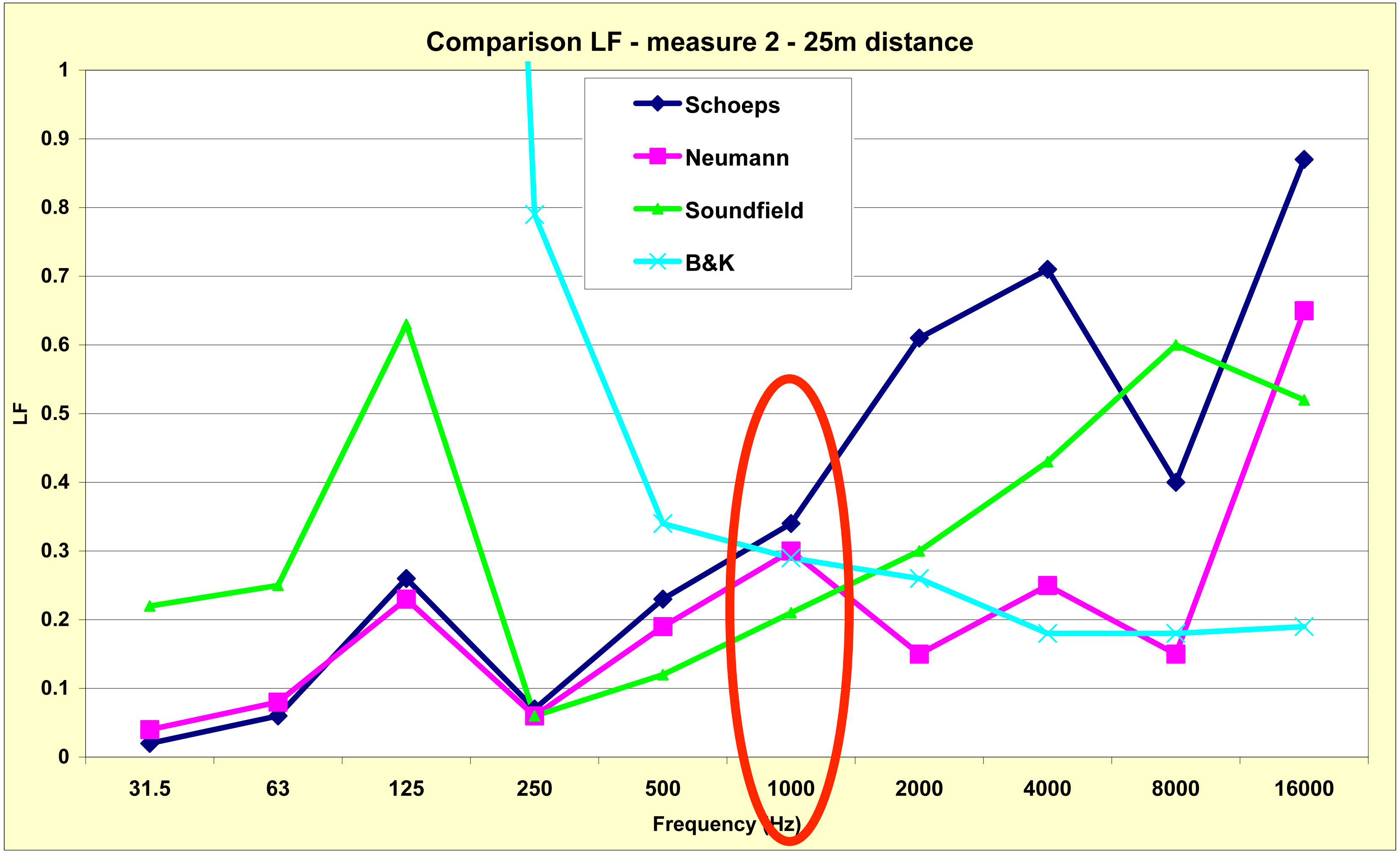


Are LF measurents reproducible?

- Experiment performed in the Auditorium of Parma - same loudspeaker, same source and receiver positions, 4 pressure-velocity microphones

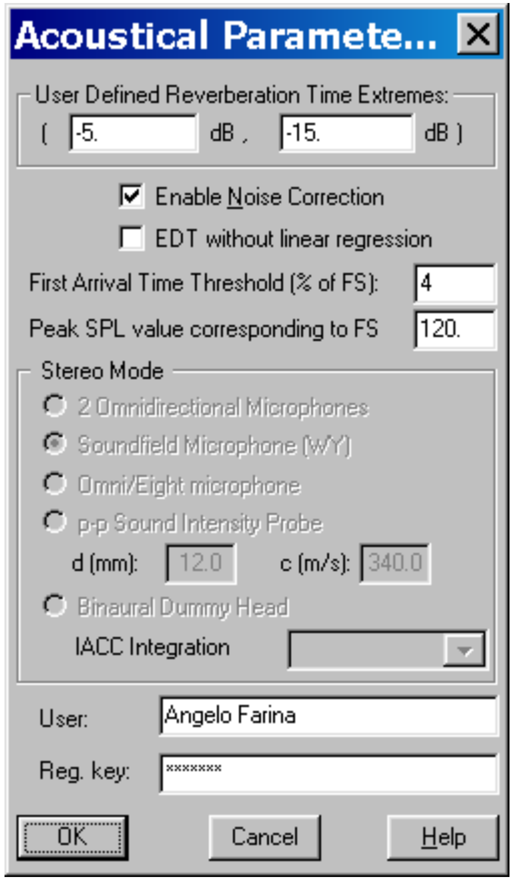
Are LF measurents reproducible?

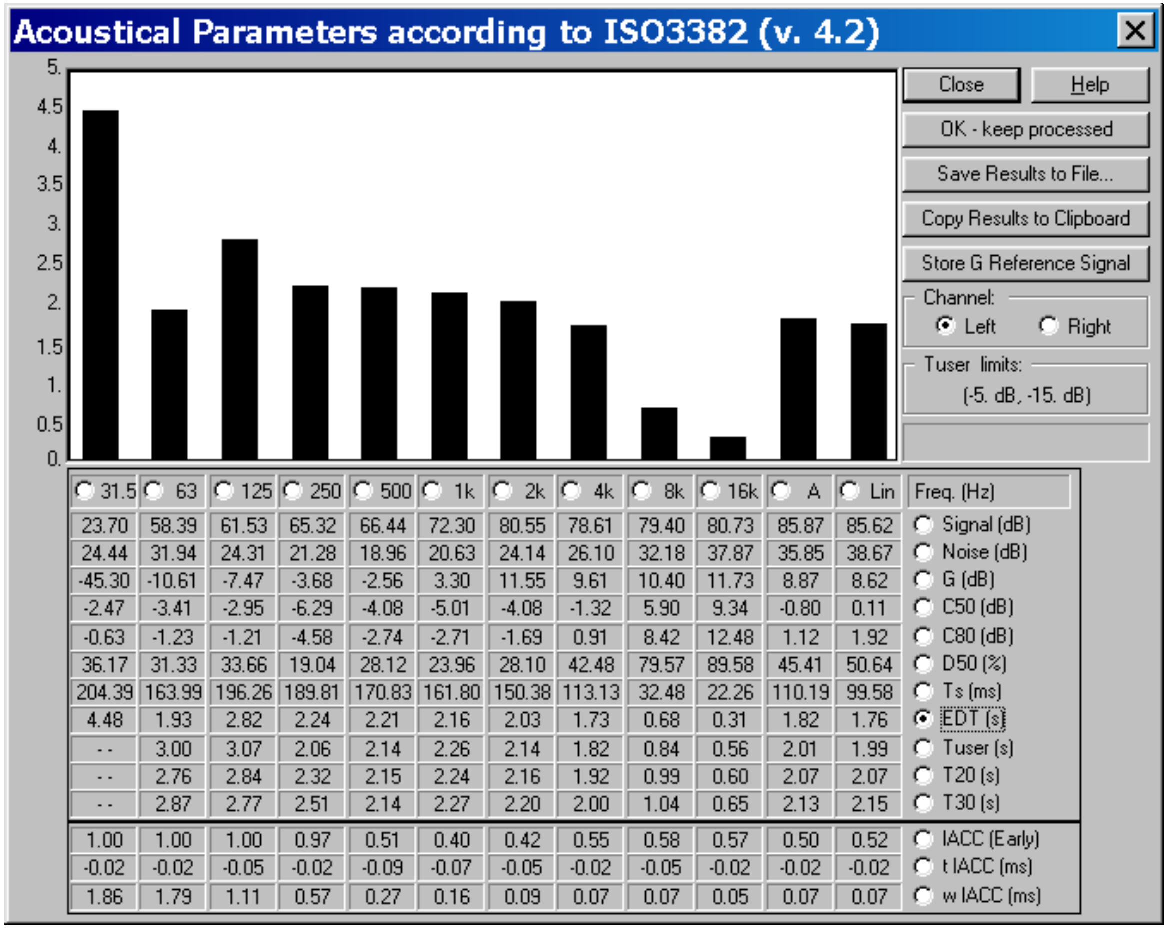
- At 25 m distance, the scatter is really large



Post processing of impulse responses

- A special plugin has been developed for performing analysis of acoustical parameters according to ISO-3382





Post processing of impulse responses

- A special plugin has been developed for the computation of STI according to IEC-EN 60268-16:2003