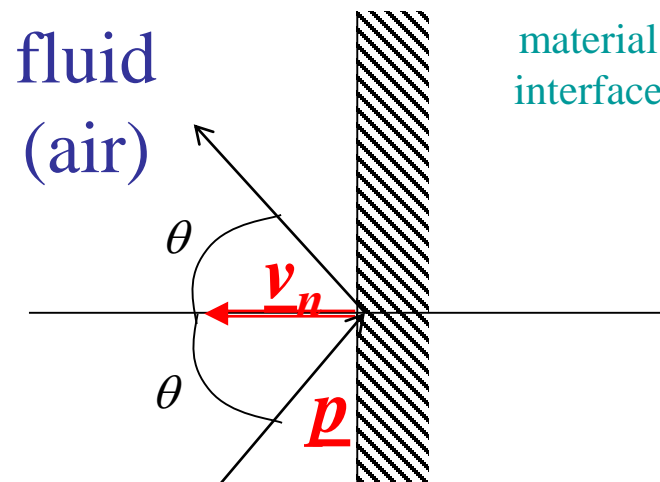


3.3 Geometrical Acoustics

Geometrical Acoustics

- We know the wave equation and its solutions (at least for simple room geometries)
- We can simplify the processing using sound rays instead
- Hypothesis: specular reflections according to Snell-Descartes's law



Geometrical Acoustics

- We know the wave equation and its solutions (at least for simple room geometries)
- We can simplify the processing using sound rays instead
 - This can speed up the calculations considerably
 - Diffusion and diffraction on surfaces can also be approximated to improve the simulations

Geometrical Acoustics

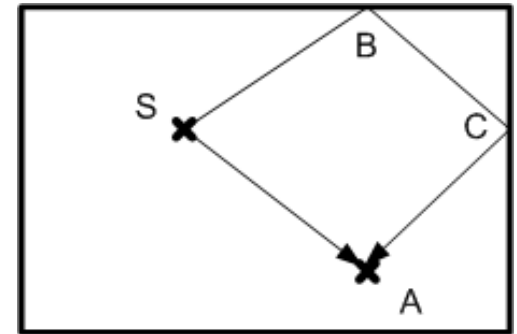
- Ray acoustics:

- Principle:

- to trace sound rays
 - Reflections on walls after Snell-Descartes (direction w/ refraction index)
 - variate S and A (S = stage/podium; A = audience)
 - Reflections on lateral walls/ceiling/ground

- Goals:

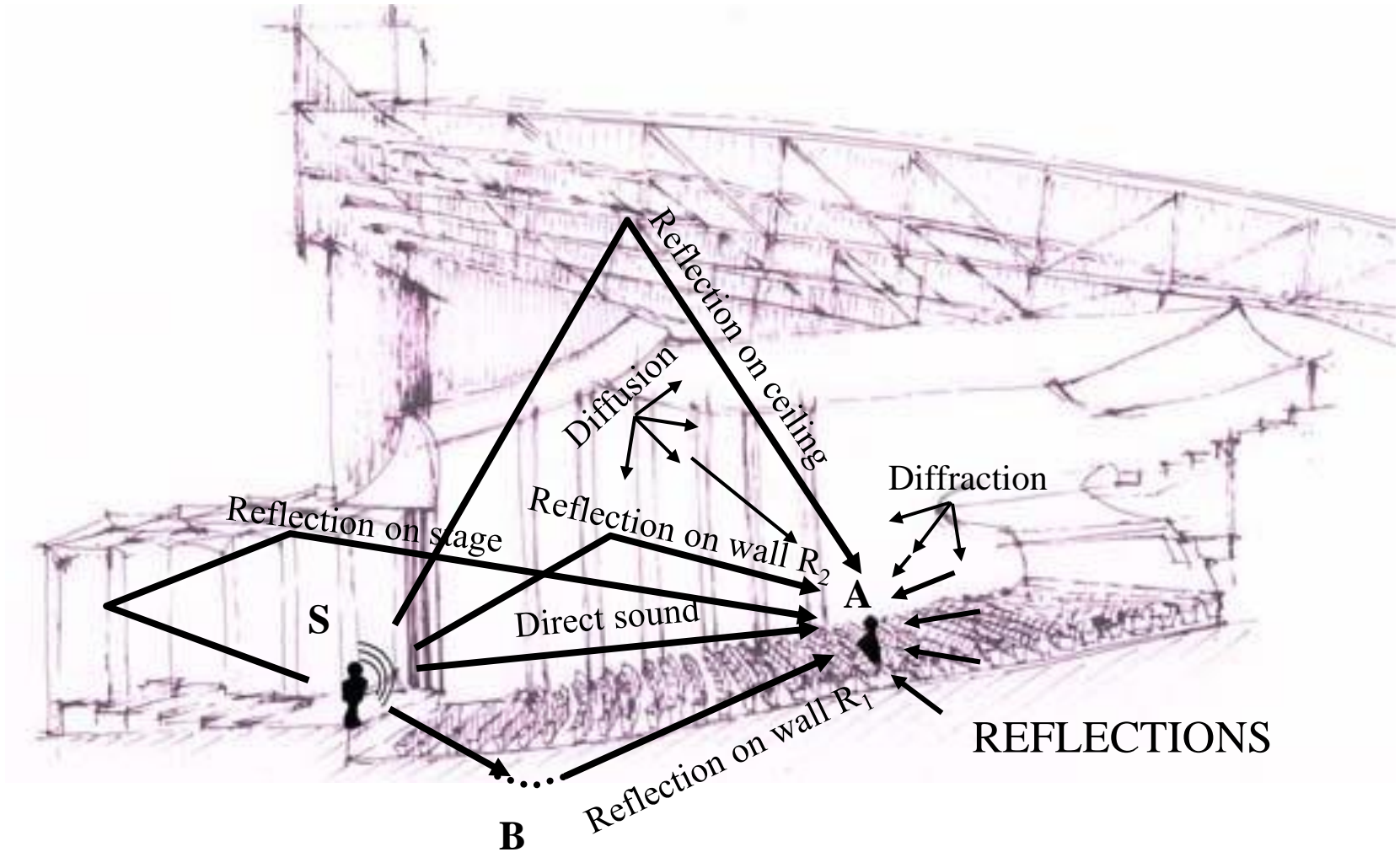
- define « good shapes », prevent bad ones
 - absorbing/reflecting treatment of walls



Geometrical Acoustics

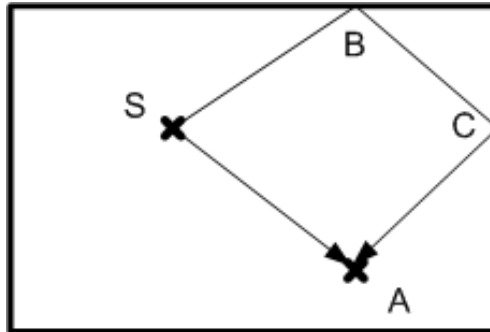


Principle



Directs and indirect sound rays

- ray SA is direct, it is not reflected
- ray SBCA is indirect since it comprises at least one reflection
- there exists an infinity of indirect rays
 - Increasing orders
 - Image sources



Temporal dispersion

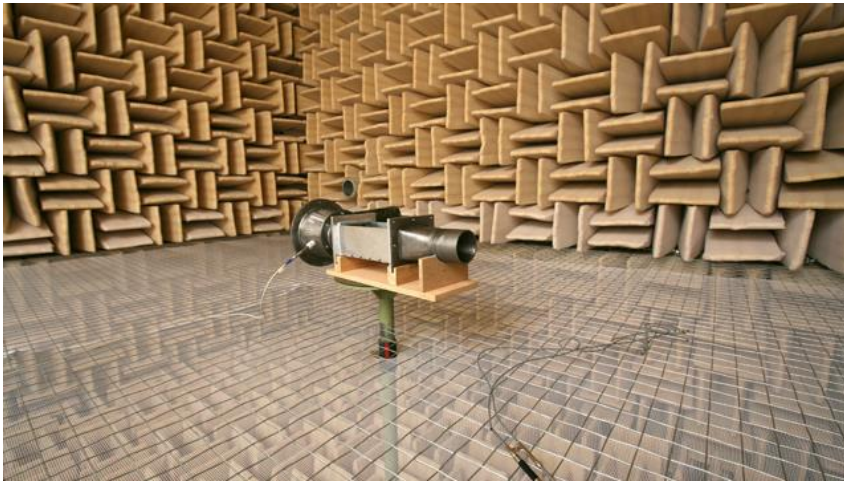
- indirect events arrive in dispersed order
- dispersion=delay/direct sound (longer trajectories)
- For an order of magnitude:

$$c = 340 \text{ m/s:} \quad \Delta l = 1 \text{ m} \rightarrow \delta t \approx 3 \text{ ms}$$

$$\Delta l = 10 \text{ m} \rightarrow \delta t \approx 30 \text{ ms}$$


Effects of reflection on sound

- Examples:



 Recording (anechoic room)



 Recording (empty room)

 Recording (w/ absorber)

Reflections can have prejudicial effect on speech, music diffusion, etc.

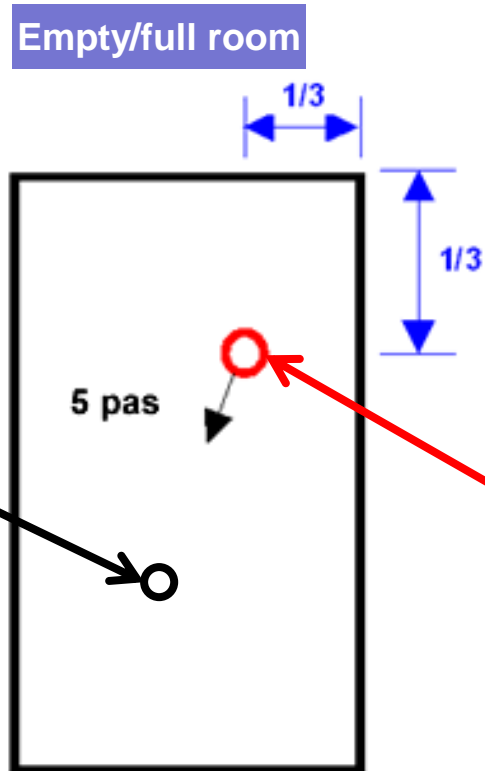
Reflectogram/Echogram

- Time series of reflection in a room
 - ➔ Impulse response (IR)
- Can be measured:
 - with an impulse sound (hand clap, balloon blast, etc.)
 - With stationary broad band noise
 - With pseudo-random noise (eg. multi-length sequences)

IR Measurement



Source
(clap, balloon, gunshot,
loudspeaker, etc.)



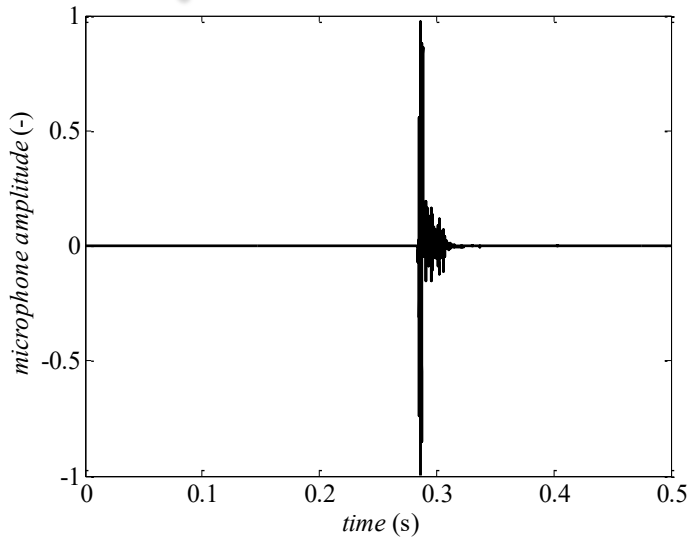
Recorder
(MP3/WAV recorder,
aptop, smartphone, etc.)



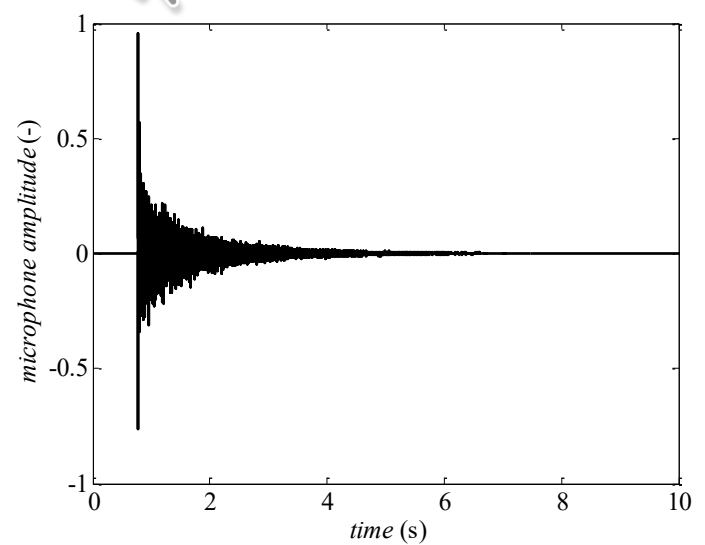
IR Measurement



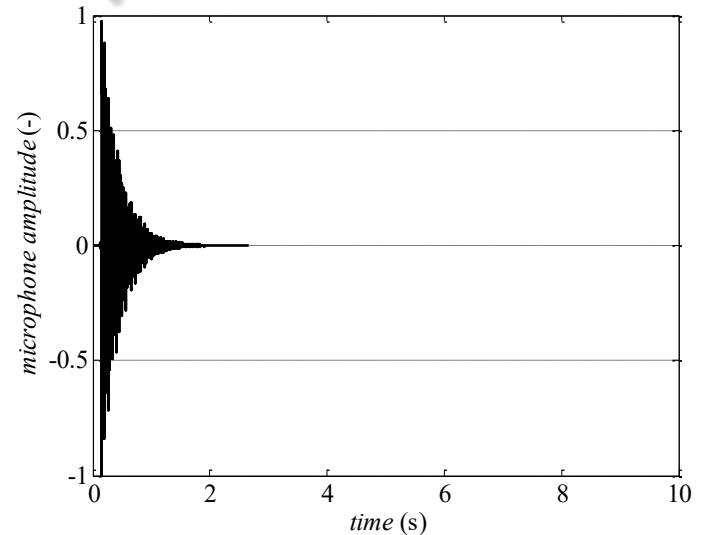
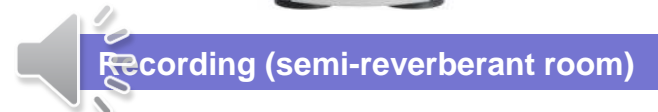
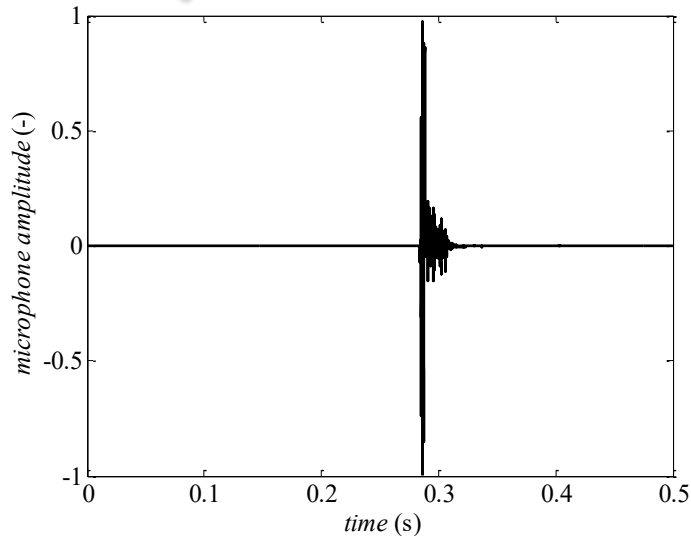
Recording (anechoic room)



Recording (reverberant room)

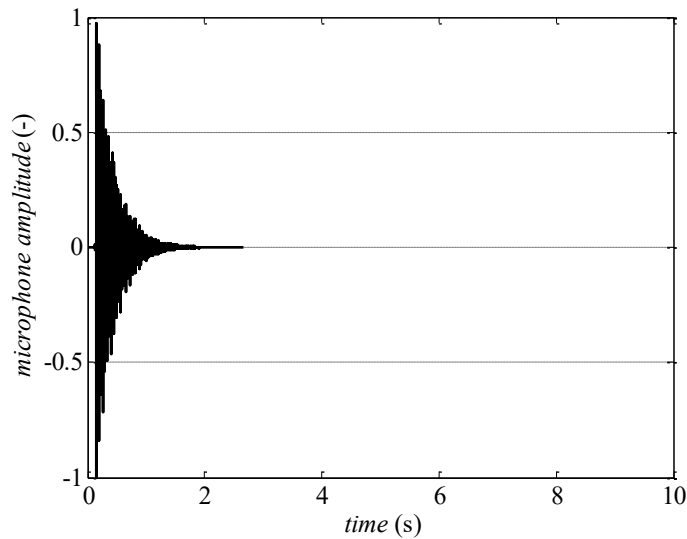


Reverberation time - measurement

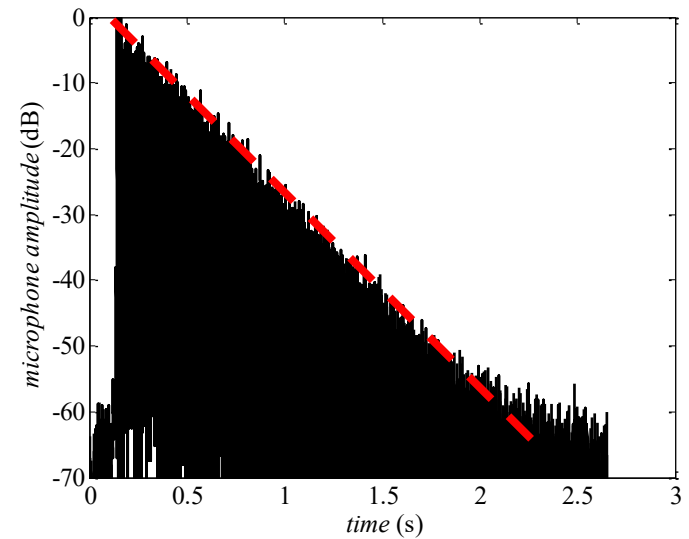


Reverberation time - processing

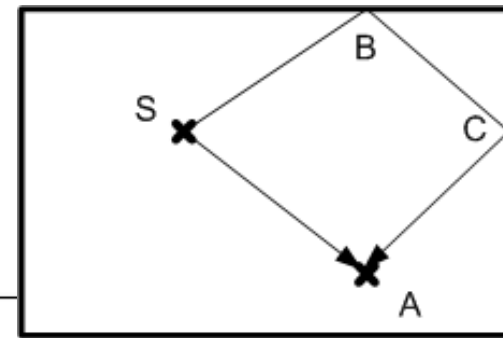
Recording (semi-reverberant room)



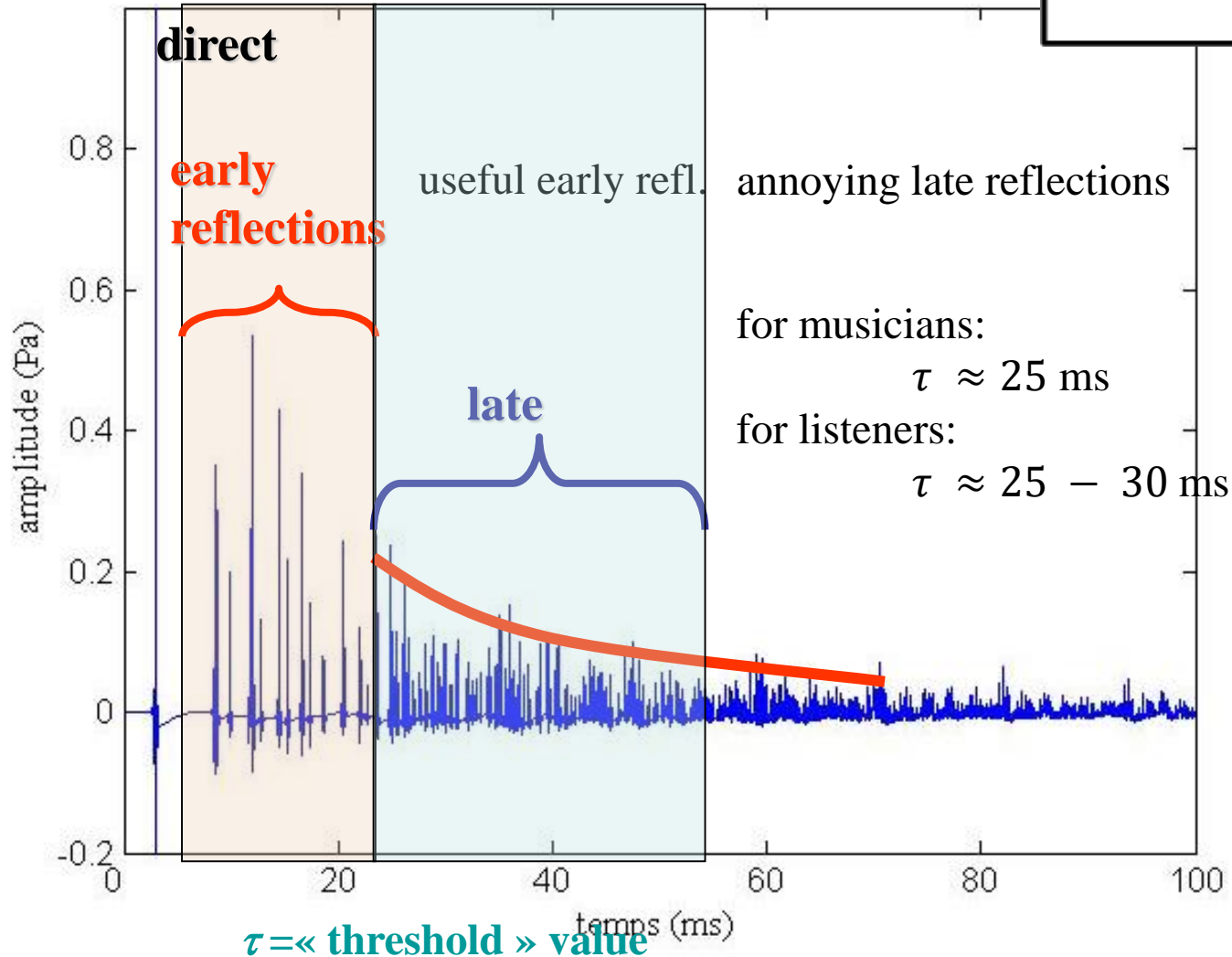
$20 * \log_{10}(|signal|)$
→
(dB)



Reflectogram



émission



Echogram

- impulse response
- arrival times depend on propagation times
- magnitudes of each event depend on geometrical damping, losses, absorption factor of walls



Direct sound



Direct sound + reflection



Direct sound + reverberation



Direct sound + reflections + reverberation

Reflections can have prejudicial effect on speech, music diffusion, etc.

→ Design rules preventing this?

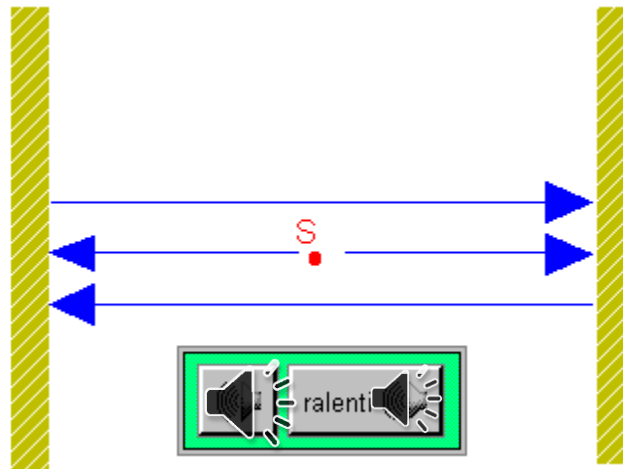
Temporal integration of the ear

- echo: dispersion $> \sim \frac{1}{15} \text{ s}$
→ $\Delta \text{trajectory} \approx 23 \text{ m}$

There is a high risk of straight echo when room dimensions exceed 11 m

Critical area: back of a hall

Flutter echo

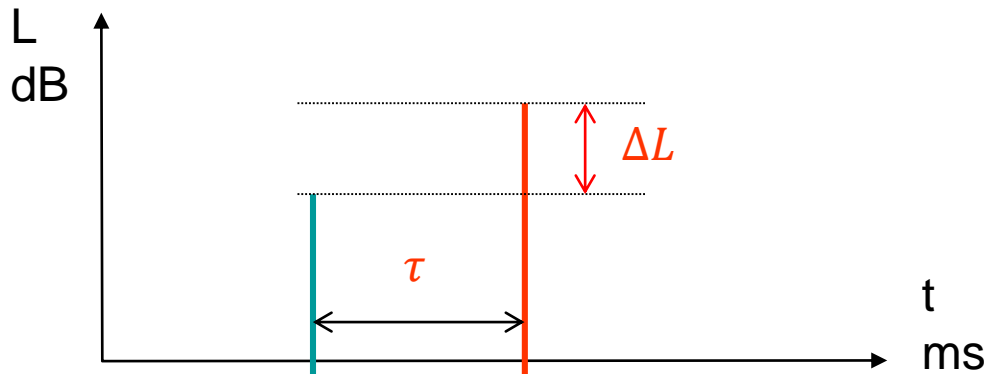


If the periodicity is large -> flutter echo
If the periodicity is small -> tonal echo («coloration»)

Localization

localization of a sound source is the one of the first direct, if the first indirect:

- arrives at least 10 ms later (no matter)
- is less than 10 dB louder



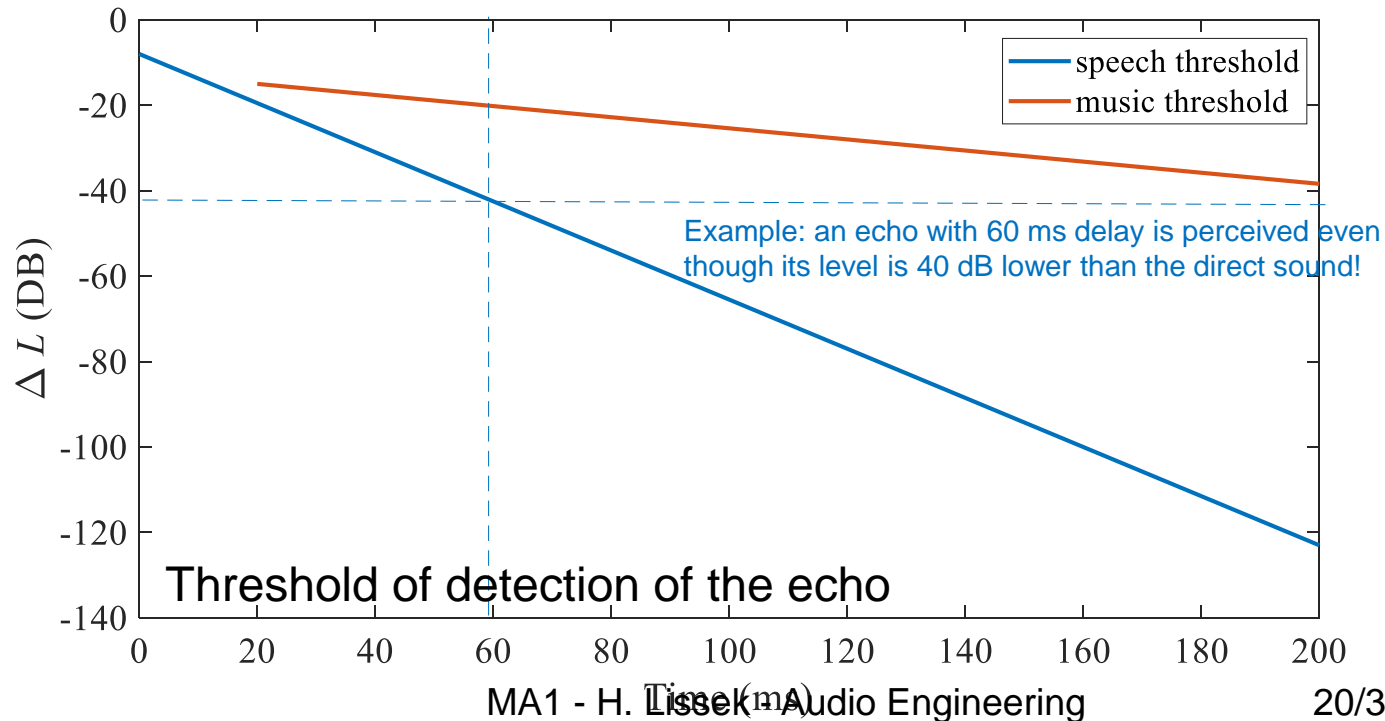
This also applies for a *dispatched sound reinforcement system*

- use of delays
- difficult to handle/control
- induce a limitation in the gain of the sound reinforcement system, before a Larsen effect occurs

Detection of echoes

- Single echo (frontal) : $\Delta L = 20 \cdot \log \frac{\tilde{p}_{echo}}{\tilde{p}_{direct}}$

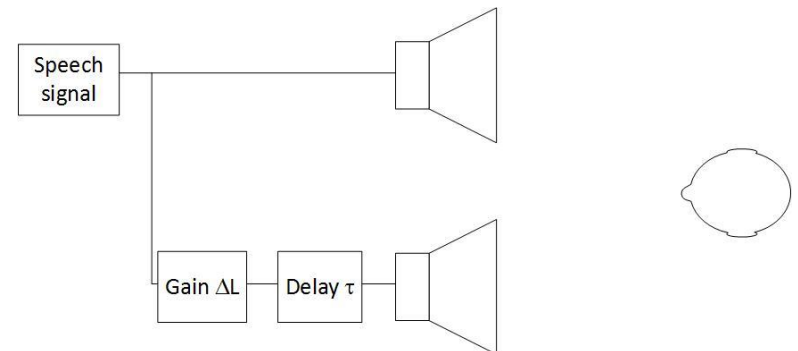
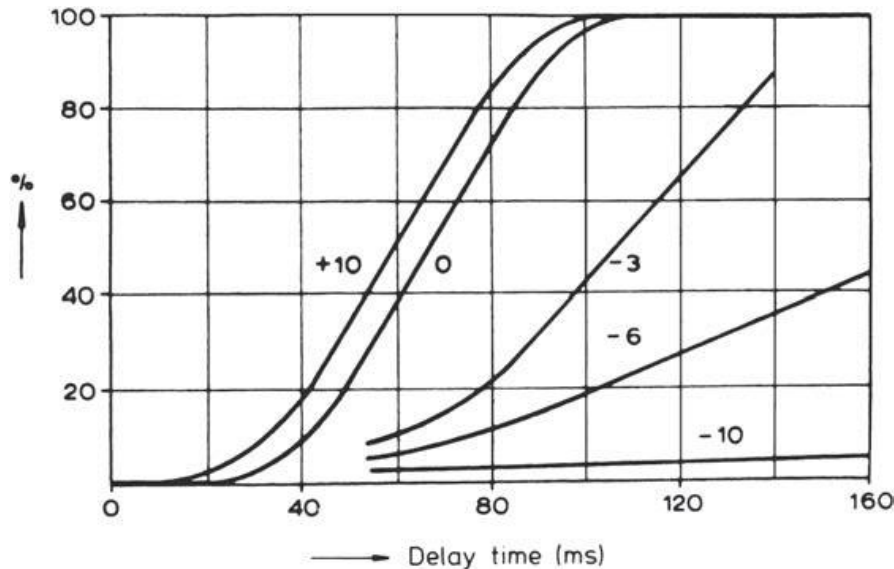
detection threshold (at 50 %) of reflections ($L_{pi}=70$ dB):
 for speech $\Delta L = -(8 + 0,575\tau)$ with τ in ms
 for music $\Delta L = -(15 + 0,13(\tau - 20))$



Perception (annoyance) of echoes

- Case of direct + frontal echoes

Echoes annoyance: Haas effect (for a single reflection, with speech)



5% listeners annoyed for $\Delta L = -10$ dB, until $\tau \sim 160$ ms
10% listeners annoyed for $\Delta L = 0$ dB, until $\tau \sim 40$ ms
10% listeners annoyed for $\Delta L = +10$ dB, until $\tau \sim 30$ ms

Dispersion of the 1st indirect

- $\tau > 60$ ms : echo
- $30 < \tau < 60$ ms : detrimental effect
- Beranek et al.:
 - Good rooms $20 < \tau < 35$ ms
 - Bad rooms $40 < \tau < 55$ ms

Favourable/detrimental effects of indirect sounds

- First to arrive are useful: τ from 30 to 50 ms
- Indices (defined after room impulse response $p(\tau)$):
 - « Definition index » (Thiele) = speech intelligibility

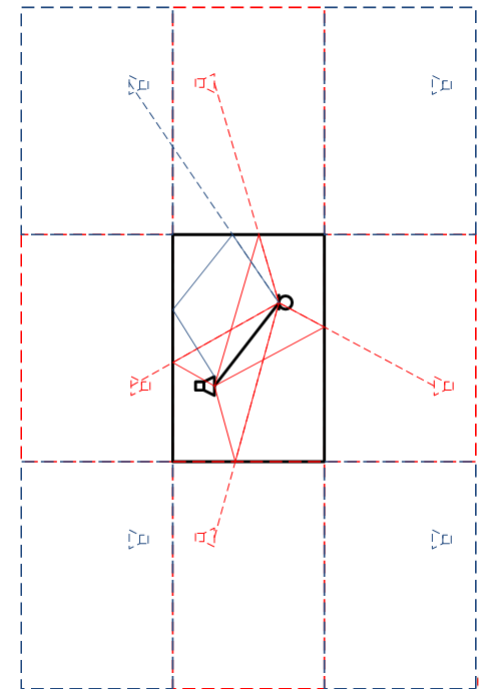
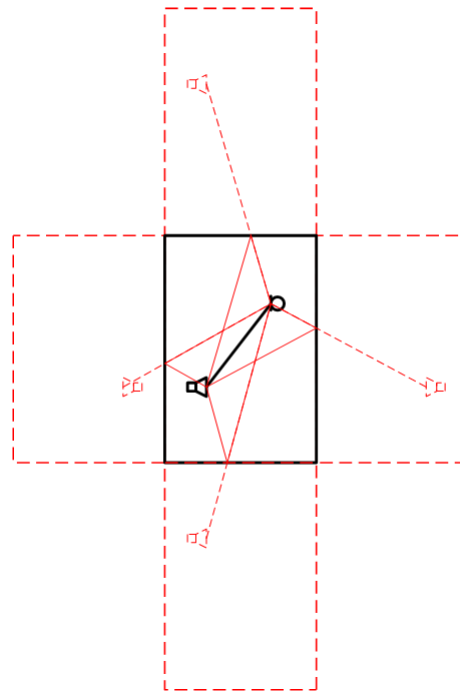
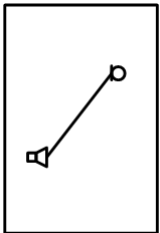
$$D = \frac{\text{energy from 0 to 50 ms}}{\text{total energy}} = \frac{\int_0^{50\text{ms}} p(t)^2 dt}{\int_0^{\infty} p(t)^2 dt}$$

- « Clarity index » (Alim) = music precision

$$C_{80} = \frac{\text{energy from 0 to 80 ms}}{\text{energy from 80 ms to } \infty} = \frac{\int_0^{80\text{ms}} p(t)^2 dt}{\int_{80\text{ms}}^{\infty} p(t)^2 dt}$$

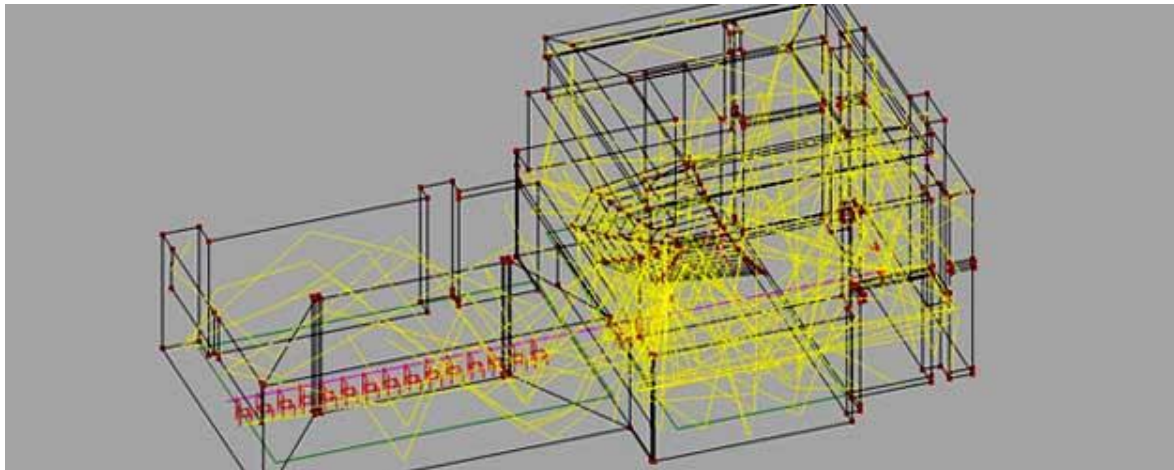
Applications

- Simple cases, preliminary draft: geometrical acoustics
 - handmade drawing (2D)
 - Computer assisted: ray tracing, image sources



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Applications

- Simple cases, preliminary draft: geometrical acoustics
 - handmade drawing (2D)
 - Computer assisted: ray tracing, image sources
 - Small scale models
 - Frequency domain translation → ultrasounds
 - limitations: absorption by air is higher at high frequencies than in the audio range

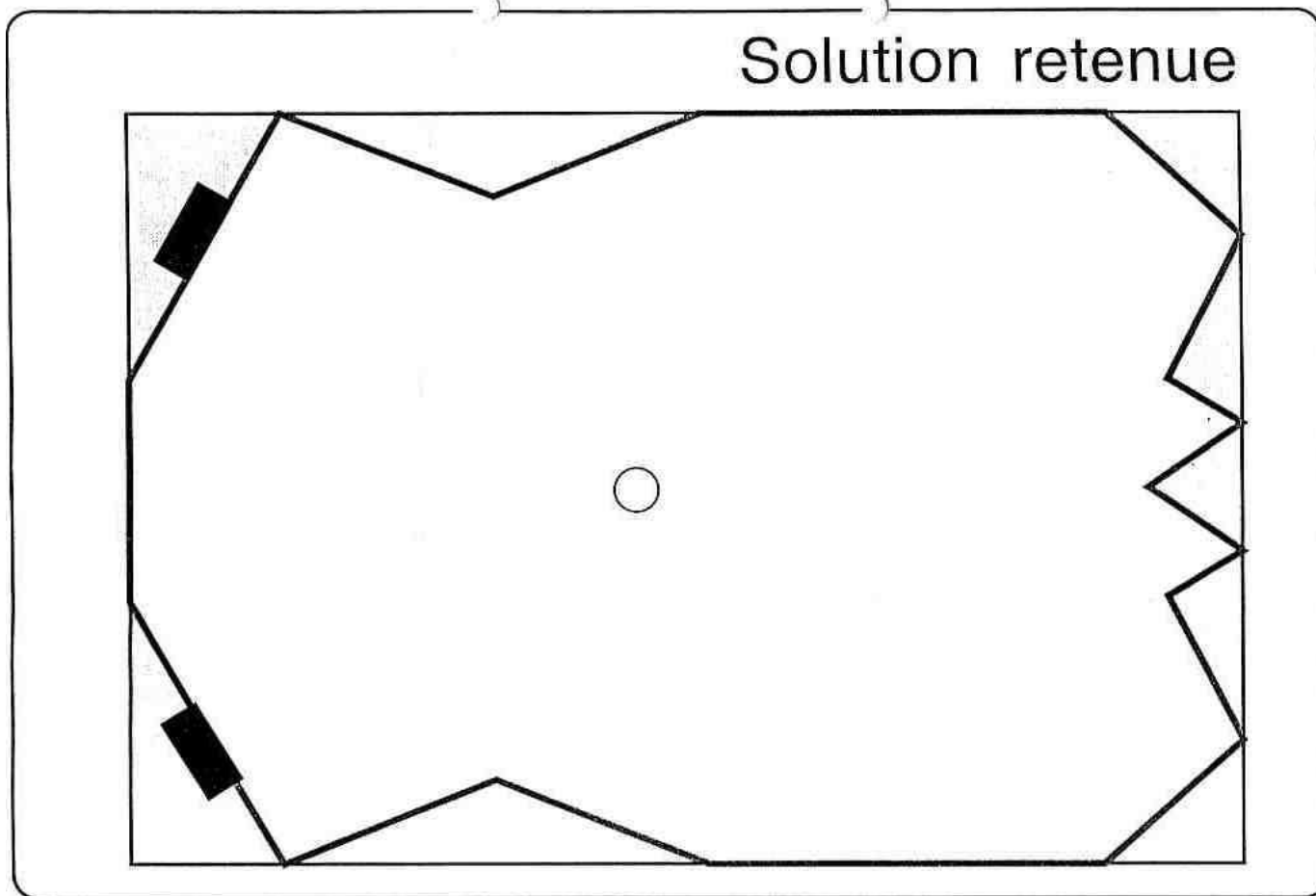
Geometrical acoustics criteria

- Room shape
 - create or favour useful indirect sounds (first ones)
 - incurvation/inclination of walls
 - reflecting covering
 - suppress detrimental indirects (late ones):
 - incurvation/inclination of walls,
 - absorbing covering,
 - diffusing covering (prevent specular reflections)

Geometrical acoustics criteria

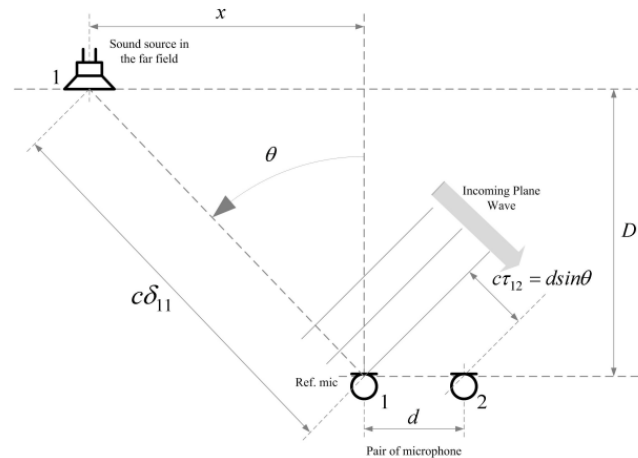
- Good spatial distribution of useful indirects:
 - prevent « deaf » areas (deficit of indirect)
 - prevent focal points (excess of indirect)
- Prevent flutter echoes=multiple reflections between 2 walls
- essential: dispersion of the 1st indirect determines the quality of the room:
 - Good $\tau = 10 - 25$ ms
 - Bad $\tau > 40$ ms

Example: Auditorium Stravinski



Example: Auditorium Stravinski

- Early lateral energy ratio
 - 2 microphones (omni & figure-of-8)
- Trend towards spatial analysis of echograms
 - (chrono-)goniometry



$$\tau_{12} = \frac{d}{c} \sin \theta,$$

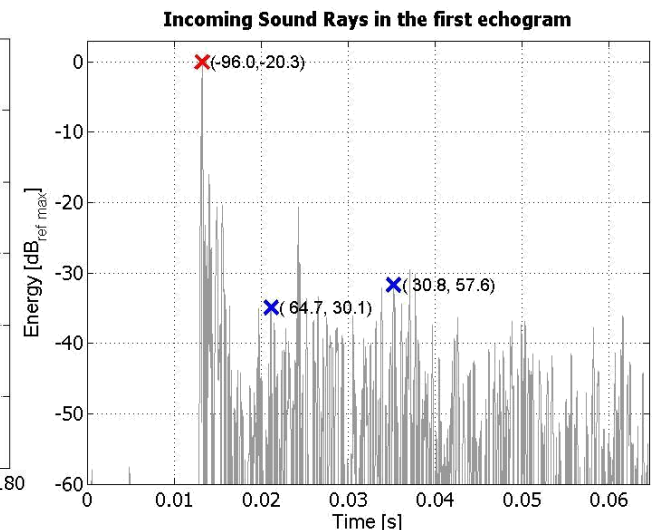
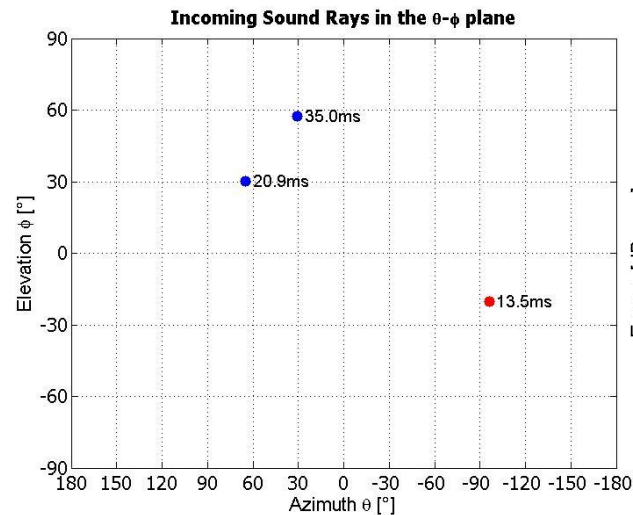
Can be estimated as

$$\hat{\tau}_{12} = \arg \max_{\tau} R(\tau).$$

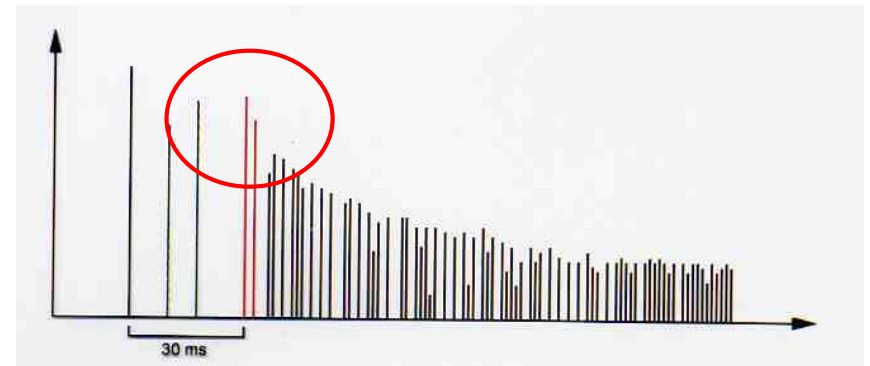
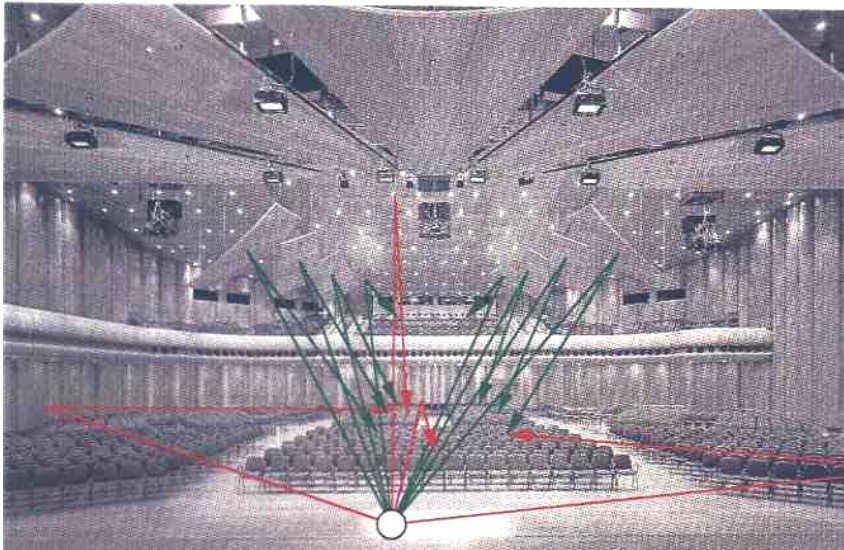
$$R(\tau) = \int_{-\infty}^{+\infty} Y_1(f) Y_2^*(f) e^{i2\pi f \tau} df$$

Example: Auditorium Stravinski

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Exemple: Auditorium Stravinski



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