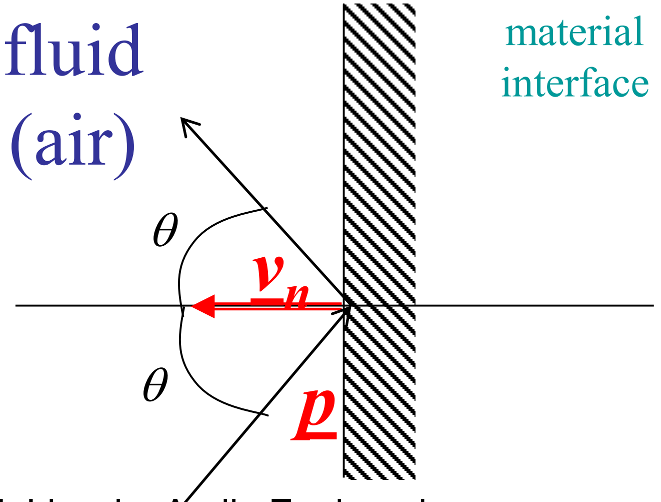
3.2 Geometrical Acoustics

Geometrical Acoustics

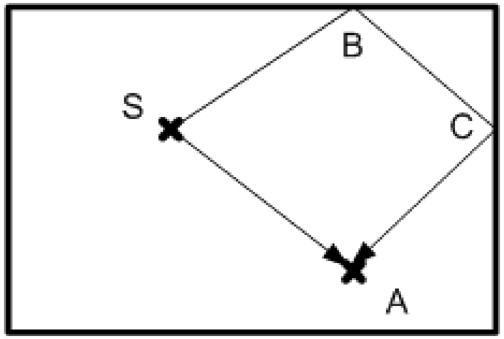
- We know the wave equation and its solutions (at least for simple room geometries)
- We can simplify the processing using sound rays instead
- Hypothesis: specular reflections according to Snell-Descartes's law



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



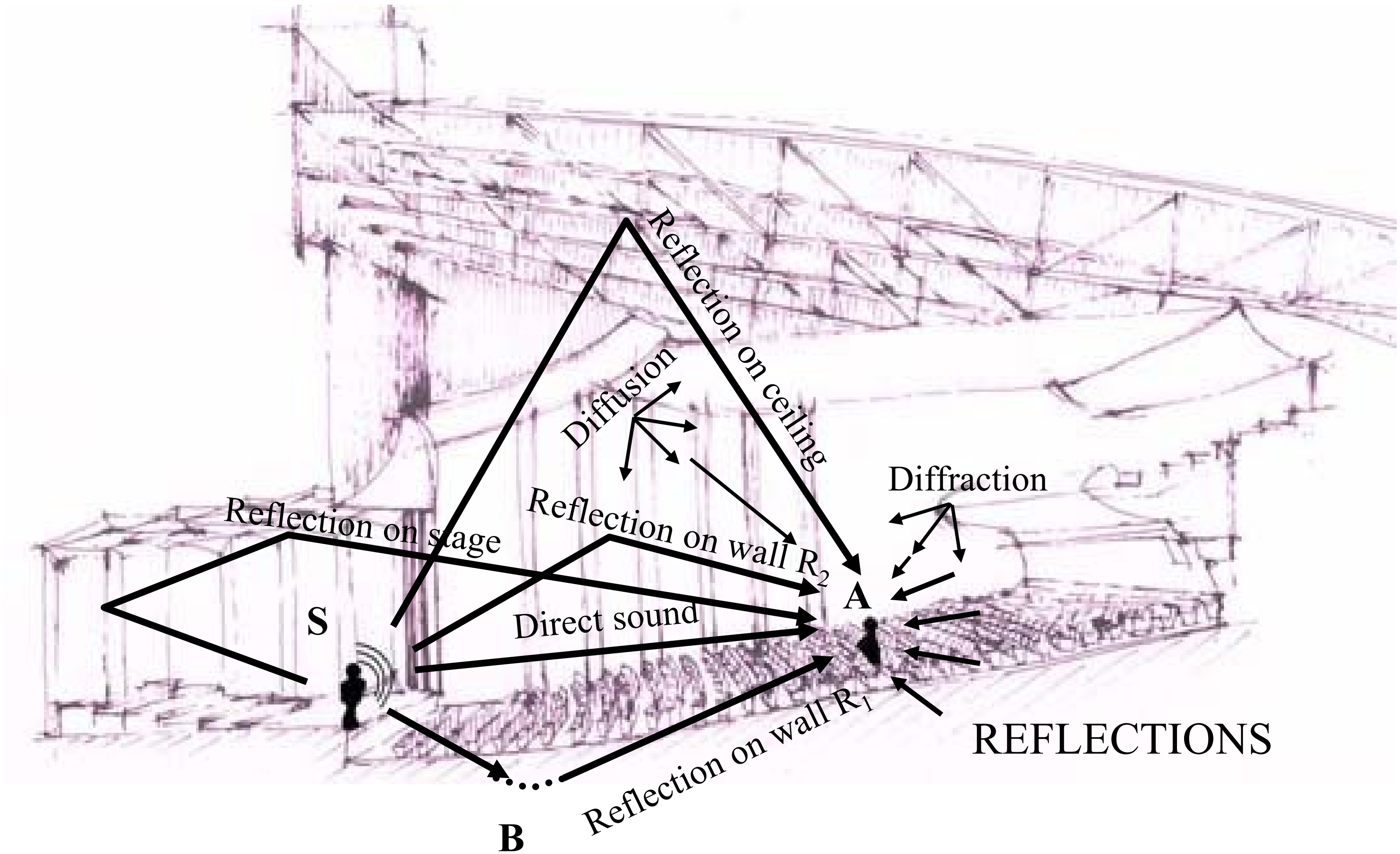
- Ray acoustics:
  - Principle:
    - to trace sound rays
    - Reflections on walls after Snell-Descartes (direction w/ refraction index)
    - variate S and A (S = stage/podium; A = audience)
    - Reflections on lateral walls/ceiling/ground
  - Goals:
    - define « good shapes », prevent bad ones
    - absorbing/reflecting treatment of walls

Geometrical Acoustics



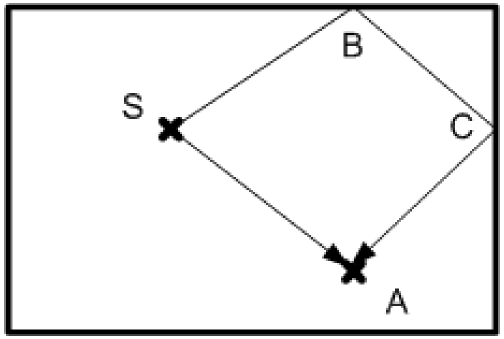


Principle


Reflection on ceiling
Diffusion
Diffraction
Reflection on stage
Reflection on wall R_2
A
S
Direct sound
Reflection on wall R_1
REFLECTIONS
B

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)

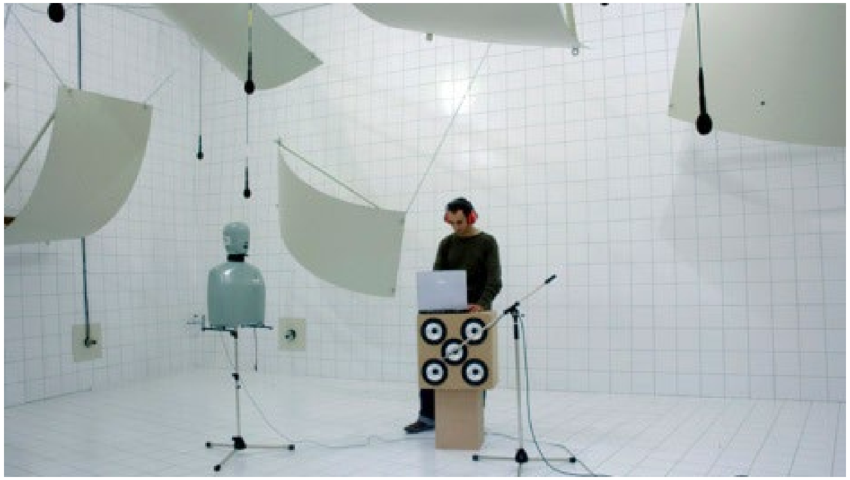
- For an order of magnitude:

$c = 340$ m/s: $\Delta l = 1$ m ➔ $\delta t \approx 3$ ms

$\Delta l = 10$ m ➔ $\delta t \approx 30$ 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.

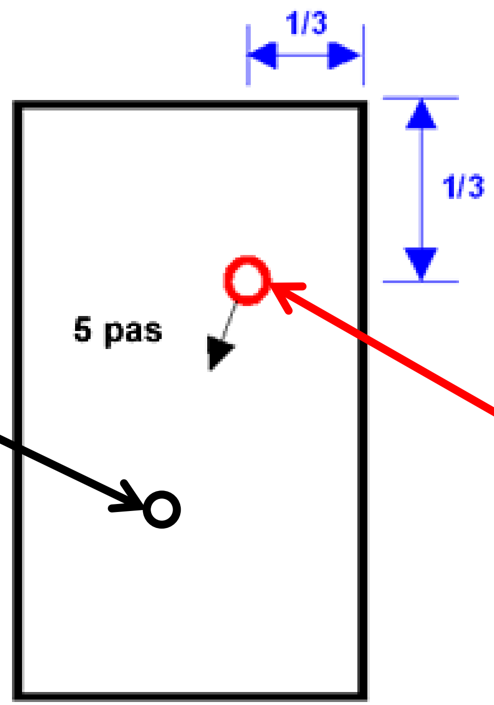
Reflectogram/Echogram

- Time series of reflection in a room
  - ➔ Impulse response (IR)

- Can be measured:
  - with an impulse sound (hand clap, balloon blast, etc.)
  - With stationnary broad band noise
  - With pseudo-random noise (eg. multi-length sequences)

IR Measurement

Empty/full room



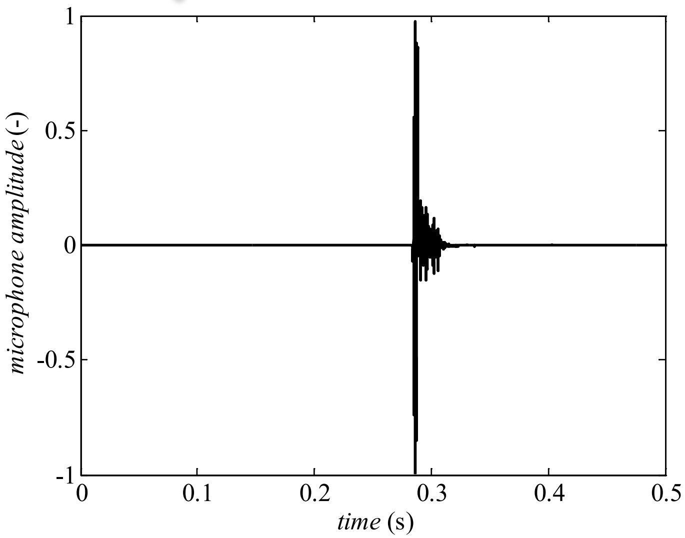
Source
(clap, balloon, gunshot, loudspeaker, etc.)

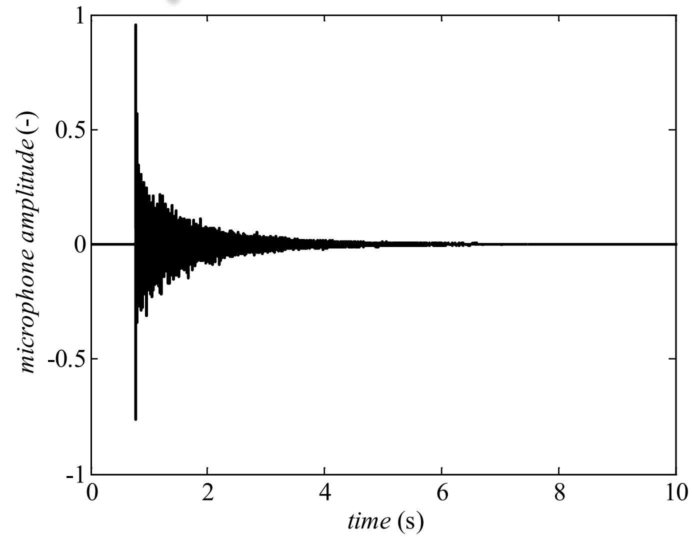
Recorder
(MP3/WAV recorder, laptop, smartphone, etc.)

IR Measurement

Recording (anechoic room)

Recording (reverberant room)

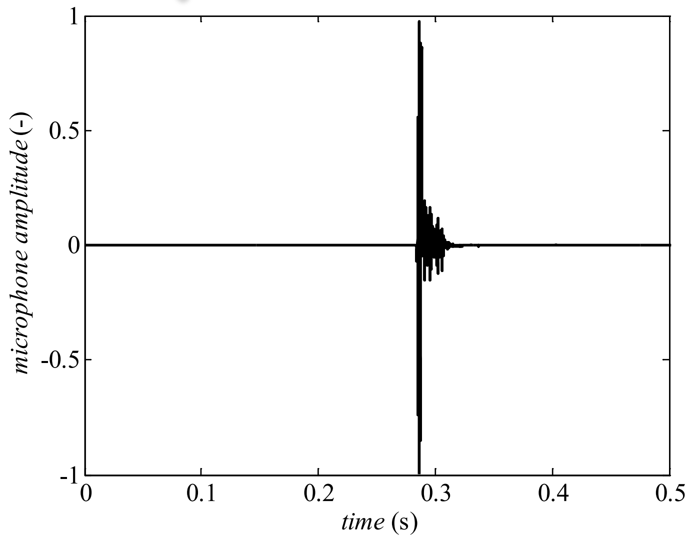


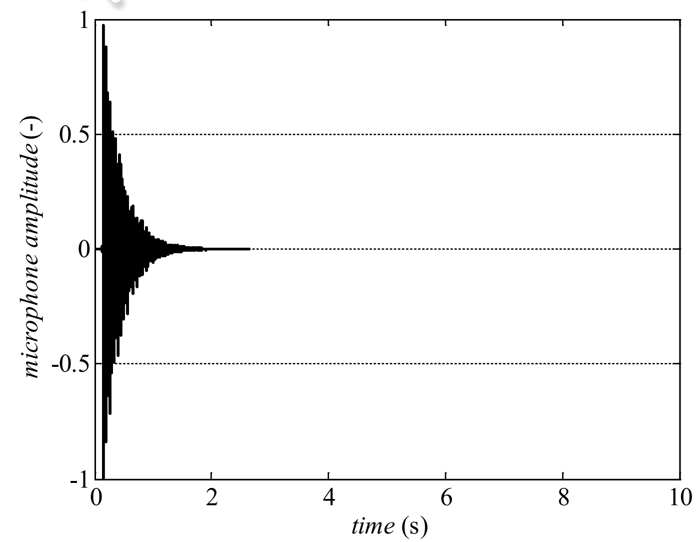


Reverberation time - measurement

Recording (anechoic room)

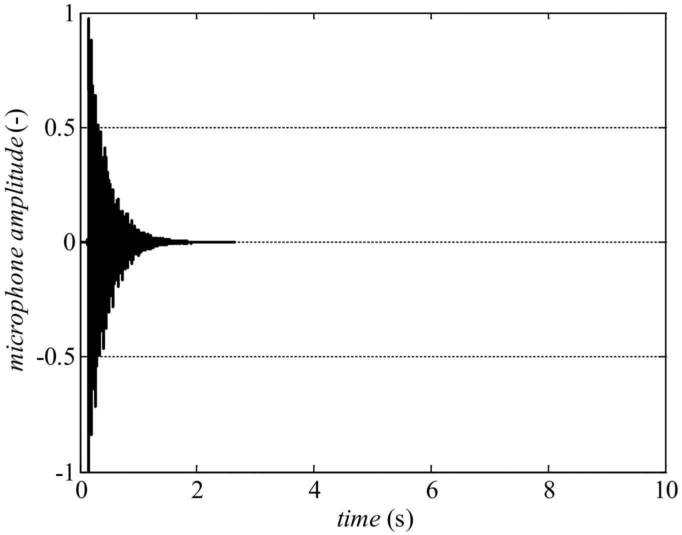
Recording (semi-reverberant room)





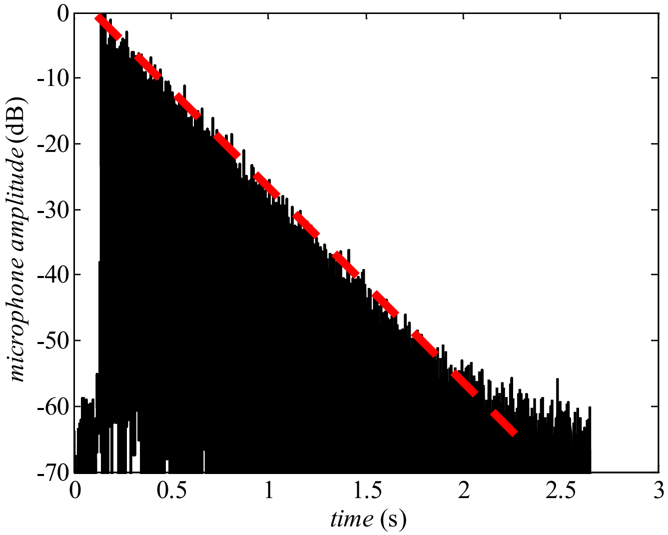
Reverberation time - processing

Recording (semi-reverberant room)

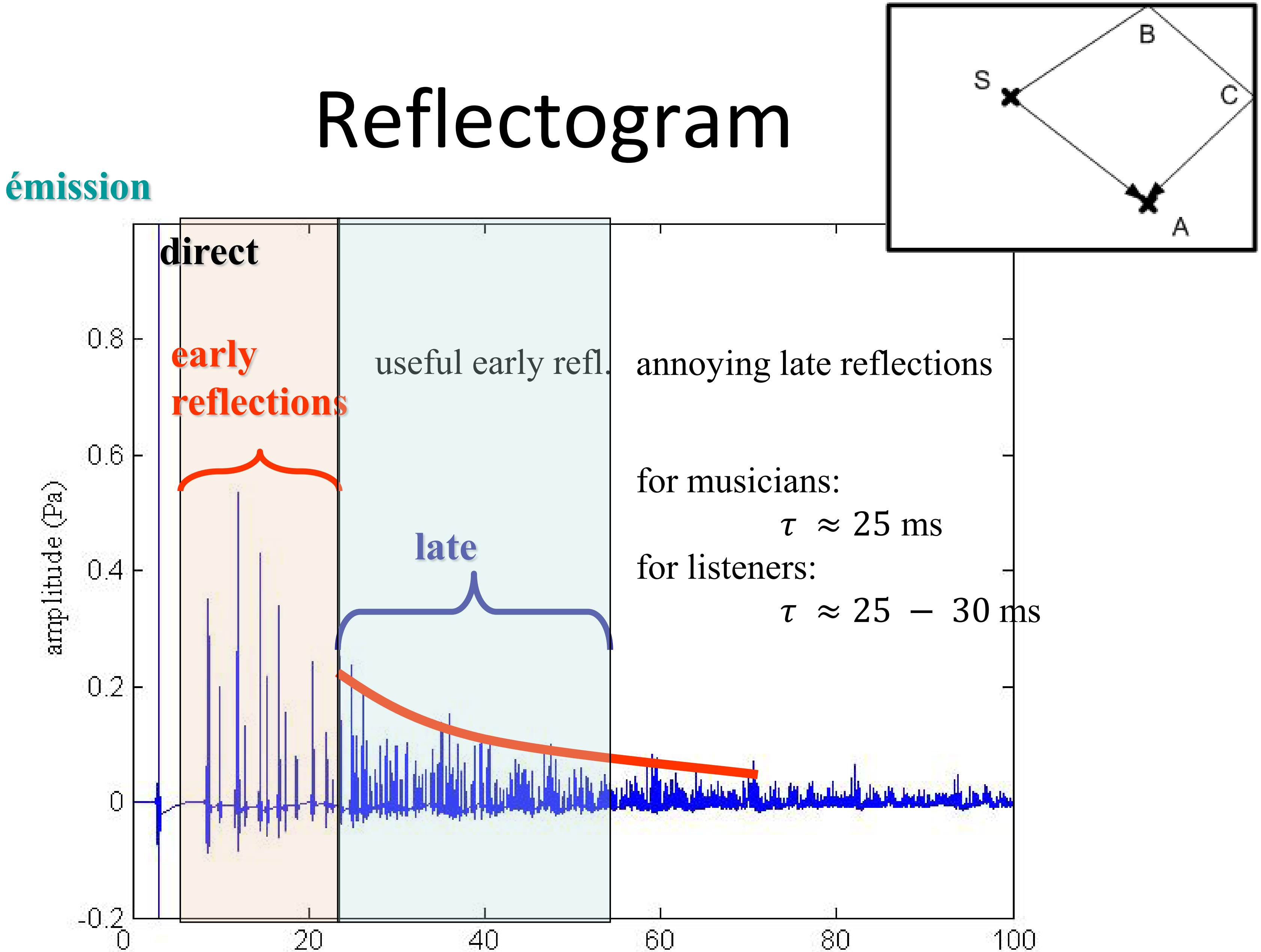


$$20 * log_{10}(|signal|)$$

(dB)



Reflectogram



τ =« threshold » value

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

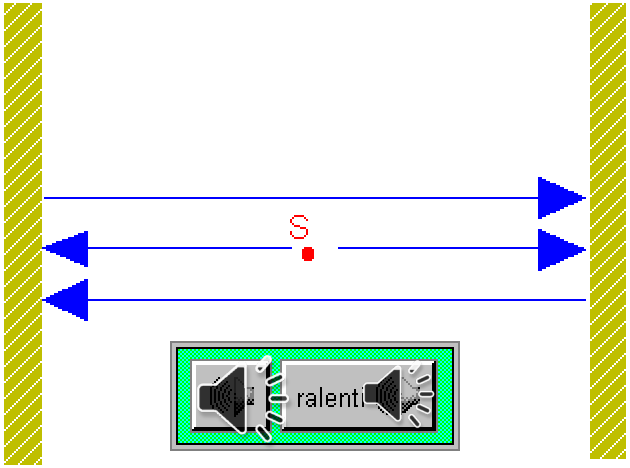
- echo: dispersion $> \sim\frac{1}{15}\,\mathrm{s}$

  ➔ $\Delta\text{trajectory} \approx 23\ \mathrm{m}$

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

Critical area: back of a hall

Flutter echo

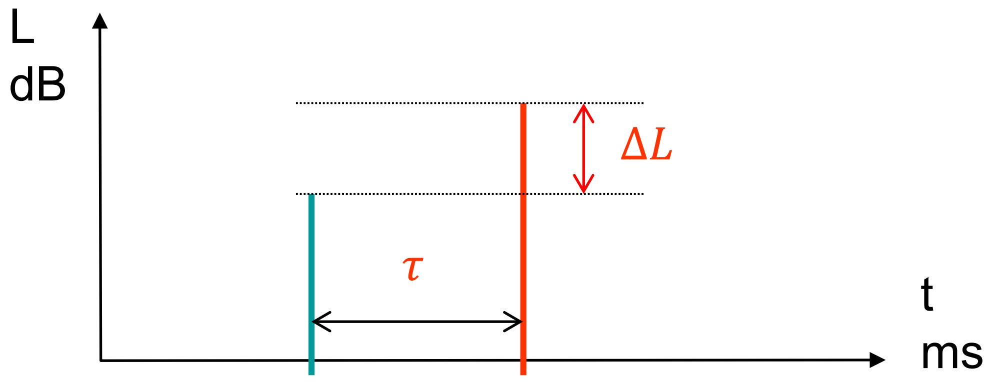


If the periodicity is large -> flutter echo
If the periodicity is small -> tonal echo («coloration»)

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

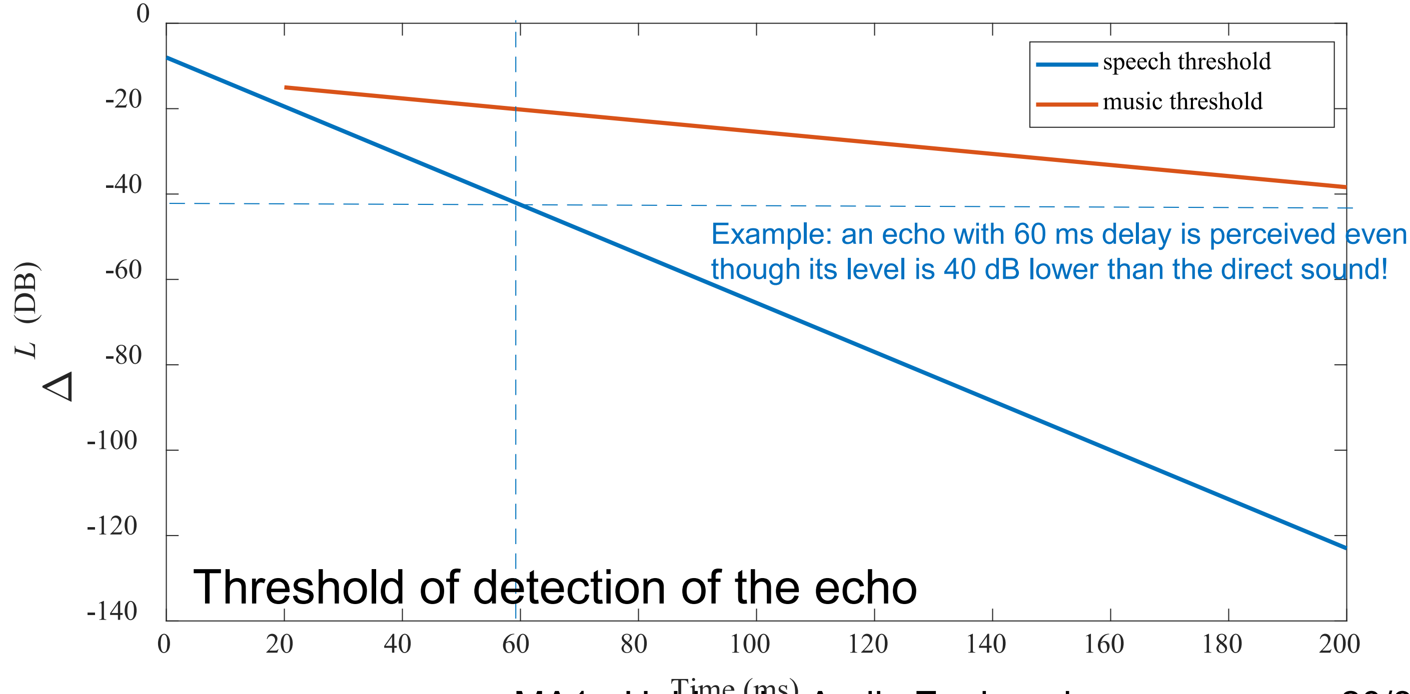
Detection of echoes

- 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 $\Delta L = -(15 + 0{,}13(\tau - 20))$

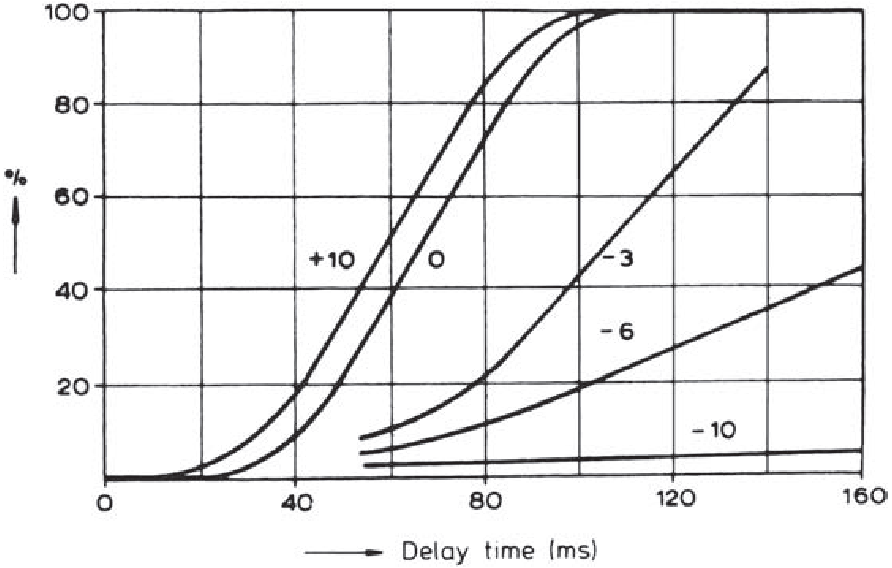


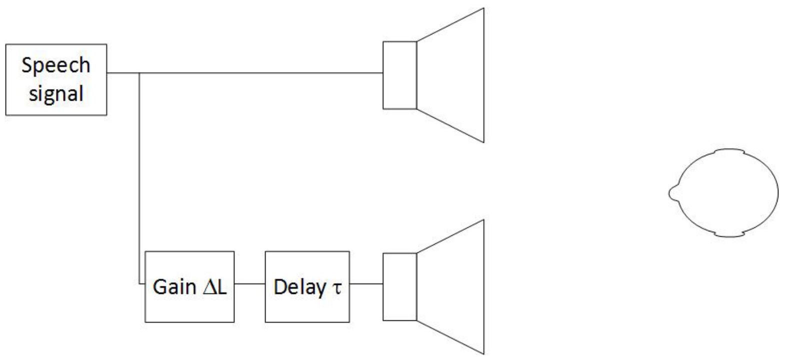
EPFL

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

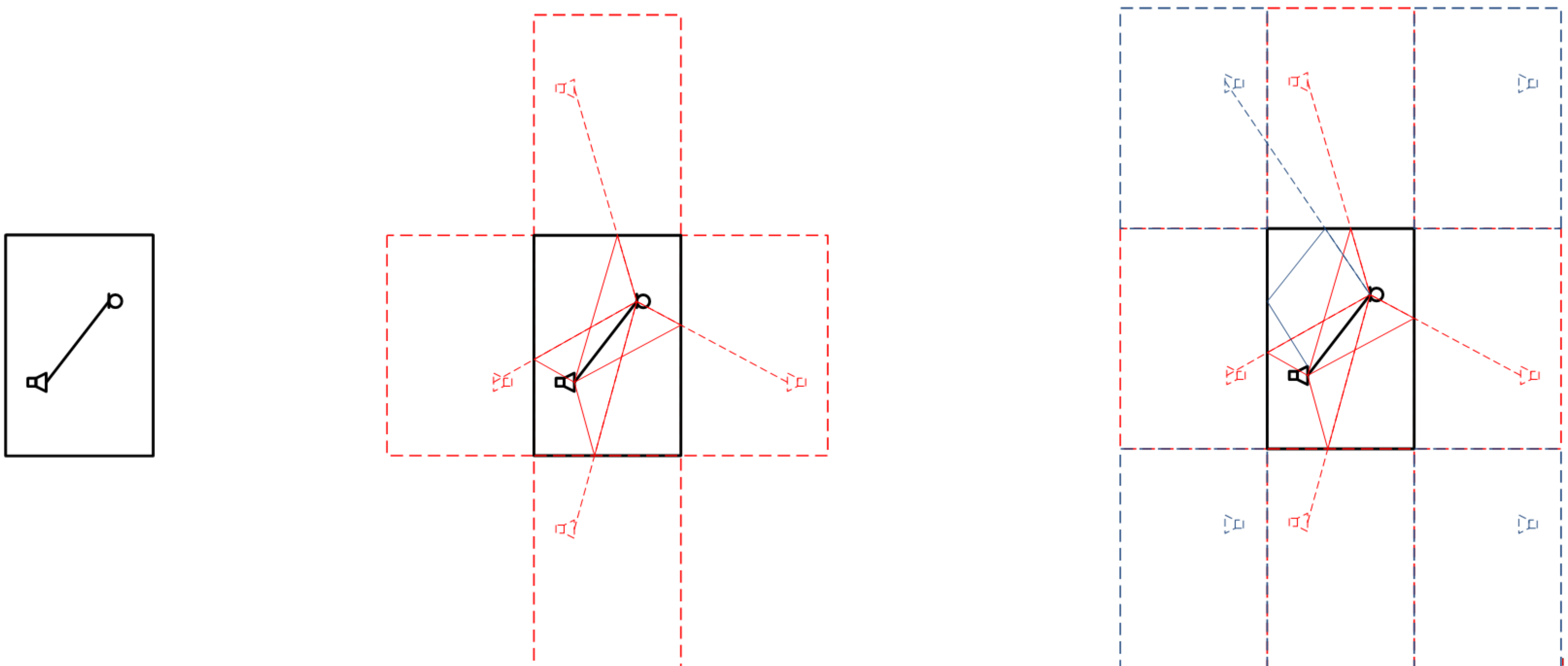
$$D = \frac{\text{energy from 0 to 50 ms}}{\text{total energy}} = \frac{\int_0^{50ms} p(t)^2\,dt}{\int_0^{\infty} p(t)^2\,dt}$$

  - « Clarity index » (Alim) = music precision

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

Applications

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



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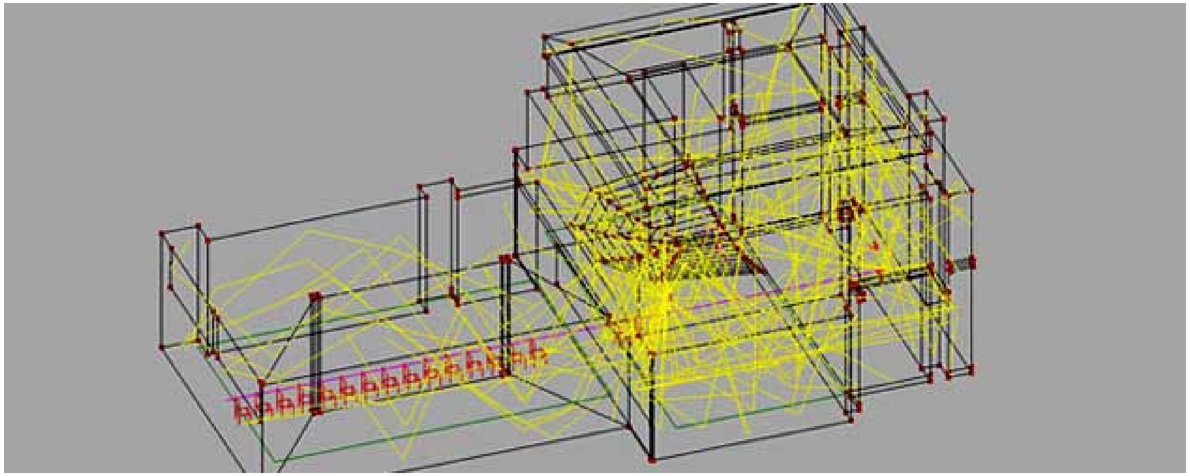


Applications

- Simples 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

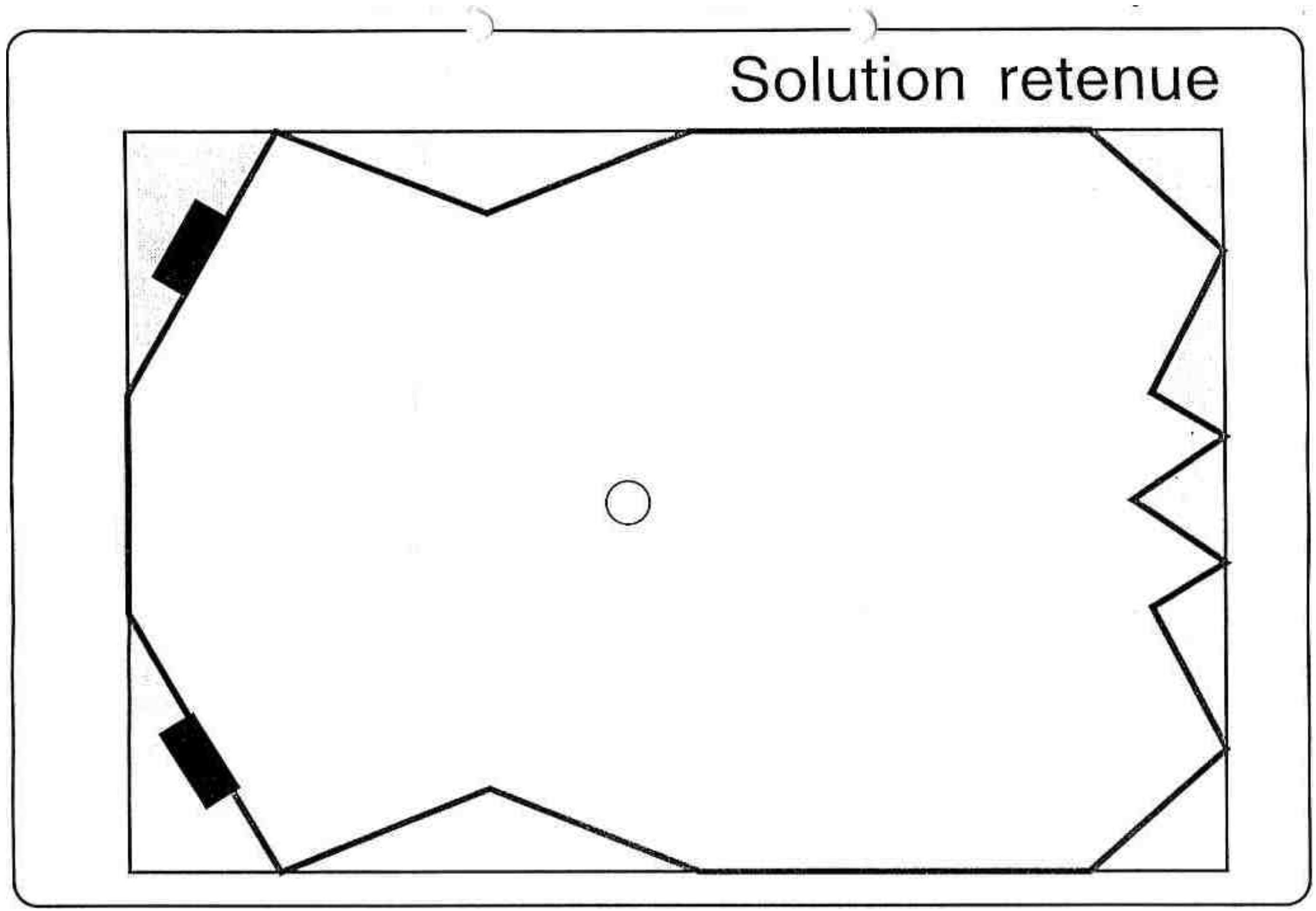
Geometrical acoustics criteria

- 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



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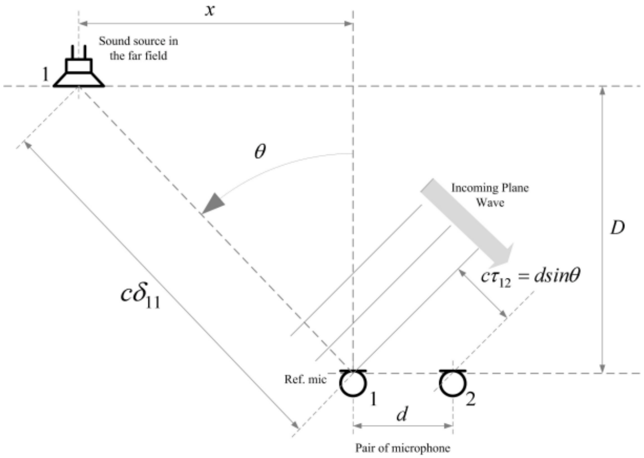
Example: Auditorium Stravinski

- 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

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

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

Example: Auditorium Stravinski

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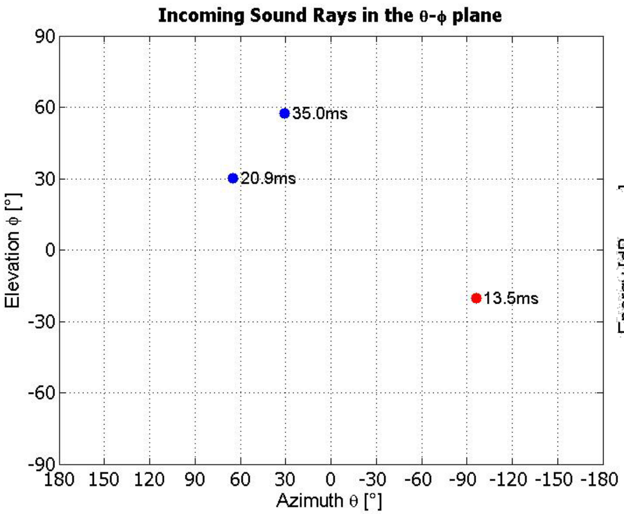

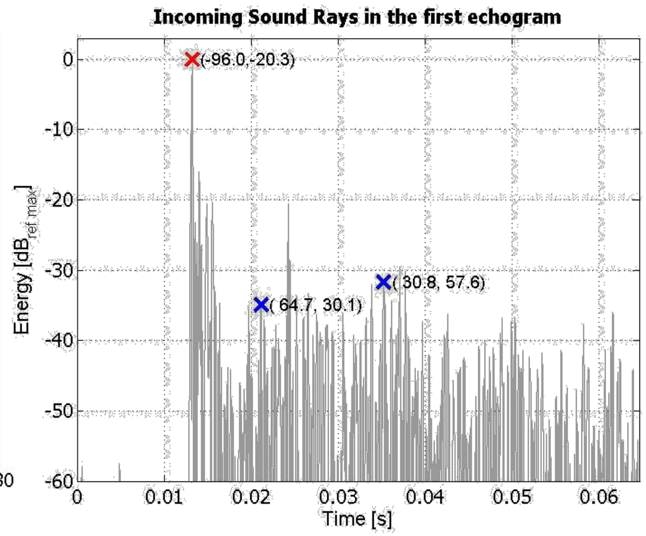

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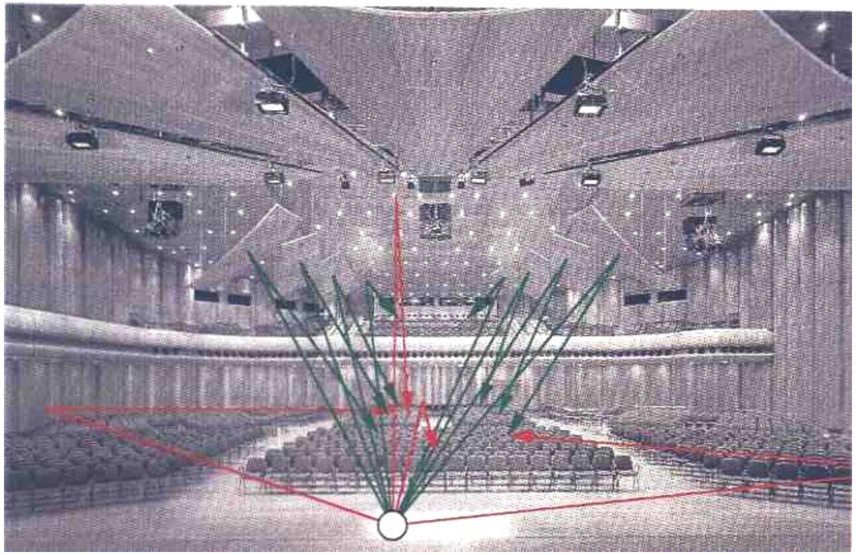
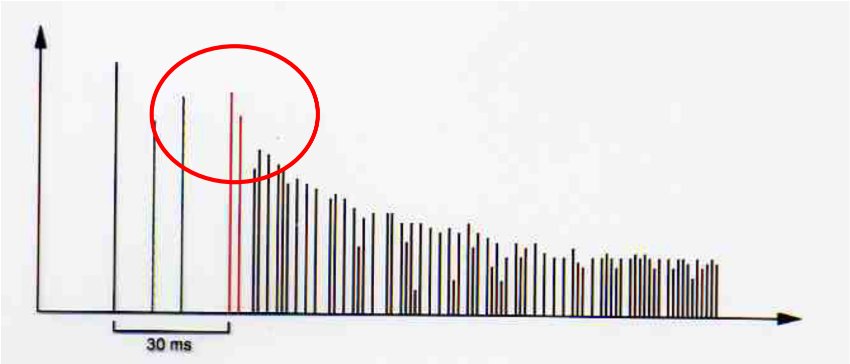
Exemple: Auditorium Stravinski





Exemple: Auditorium Stravinski