Acoustics II

Auralization: Propagation simulation

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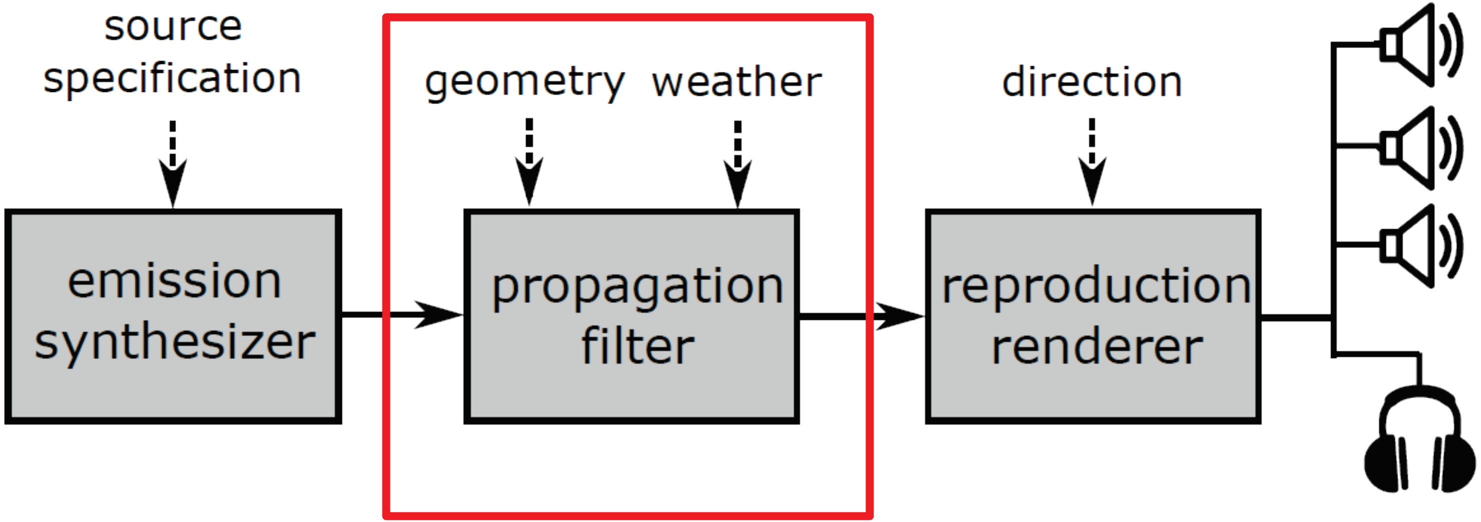
2024

Flexible auralization approach



Propagation simulation

Propagation simulation for fixed sources

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Applications: Evaluation and design of…

Object	Sound sources
Performance space like concert hall	Musical instruments
Radio/TV studio	Natural speaker
Electronic announcement system	Distributed loudspeakers
Open plan office	Many natural speakers + noise masking system
Vehicle interior	Engine, fans, loudspeakers,…

Principle: Requirements

- Propagation simulation should capture
  - Attenuation → correct absolute sound level, loudness
  - Spectral modification → coloration, timbre
  - Echos, reflection patterns, reverberation → spatial impression, diffusivity
  - Directional information → spatial impression, localization

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Principle: Characteristics

- Assumptions on sound propagation conditions
  - No non-linear distortions → Linearity
  - No movements of sources, receiver and objects + air at rest
→ Time-invariance
- Linear, time-invariant (LTI) system
  - Multiple sources: Receiver signal = sum of contributions from all sources

$$y_{\mathrm{tot}}(t) = \sum_i y_i(t)$$

  - Propagation description: input-output relation by impulse response

Principle: Characteristics

- Basic case: Point-to-point propagation with omni-directional source and omni-directional receiver

$$y(t) = (x * h)(t) \triangleq \int_{-\infty}^{\infty} x(t-\tau)h(\tau)d\tau$$
$$\approx \int_{0}^{T_h} x(t-\tau)h(\tau)d\tau$$

$y(t)$: sound pressure at receiver location
$x(t)$: dry source signal
$h(t)$: impulse response for propagation
T_h: truncation length
Operator $*$: linear convolution

Principle: Source and receiver directivity

- Usually of relevance:
  - Directional source, i.e. voice, loudspeaker, instrument
  - Directional receiver for spatial audio reproduction
- Relate source components to receiver components through multiple spatial impulse responses

$$\begin{bmatrix} y_1(t) \\ \vdots \\ y_M(t) \end{bmatrix} = \begin{bmatrix} h_{11}(t) & \cdots & h_{1N}(t) \\ \vdots & \ddots & \vdots \\ h_{M1}(t) & \cdots & h_{MN}(t) \end{bmatrix} * \begin{bmatrix} x_1(t) \\ \vdots \\ x_N(t) \end{bmatrix}$$

x: source component, e.g. spherical harmonics

y : receiver components, e.g. speaker channels or B-format

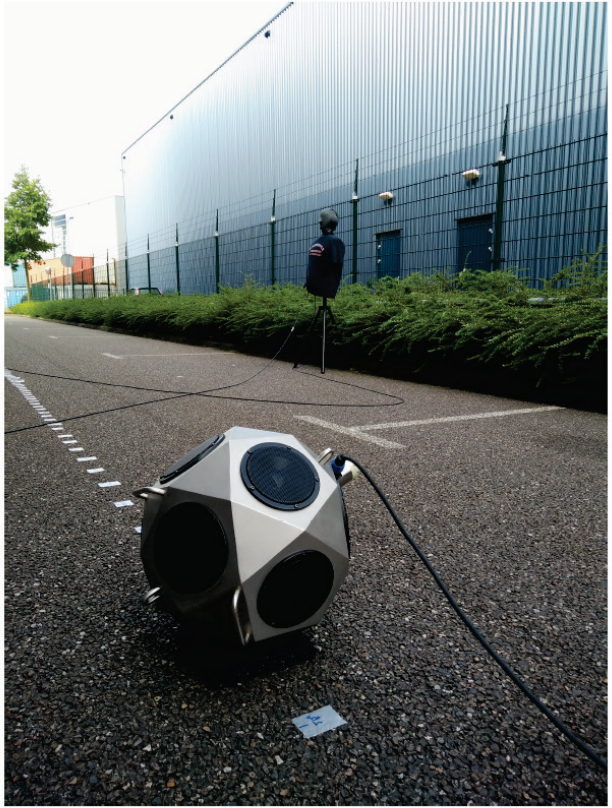
h: spatial impulse responses

Principle: Impulse responses

$$\begin{bmatrix} y_1(t) \\ \vdots \\ y_M(t) \end{bmatrix} = \begin{bmatrix} h_{11}(t) & \cdots & h_{1N}(t) \\ \vdots & \ddots & \vdots \\ h_{M1}(t) & \cdots & h_{MN}(t) \end{bmatrix} * \begin{bmatrix} x_1(t) \\ \vdots \\ x_N(t) \end{bmatrix}$$

- Where to get IRs from?
  1. Real world: In-situ measurements
  2. In the lab: Physical models
  3. From the computer: Computational models

In-situ measurements



- Impulse response measurements with
  - a controlled source
  - specific signals (MLS, sweep,...)
  - microphone arrays
- Source conditions
  - Compensation of speaker characteristics
  - Calibration of source
  - Consideration of source directivity

[Georgiou 2018. Modeling for auralization of urban environments: incorporation of directivity in sound propagation and analysis of a framework for auralizing a car pass-by. TU Eindhoven, PhD thesis.]

Physical models

Physical models (scale model measurements)

- Wave phenomena correctly reproduced, e.g. diffraction, reflection, interference
- Build model in scale 1:N, typical 1:10
  - Wavelength in model: λ/N
  - Frequency in model: fN → ultrasound
  - Use of frequency-matching materials
  - Specific loudspeakers and microphones
  - Difference in air absorption: Compensation of impulse responses necessary

Physical model: Elbphilarmonie Hamburg

Physical model: Copenhagen Concert Hall

Photos: Kurt Eggenschwiler

Physical model: Goetheanum Dornach

Bild: Zeitschrift «Das Goetheanum»

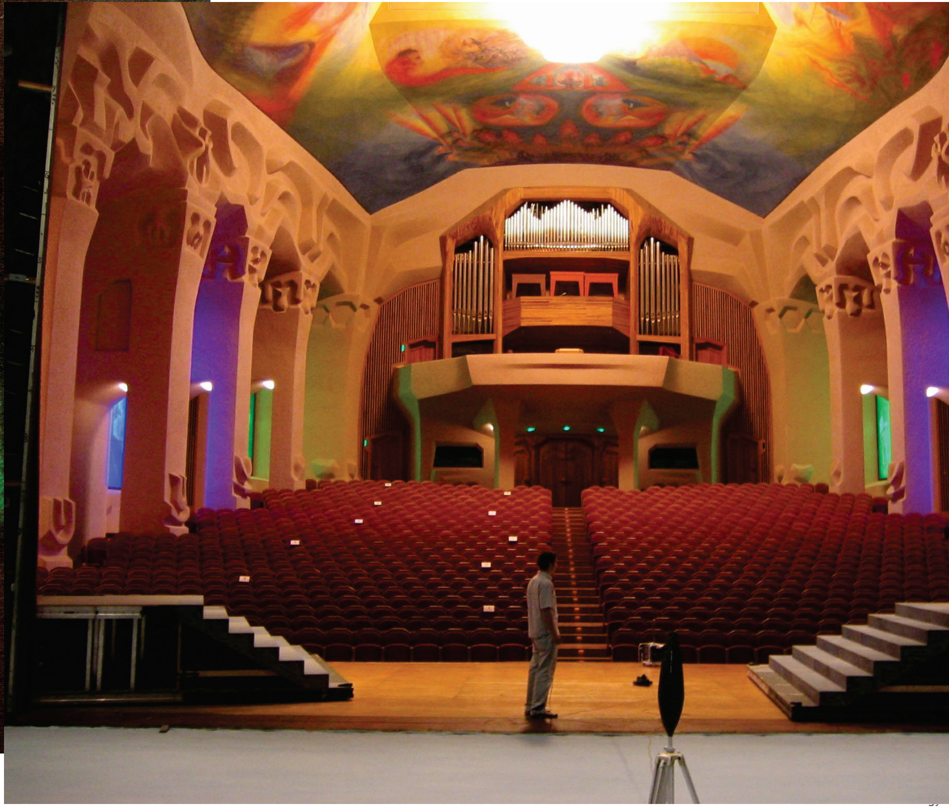
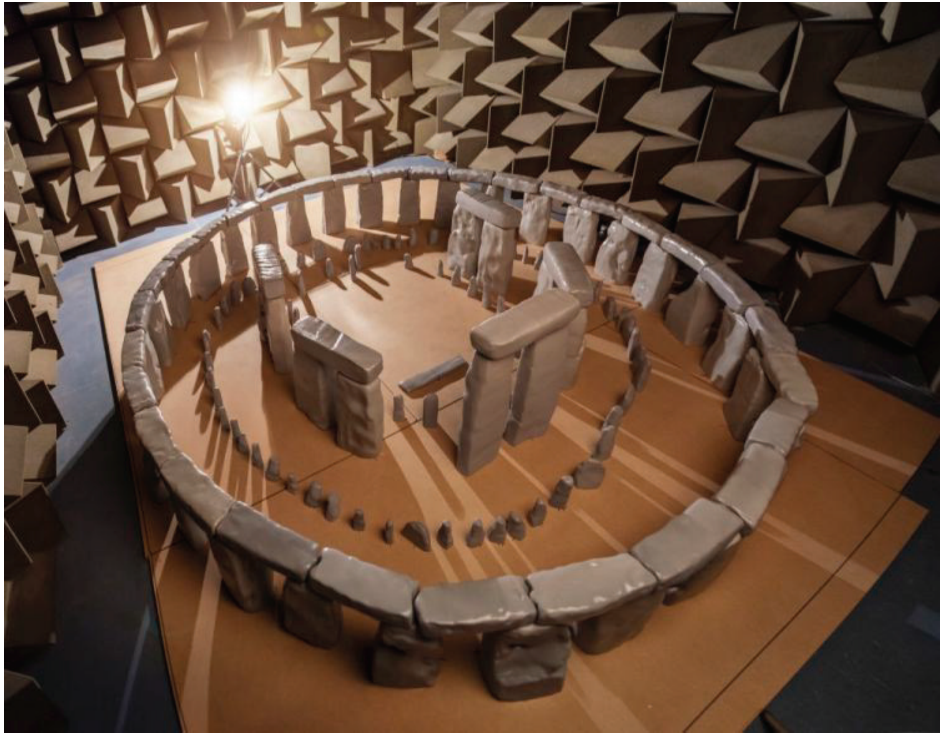
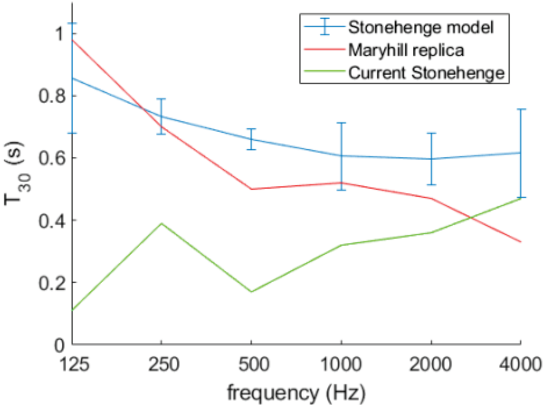


Photo in real room: Kurt Eggenschwiler

Physical models (scale model measurements)



- Stonehenge 1:12 model (Trevor Cox, 2020)
- 3d printed model inside anechoic chamber



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Computational models

Computational models

- Wave-based methods
  - Limit in upper frequency range
  - Ongoing research
- Geometrical acoustical models
  - Used in practice
  - High-frequency approximation
  - Types
    - Image models: mirror source
    - Ray tracing models
    - Hybrid models

[Savioja, L. & Svensson, U.P. 2015. Overview of geometrical room acoustic modeling techniques. *Journal of the Acoustical Society of America*, 138(2).]

Computational models: Hybrid geometrical models

- Combination of mirror source and raytracing
  - Mirror source: First, discrete reflections
  - Ray tracing: Diffuse sound/reverberation

- Commercial software available for room acoustics
  - ODEON, CATT-Acoustic,…

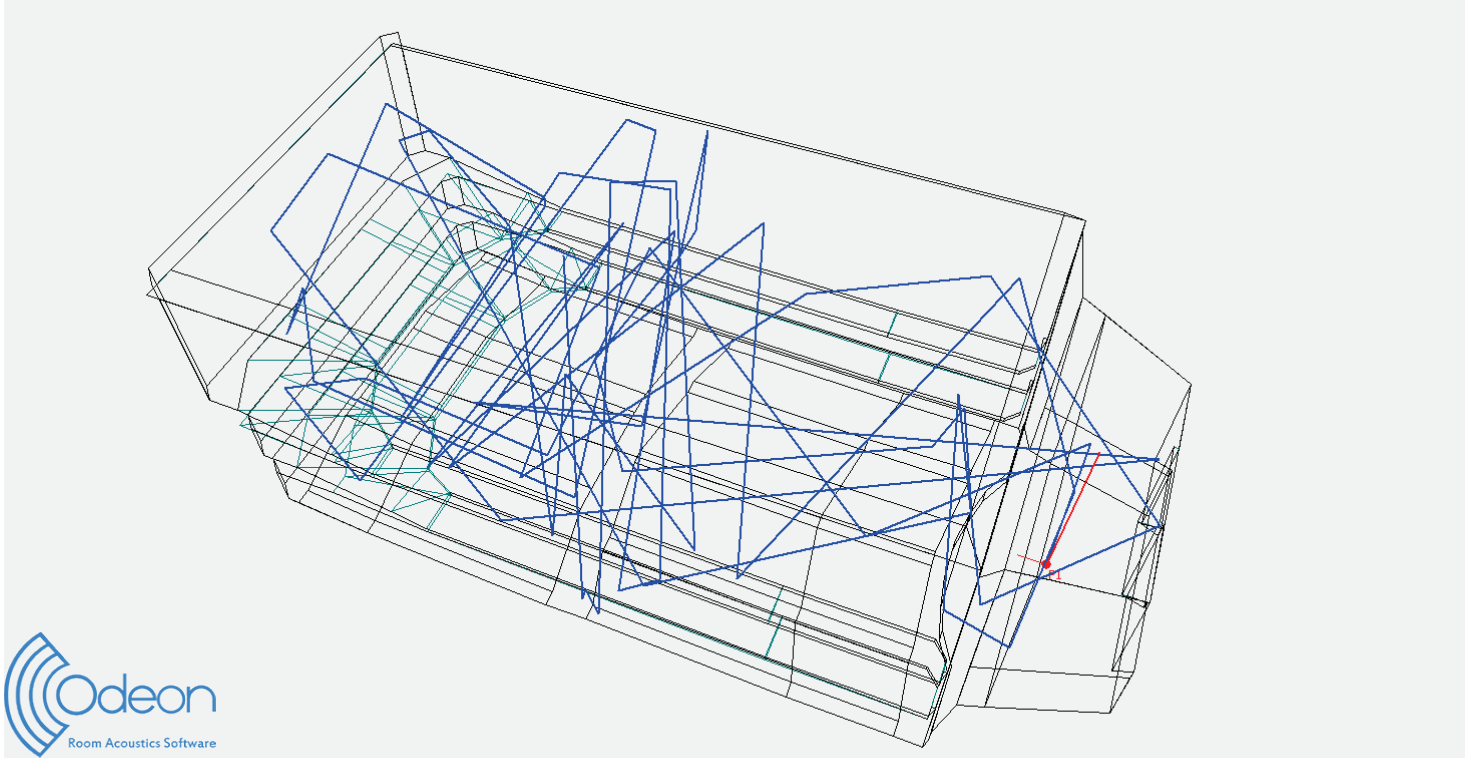
Computational models: Properties of hybrid geometrical models

- Consideration of directional
  - sources → spectral directivity
  - receivers → binaural or first-order Ambisonics

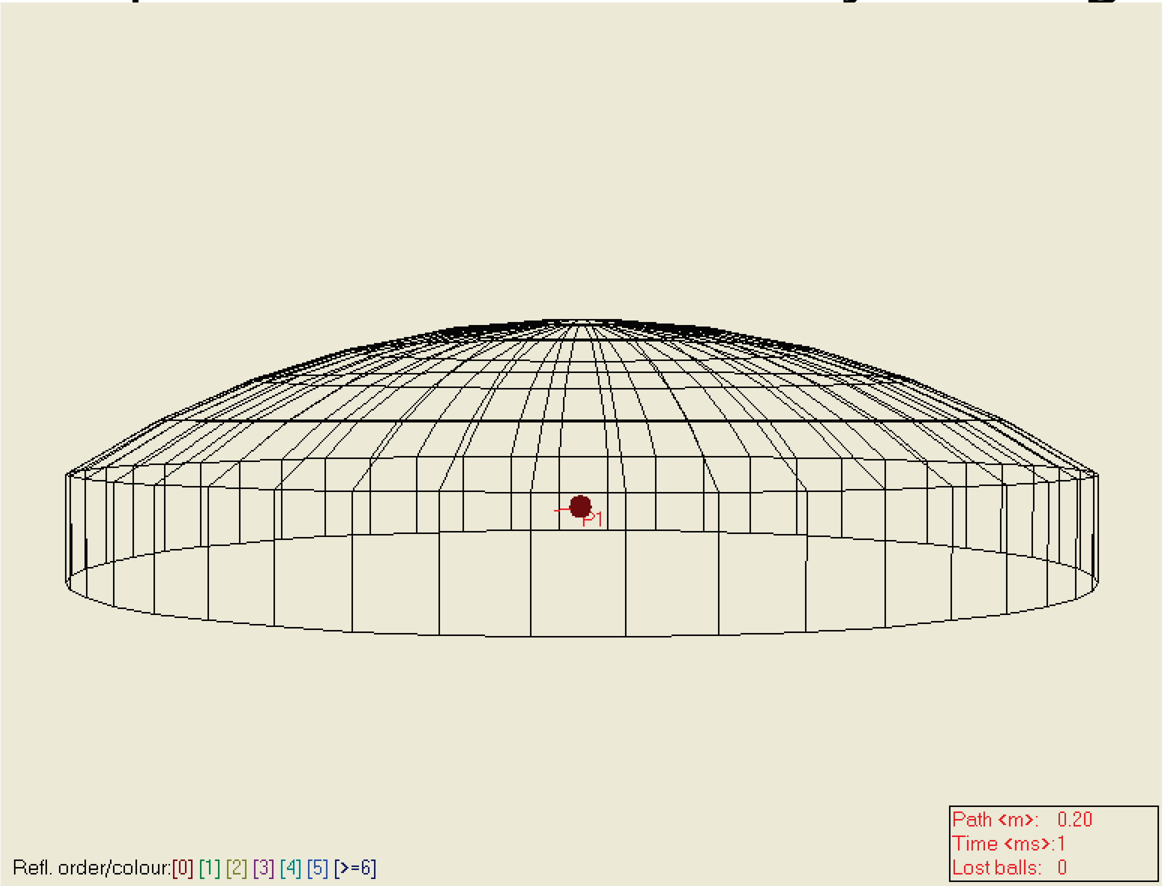
- Modelling reflections at surfaces
  - Energy loss: frequency-dependent, non-directional absorption coefficient
  - Scattering: using Lambert’s law and a scattering coefficient

- Calculation of energy impulse responses
  → conversion into pressure impulse responses

Computational models: Ray tracing



Computational models: Ray tracing



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Path <m>:   0.20
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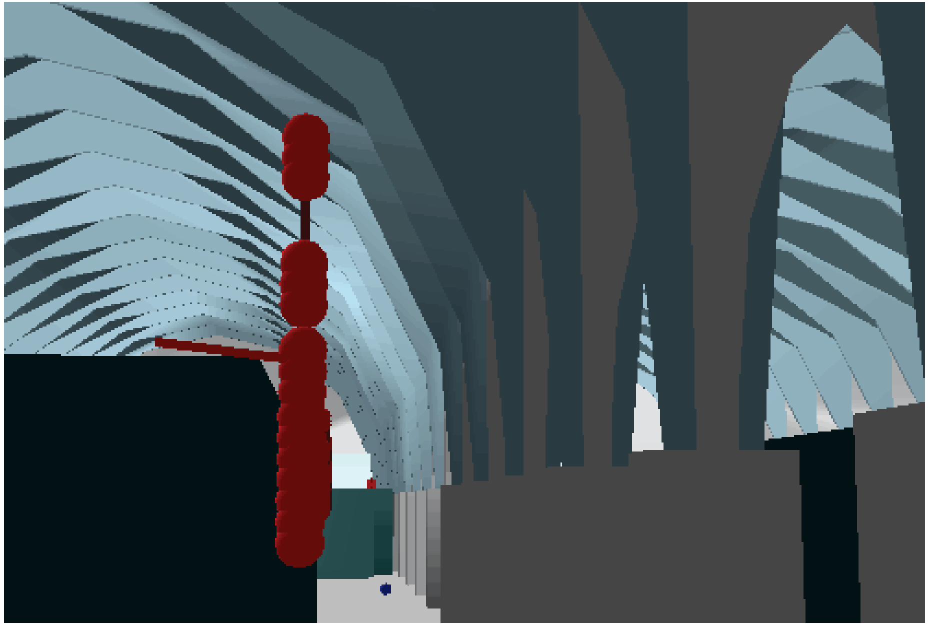
- Flutter echo and focussing from concave surface

ODEON example: Array loudspeakers in Copenhagen Central Station (RT=4s)



Near loudspeaker: 🔊

Remote loudspeaker: 🔊

Complete system: 🔊

https://odeon.dk/copenhagen-central-station/

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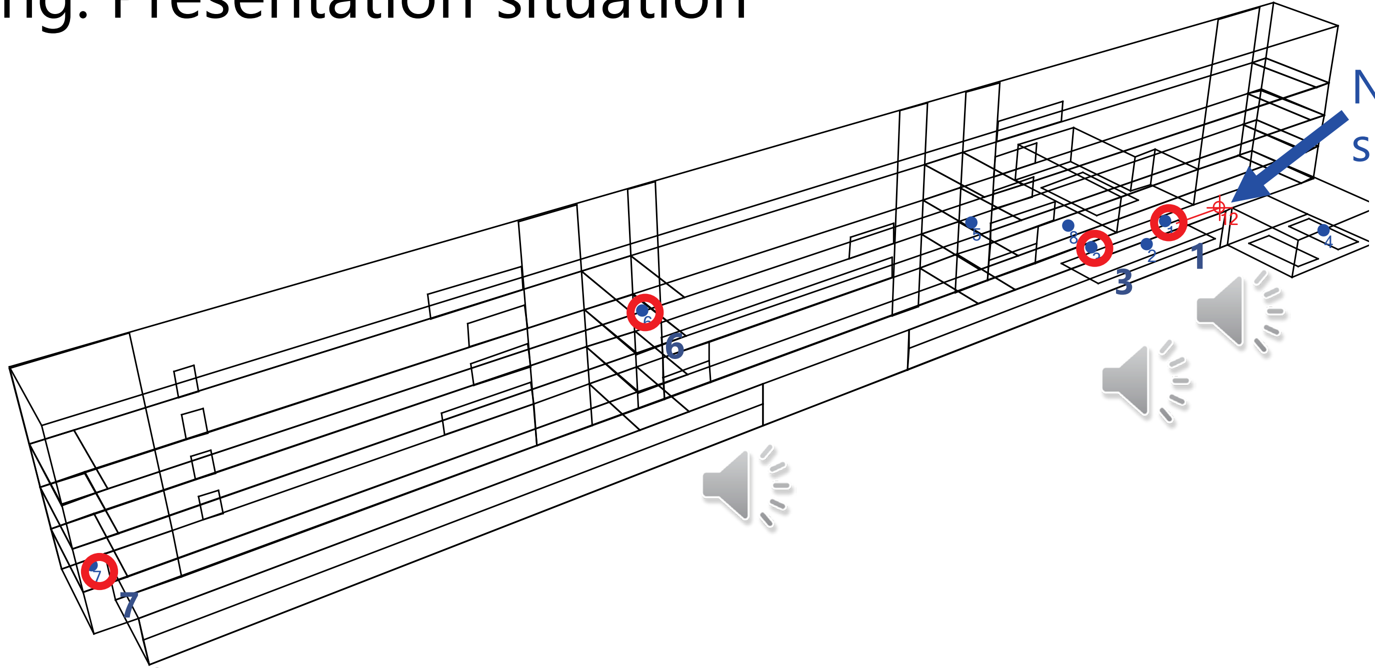
ODEON example: Long atrium in an office building: Presentation situation



Natural speaker

CD-KE-36 1,2,3,4

Propagation simulation for moving sources

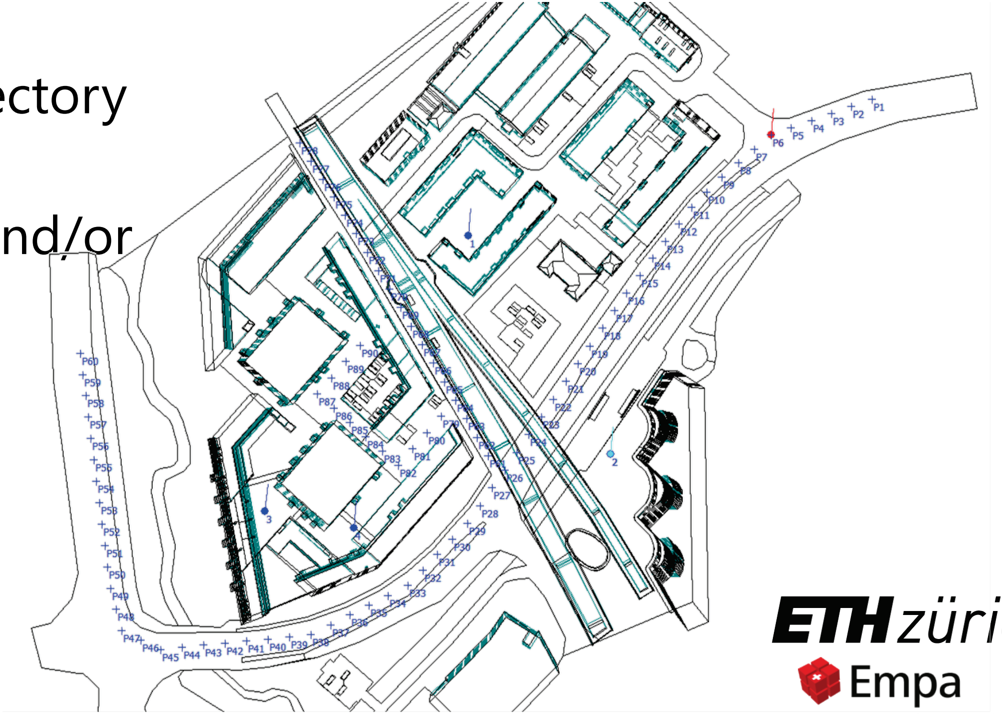
Moving sources

- Application: Traffic noise with outdoor propagation
- Sources: road and rail vehicles, aircraft
- Temporal changes:
  - Source radiation direction relative to receiver
  - Doppler effect
  - Propagation geometry changes over time
    → propagation effects vary with time (no LTI system)
    → time-variable processing of source signals

Interpolation of impulse responses

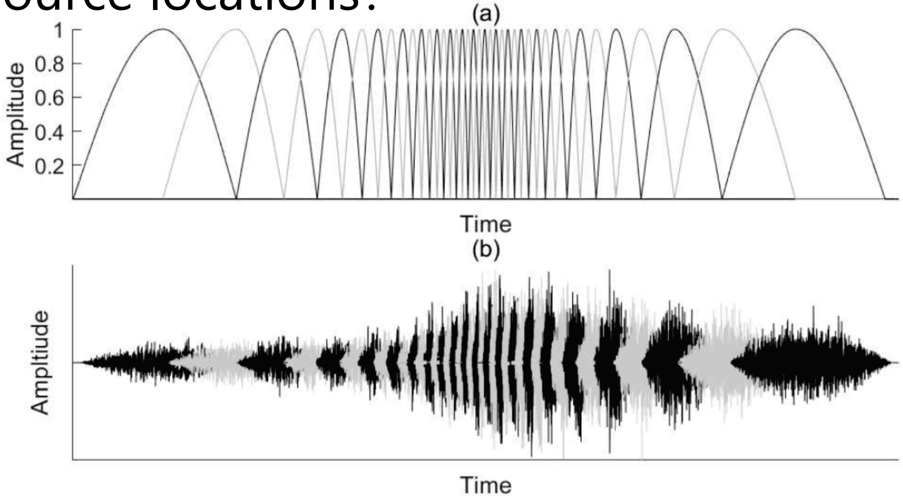
Series of point-to-point impulse responses

- Discretization of source trajectory
- Obtain series of IRs via measurements, ray tracing and/or wave-based simulation



Series of point-to-point impulse responses

- How to interpolate IRs between source locations?
  - Equal-power crossfading (Georgiou 2018)
  - → assumes incoherency
  - → no Doppler effect
  - → difficulties with impulsive and tonal sounds



  - Derivation of generic time-aligned IRs to be interpolated (Heutschi 2020)
  - → ambiguous solutions in complex cases
  - Ongoing research

Time-variant propagation filters

Network of time-variant propagation filters

- Dynamic propagation path tracing
- Representation of discrete propagation effects by filter operations
    - Doppler effect
    - Divergence
    - Air absorption
    - Ground effect
    - Edge diffraction
    - Turbulence effects

Geometrical divergence of point source

- Sound pressure amplitude of point source
  - Spherical waves (→ Acoustics I)
  - Sound pressure drops 6dB/distance doubling
  - frequency-independent

$$\underline{p}(r,t) = \frac{1}{r} \cdot \underline{p}_{\text{plane.wave}} = \frac{1}{r}\hat{p}e^{j(-kr+\phi)}e^{j\omega t}$$

- Slow amplitude modulation: $p_{\text{rec}}[k] = \dfrac{p_{1\text{m}}[k]}{r[k]}$

$p_{1\text{m}}[k]$: emission sound pressure at source time index k at virtual reference distance of 1 meter

r: source-receiver distance in meters

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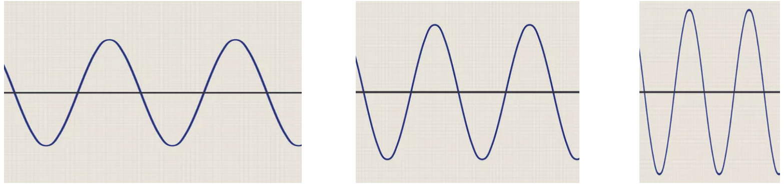
Doppler effect

- = Doppler frequency shift + Doppler amplification
- Kinematic source effect
- Application **before** frequency-dependent propagation effects
- Mechanism: Time-varying propagation delay → compression and dilatation of time axis
- Simulation by time-varying delay (vibrato effect) and AM



Doppler frequency shift

- Warped time at receiver: $t' = t + \Delta t(t) = t + \frac{r(t)}{c}$
- Discrete time → non-integer sampling indices → interpolation needed
- Interpolation methods
  - Nearest neighbor → zipper noise
  - Linear interpolation → sometimes sufficient at low speeds
  - Various methods

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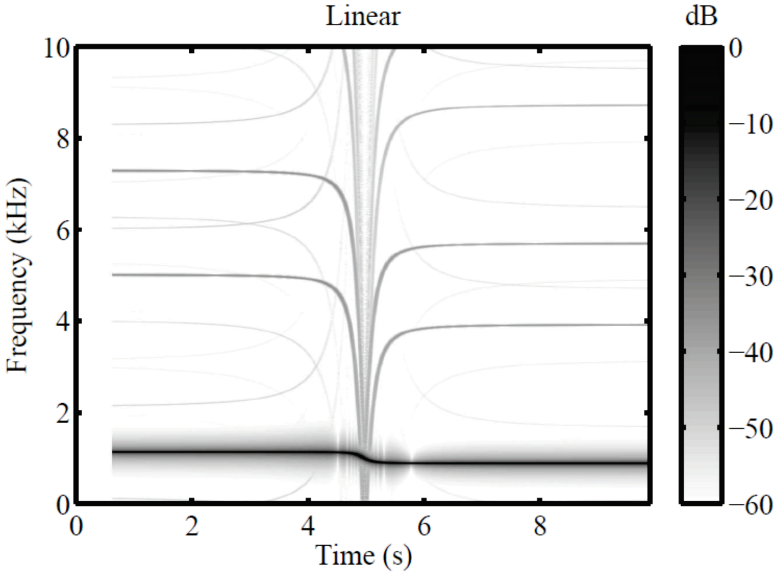
Doppler frequency shift: Interpolation artefacts

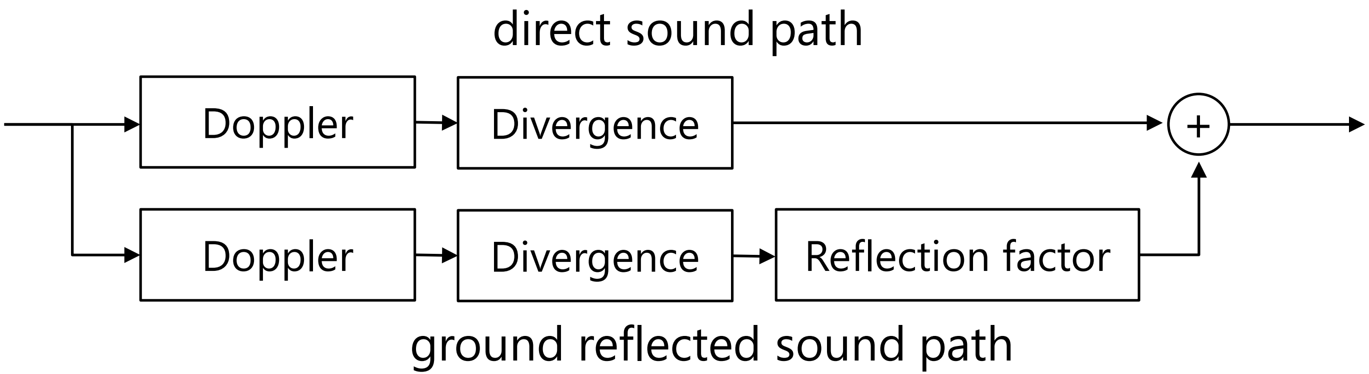
- Averaging of samples → attenuation of high frequencies
- Non-linear distortions → creation of new frequency components

1kHz source moving at
150 km/h at 7.5 distance



Ground effect

- Coloration created by interference of direct and ground reflected sound (comb filter effect)
- Simulation by summation of additional signal path



direct sound path

Doppler

Divergence

+

Doppler

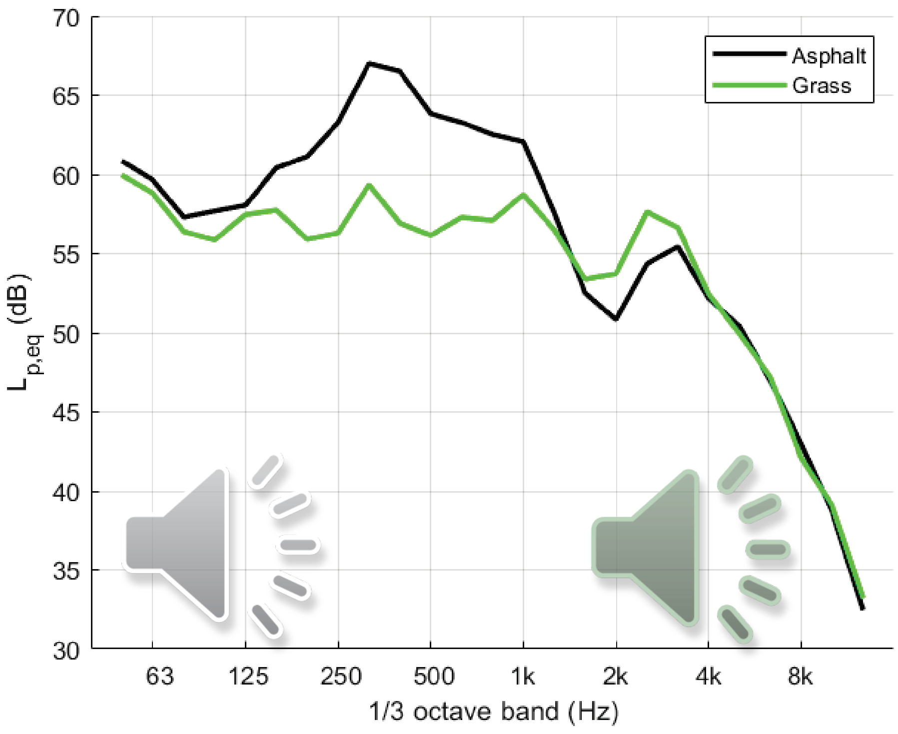
Divergence

Reflection factor

ground reflected sound path

Ground effect example

- Train pass-by
- Observer standing on ground at 34 m from track
- Propagation over flat ground



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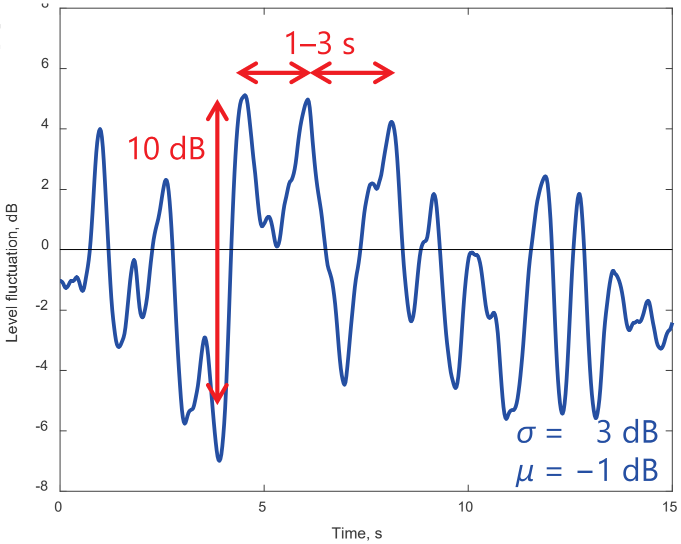
Turbulence-induced amplitude modulation

- Long-distance propagation through turbulent atmosphere
  → refraction → random AM
- Depends on distance, frequency, degree of turbulence
- Simulation run of stochastic high-frequency AM



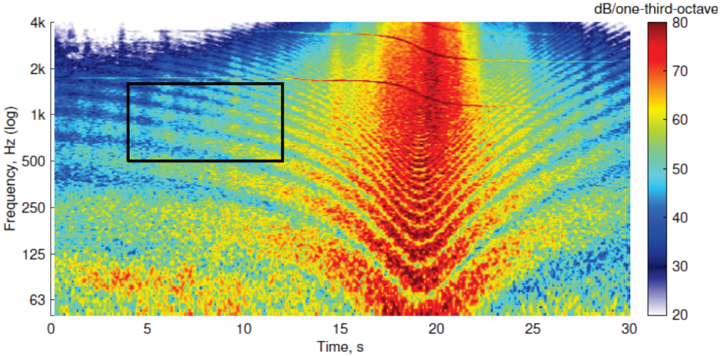
Turbulence-induced coherence loss

- Propagation through turbulent atmosphere

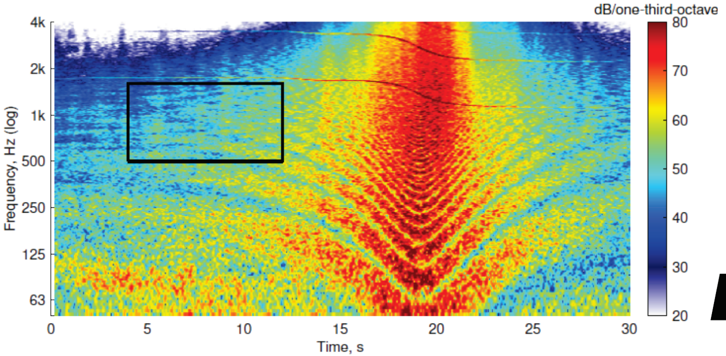
→ loss of coherence between propagation paths

→ affects ground effect at high frequencies

→ reduction of comb filter effect



(a) Synthesis without coherence loss simulation



(b) Synthesis with coherence loss simulation

[Pieren, R. & Lincke, D. 2022. Auralization of aircraft flyovers with turbulence-induced coherence loss in ground effect. *Journal of the Acoustical Society of America*, 151.]

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