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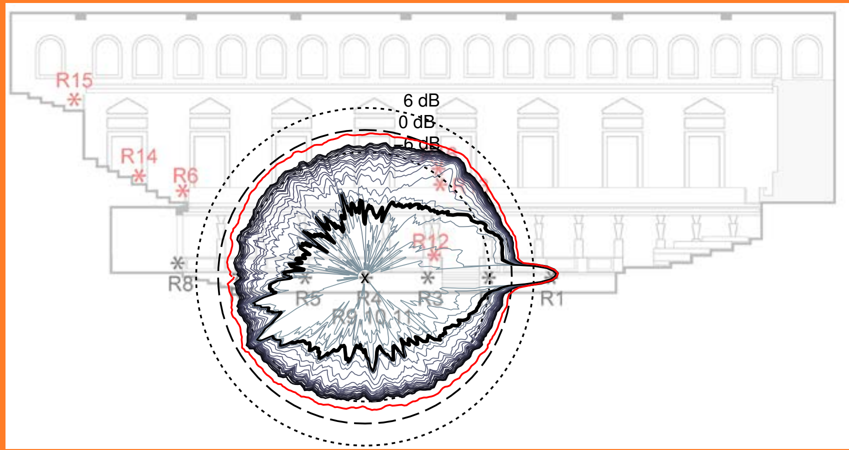

Tutorial

Detailed analysis of room acoustics by spatiotemporal methods

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- Post-doctoral researcher, PhD in 2011
- Virtual acoustics research team (Prof. Tapio Lokki)
- Main topics: room acoustics perception and analysis, auralization, music acoustics

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- Post-doctoral researcher, PhD in 2012
- Virtual acoustics research team (Prof. Tapio Lokki)
- Main topics: microphone array processing, spatial audio reproduction

Tutorial outline

Part 1: Motivation

Part 2: Analysis & Spatial decomposition method (SDM)

Part 3: Room impulse response measurements

Part 4: Example room-acoustic research and applications

Part 5: Matlab toolbox demo

Part 1: Motivation

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Motivation

- **Importance of acoustic environments**
- **Learning spaces**
- **Artistic enjoyment**
- **Huge costs**

Motivation

- **How rooms work acoustically?**
- **Reliance on parameter values**
- **Describe systems with few numbers**

- **Analogous example:**

(A picture of a colorful painting)

Motivation

- **Objective parameters describe "what"**
- **A method for "how" and "why"?**

The variety in acoustic environments

- **Small (3 m^3) – Large (30000 m^3)**
- **Dry – reverberant**
- **Critical listening – Enjoyment**
- **Fixed sources – Natural sources**
- **Sources in specific directions – Surrounded by sources**

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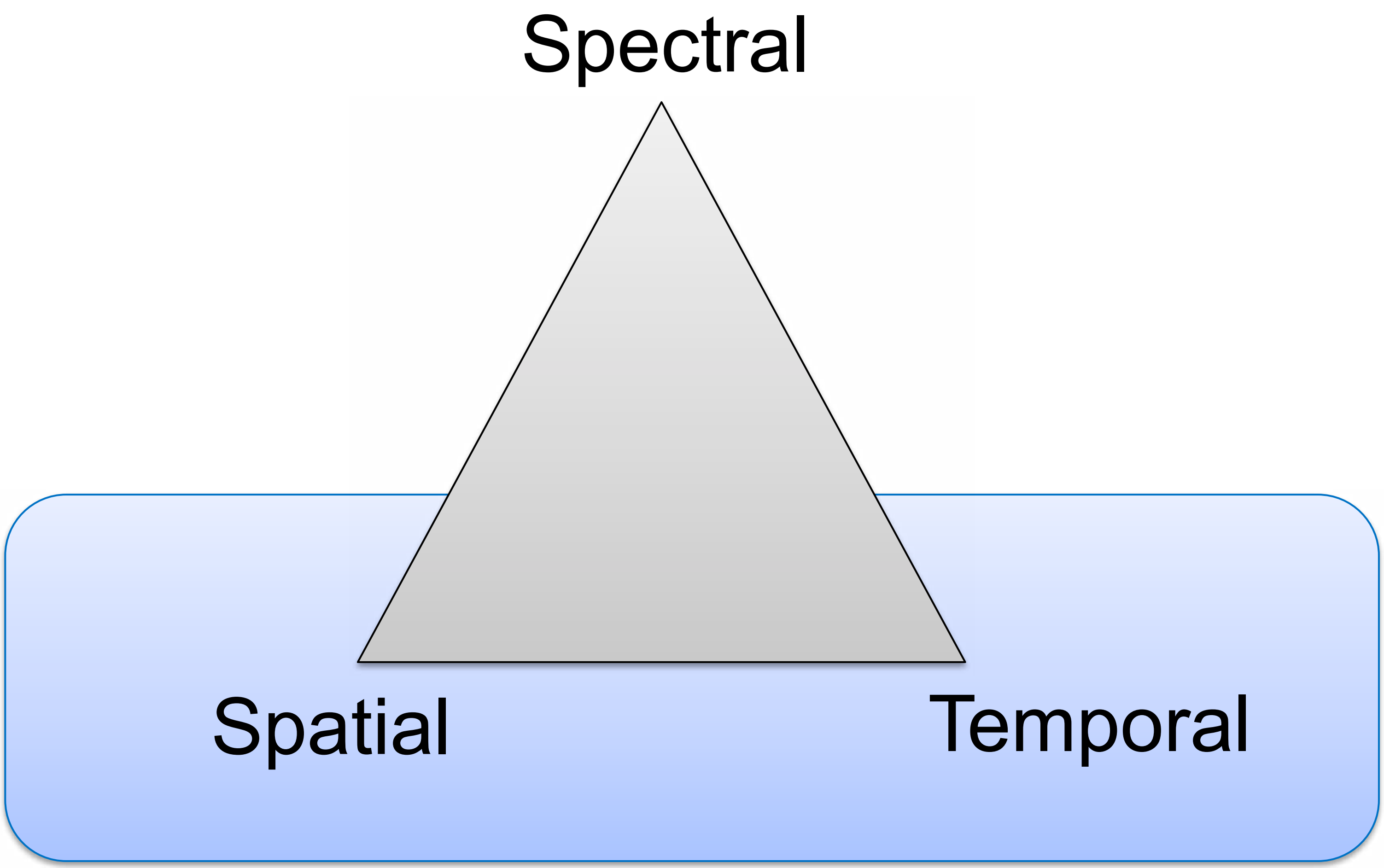
Essential properties of the sound field



Part 2:
Analysis & Spatial decomposition method (SDM)

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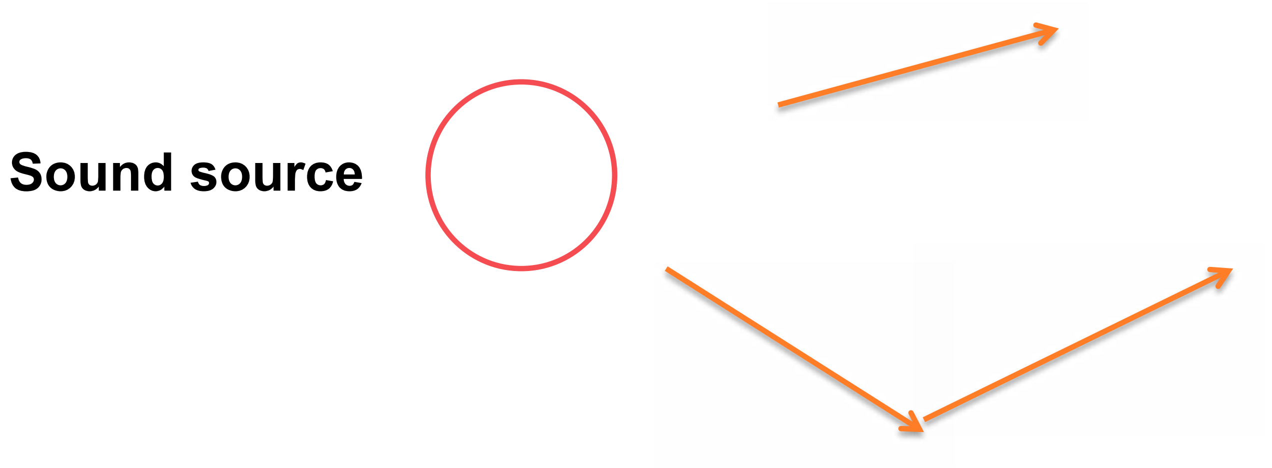
Model for sound propagation

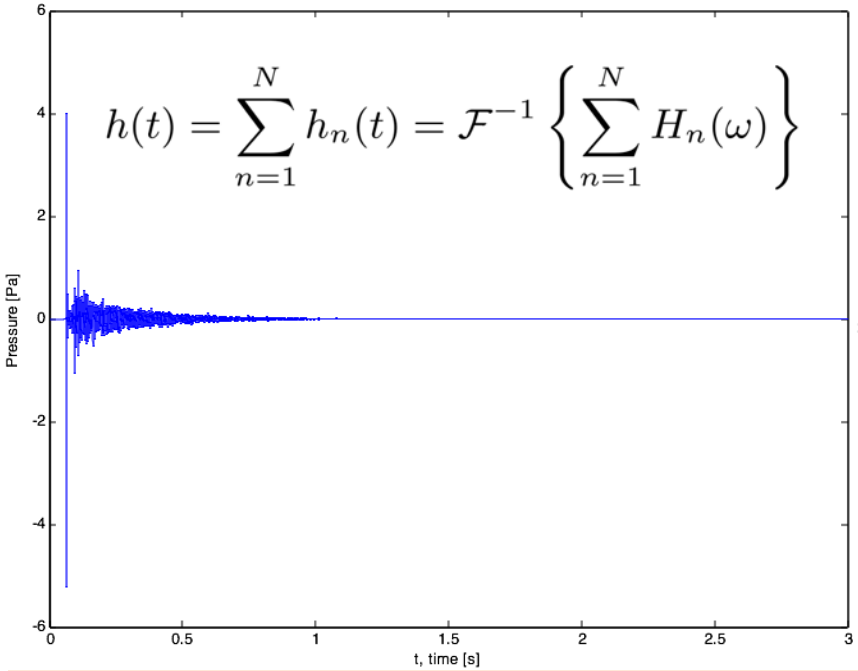
- **Parametric analysis of sound requires a scientific model of the sound propagation**
- **Parameters of a physical model are solved with estimation methods**

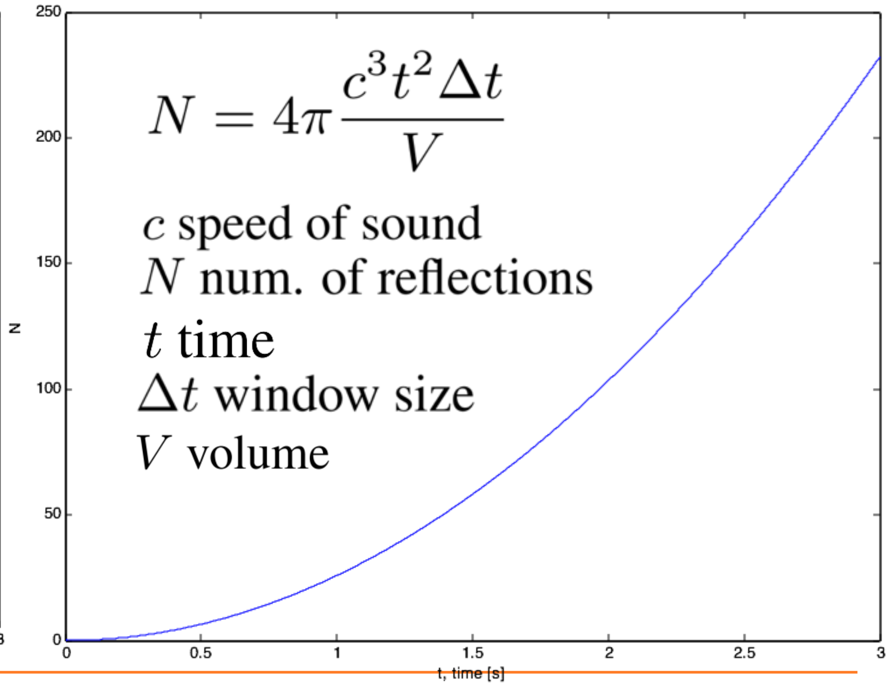


A room impulse response is the superposition of all waves!

A room impulse response

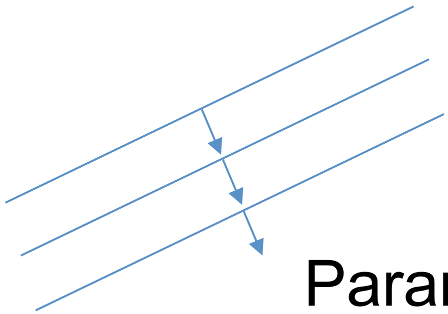
Echo density





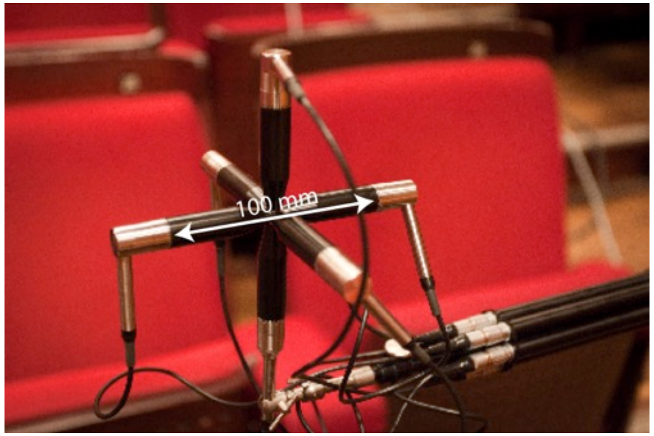
Models

- A simple physical model is the plane wave
- This is also the most applied model, since the source is typically in the far field.
- This model includes parameters related to the direction of arrival, pressure or energy, and noise



Parameters are direction, and pressure

The problem



- **Goal: Find parameters of all reflections**
- **Problem: We have overlapping reflections**
- **Solution: Use a short window**

$$N = 4\pi \frac{c^3 t^2 \Delta t}{V}$$

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Solutions and limitations

- As time window Δt shortens -> N decreases

$$N = 4\pi \frac{c^3 t^2 \Delta t}{V}$$

  – Window size is limited by the maximum array dimension

$$\Delta t \geq \frac{2 d_{\max}}{c}$$

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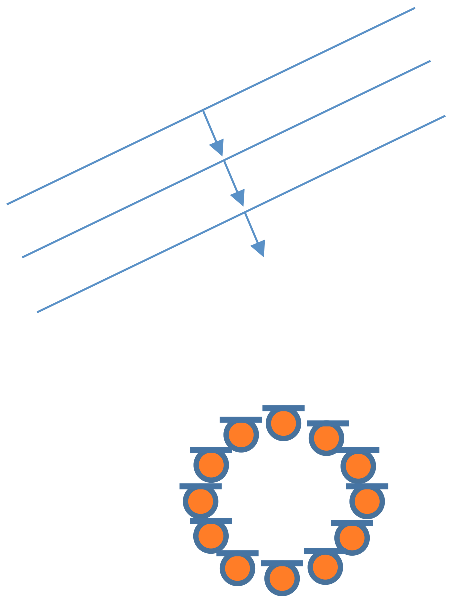
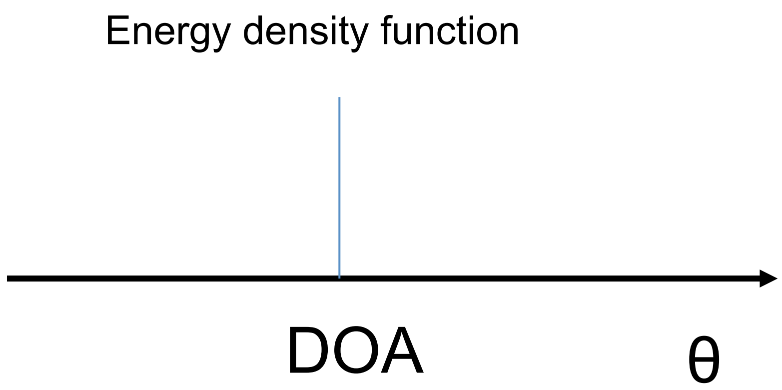
One plane wave model

Localization using a microphone array



Microphone array



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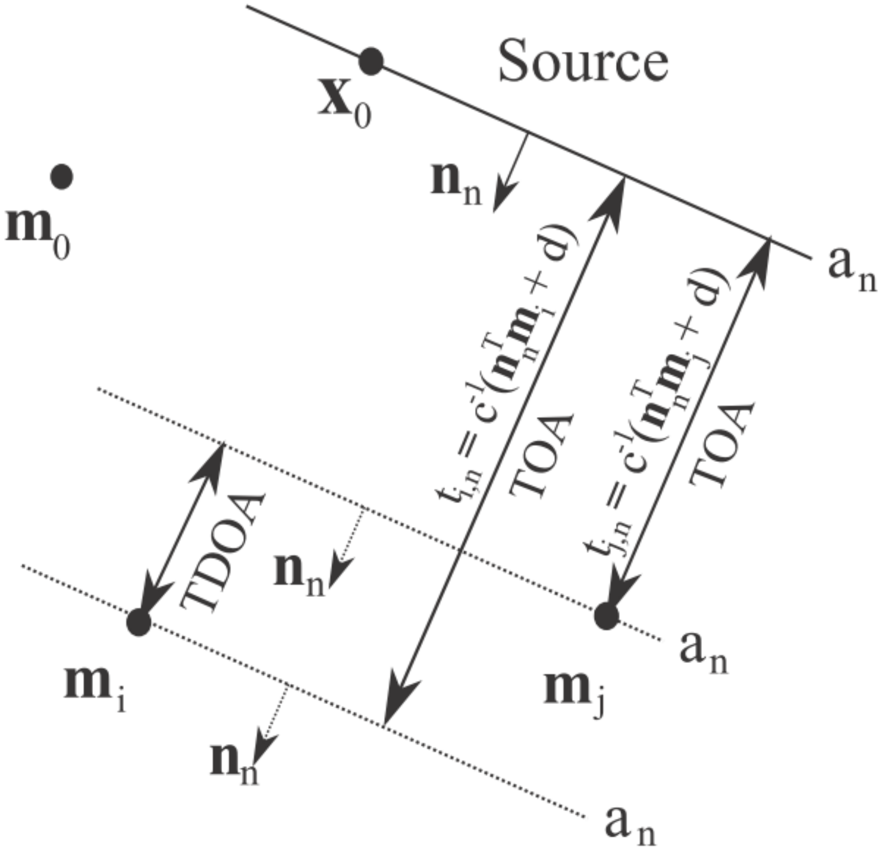
Direction of Arrival Estimation



m : microphone location

n : plane wave direction

Time difference of arrival (TDOA)

$$\tau = \frac{\mathbf{m}_i - \mathbf{m}_j}{c}\mathbf{n}^T$$

Plane wave direction

$$\mathbf{n}^T = (\mathbf{m}_i - \mathbf{m}_j)^+ \tau c$$

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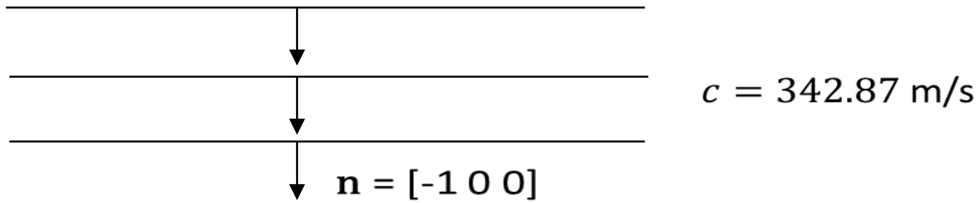
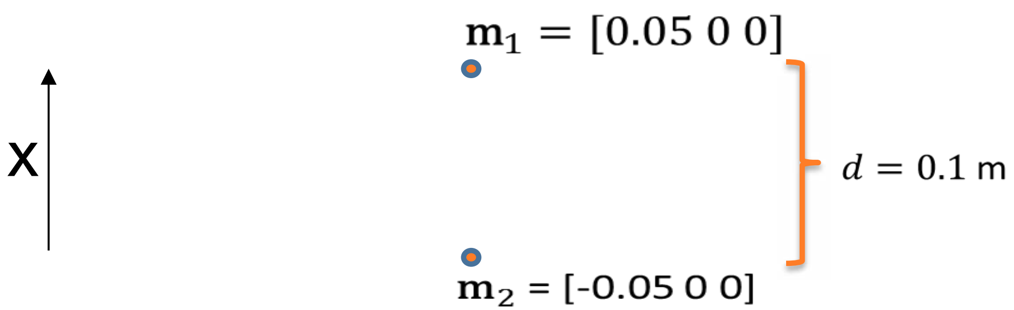
Example of DOA solving, 1-D

Plane wave direction

$$\mathbf{n} = \frac{\tau c}{(\mathbf{m}_i - \mathbf{m}_j)}$$





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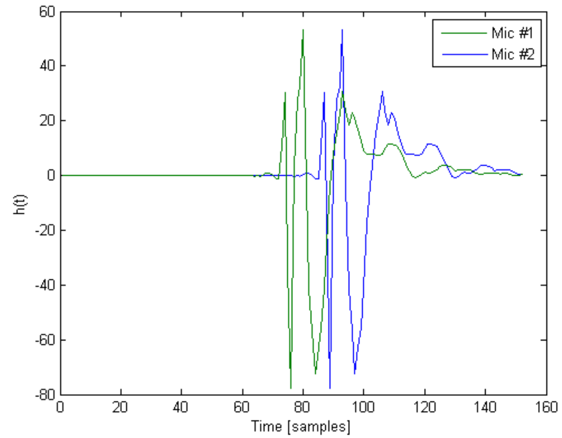
Example of DOA solving, 1-D

Observed signals $h_1(t)$ and $h_2(t)$



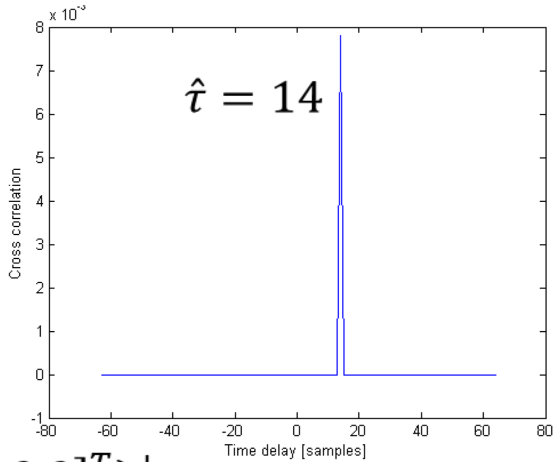
Time difference of arrival (TDOA) estimate:

$$\hat{\tau} = \arg\max \{R(\tau)\}$$

$$R(\tau) = F^{-1}\{H_1(\omega)H_2(\omega)^*\}$$ (cross-correlation)

$$H_1(\omega) = F\{h_1(t)\}$$

$$H_2(\omega) = F\{h_2(t)\}$$



Estimated direction

$$\hat{\mathbf{n}} = 14\,/f_s \times 342.87\mathrm{m/s}\,([-0.05\ 0\ 0]^T - [0.05\ 0\ 0]^T)^+$$
$$= 0.1 \times [-10\ 0\ 0] = \boxed{[-1\ 0\ 0]^T}$$

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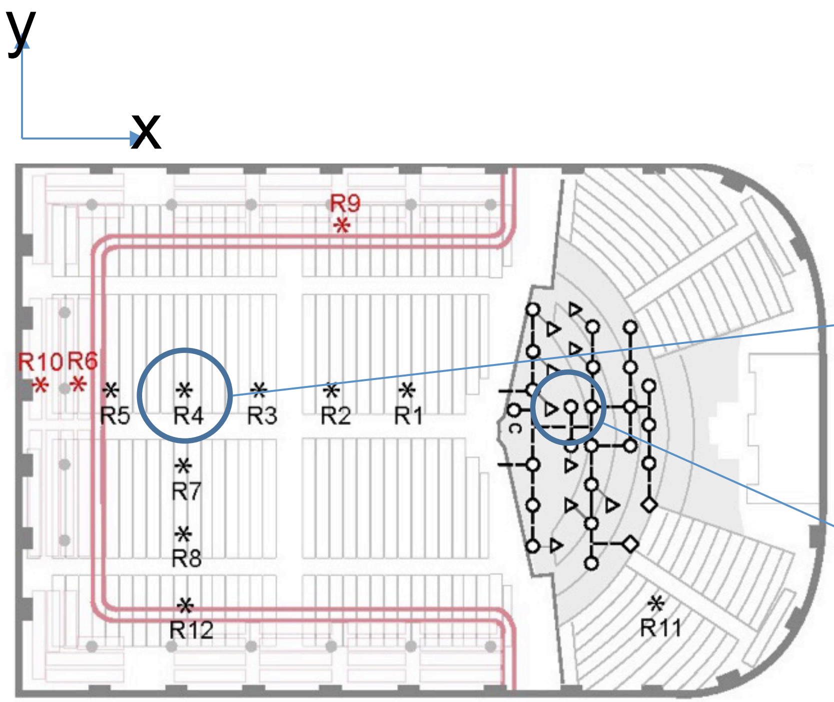
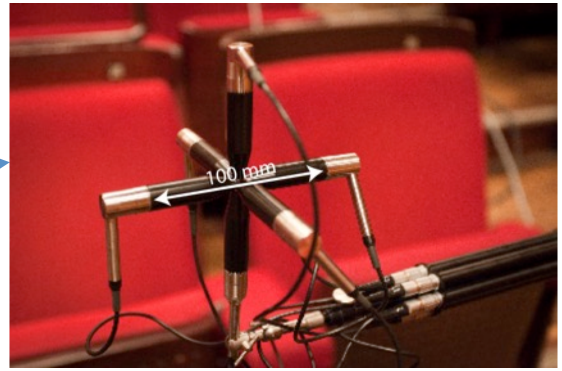
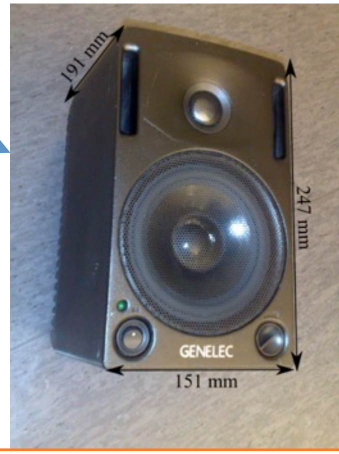
Example: loudspeaker localization







Azimuth	Elevation	Distance
−2.7 degrees	4.4 degrees	21 m

Example: loudspeaker localization

A set of linear equations

$$\tau_{1,2} = (\mathbf{m}_1 - \mathbf{m}_2)\frac{\mathbf{n}^T}{c}$$

$$\tau_{1,3} = (\mathbf{m}_1 - \mathbf{m}_3)\frac{\mathbf{n}^T}{c}$$

...

$$\tau_{M,M-1} = (\mathbf{m}_M - \mathbf{m}_{M-1})\frac{\mathbf{n}^T}{c}$$

Write down in matrix form

$$V = [(\mathbf{m}_1 - \mathbf{m}_2)^T \, (\mathbf{m}_1 - \mathbf{m}_3)^T \ldots (\mathbf{m}_M - \mathbf{m}_{M-1})^T]^T$$

$$\boldsymbol{\tau} = [\tau_{1,2}, \tau_{1,3}, \ldots, \tau_{M,M-1}]^T$$

$$\boldsymbol{\tau} c = \mathrm{V}\mathbf{n}$$

Minimum mean square error solution

$$\mathbf{n} = V^+ \boldsymbol{\tau} c$$

(Closed form DOA solution!)

M is the number of microphones

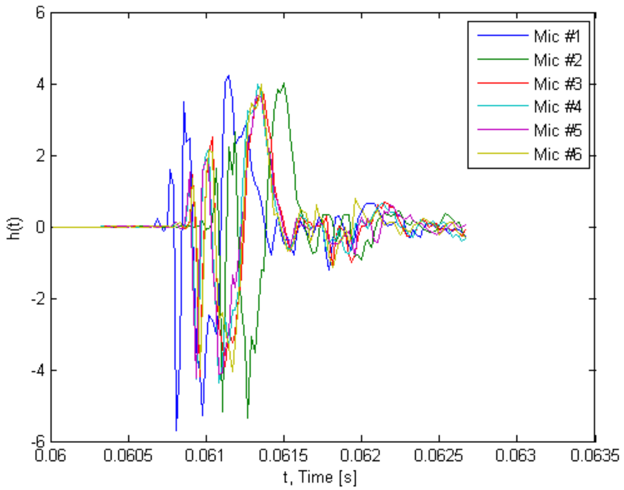
$$\frac{M(M-1)}{2}$$

is the number of microphone pairs

Example: loudspeaker localization

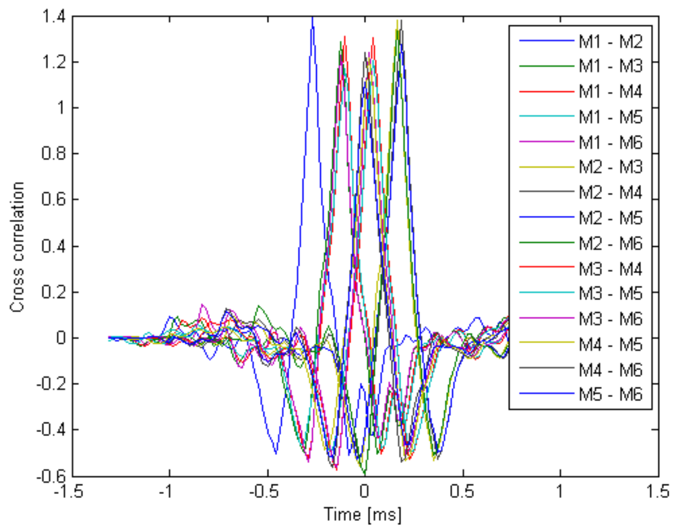
Observed signals sampled at 48 kHz

$h_i(t)$, i = 1,…,6



TDOA estimates from cross-correlation

$$R_{i,j}(\tau) = F^{-1}\{H_i(\omega)H_j(\omega)^*\}$$



Distance

$d = c \times t$ = 345 m/s × 0.061 = 21.05 m

Localization of the loudspeaker

$$\mathbf{n} = V^{+}\boldsymbol{\tau}\frac{c}{f_s} = V^{+} \times \begin{bmatrix} 13.9171 \\ 6.9619 \\ 5.9760 \\ 5.8753 \\ 6.8997 \\ -6.9398 \\ -7.9534 \\ -8.0590 \\ -6.9684 \\ -0.9956 \\ -1.0731 \\ -0.0953 \\ -0.0638 \\ 0.8764 \\ 1.0248 \end{bmatrix} \frac{c}{f_s} = \begin{bmatrix} 0.9999 \\ -0.0715 \\ 0.0729 \end{bmatrix} \rightarrow \begin{bmatrix} -4.09 \\ 4.16 \\ 1.00 \end{bmatrix}$$

Cartesian → Spherical

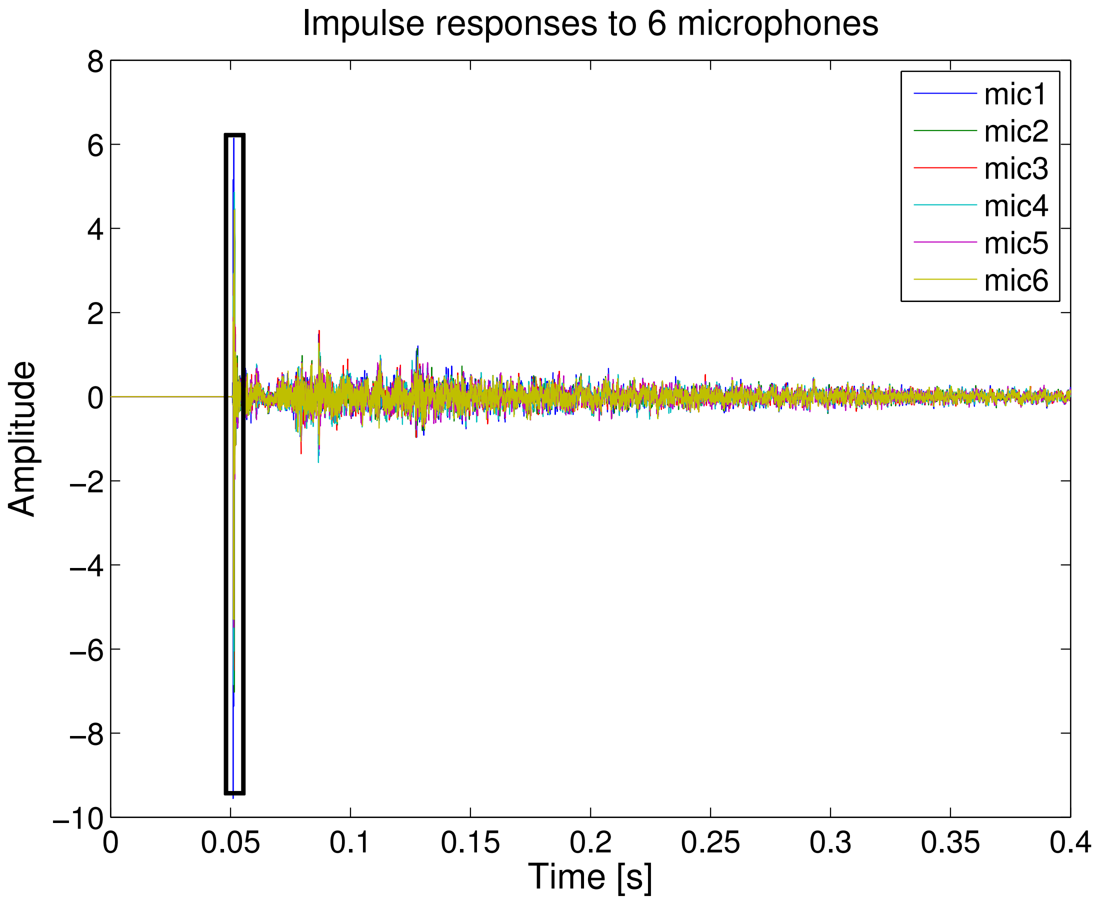
Estimation result in spherical coordinates

Azimuth	Elevation	Distance
-4.1 degrees	4.2 degrees	21.05 m

Ground truth from the geometry

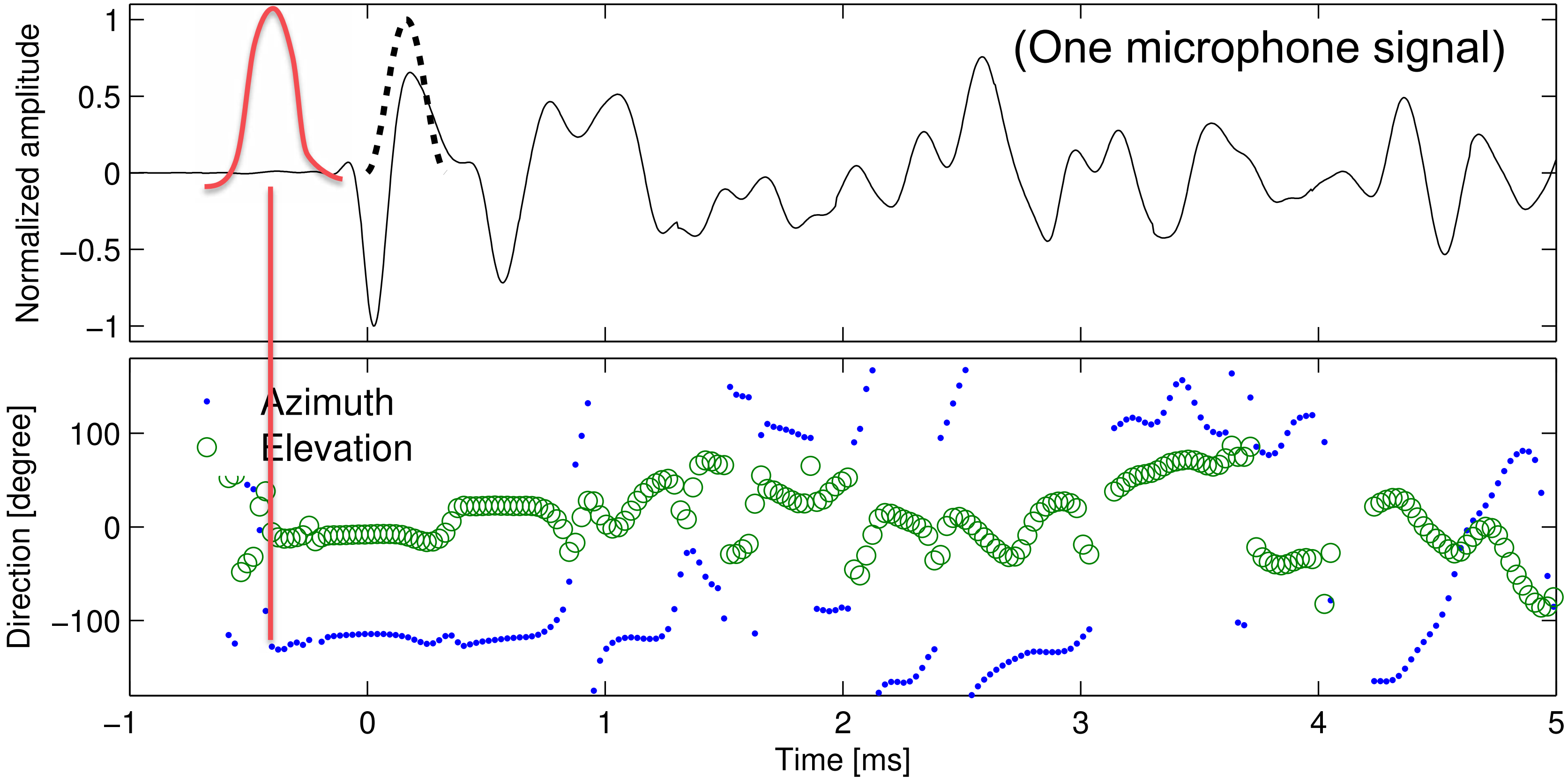
Azimuth	Elevation	Distance
-2.7 degrees	4.4 degrees	21 m

Spatial Decomposition Method (SDM)
[Tervo, Pätynen, Kuusinen and Lokki, *JAES* 2013]

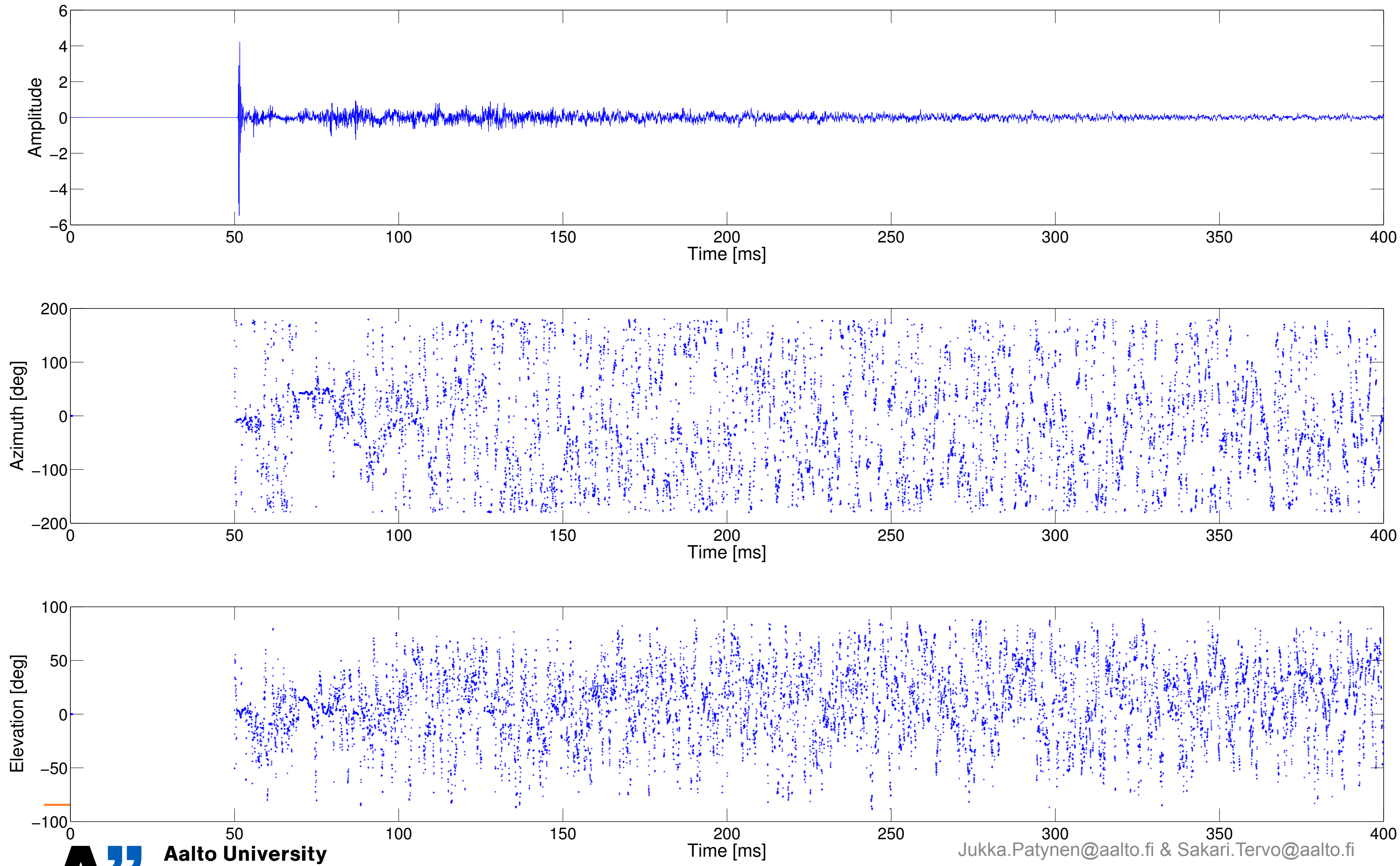


1. Analyze a direction (15 TDOAs)
2. Move window one sample
3. Analyze a direction (15 TDOAs)
4. Move window one sample
5. GOTO 2

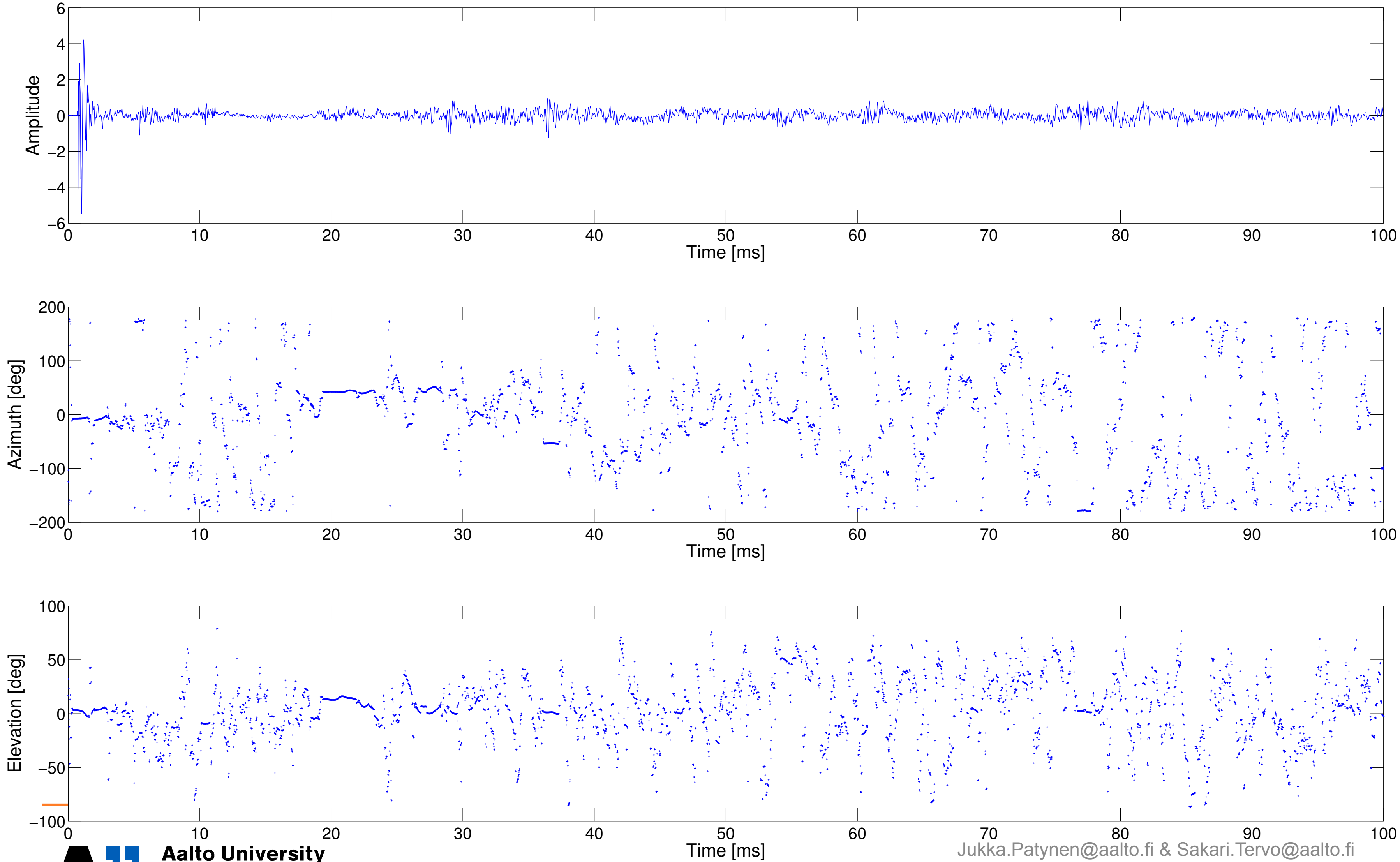
Short analysis window



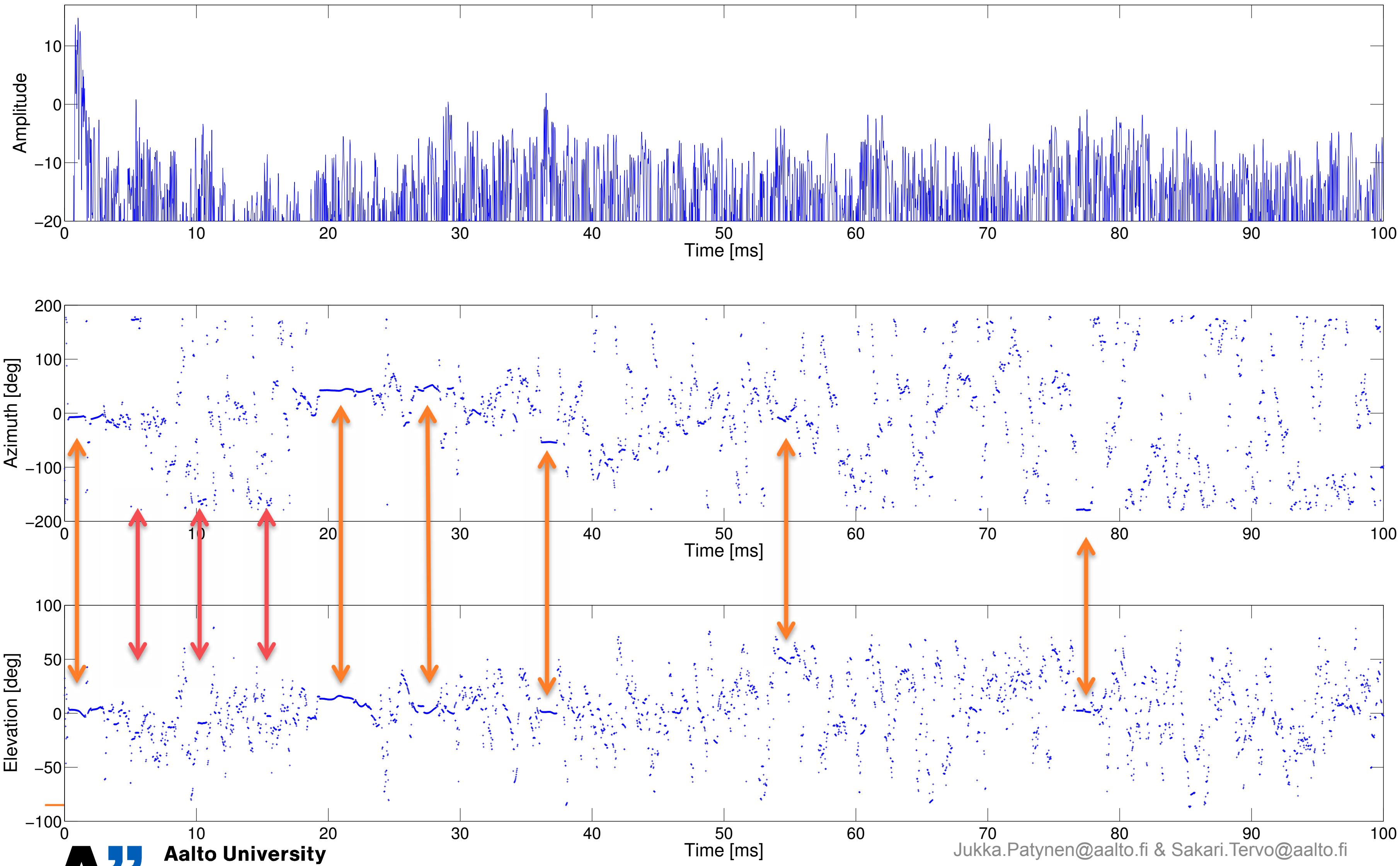
Directional analysis



Directional analysis

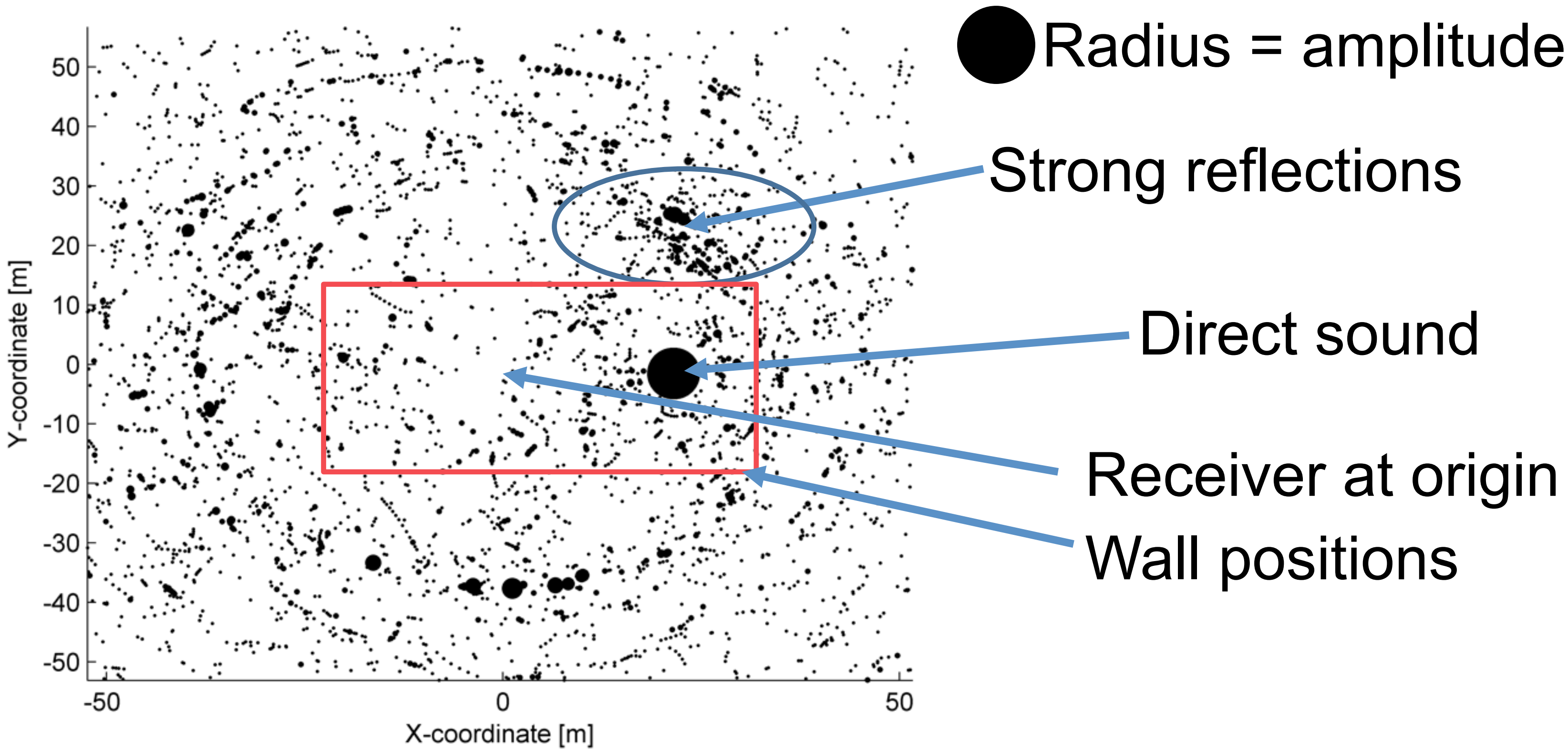


Directional analysis



Visualization 2

Alternative visualization, localized image-source, first 50 meters of propagation



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Directional analysis & SDM

More details:

S. Tervo et al. (2013): "Spatial decomposition method for room impulse responses", JAES 61(1/2).

Part 3:
Room impulse response measurements

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Excitation for room responses

- **Specific for each kind of space**
- **Studios: monitor speakers**
- **Rock clubs: PA system**
- **Cars: distributed driver elements**
- **Concert and opera halls: natural sources**

Spaces with integral sources

- **Fixed source positions**
- **Measure RIR from each channel**
- **SDM assumes point sources**
  - Multi-driver audio systems

- **Mostly direct sound**
- **Sound level controllable**

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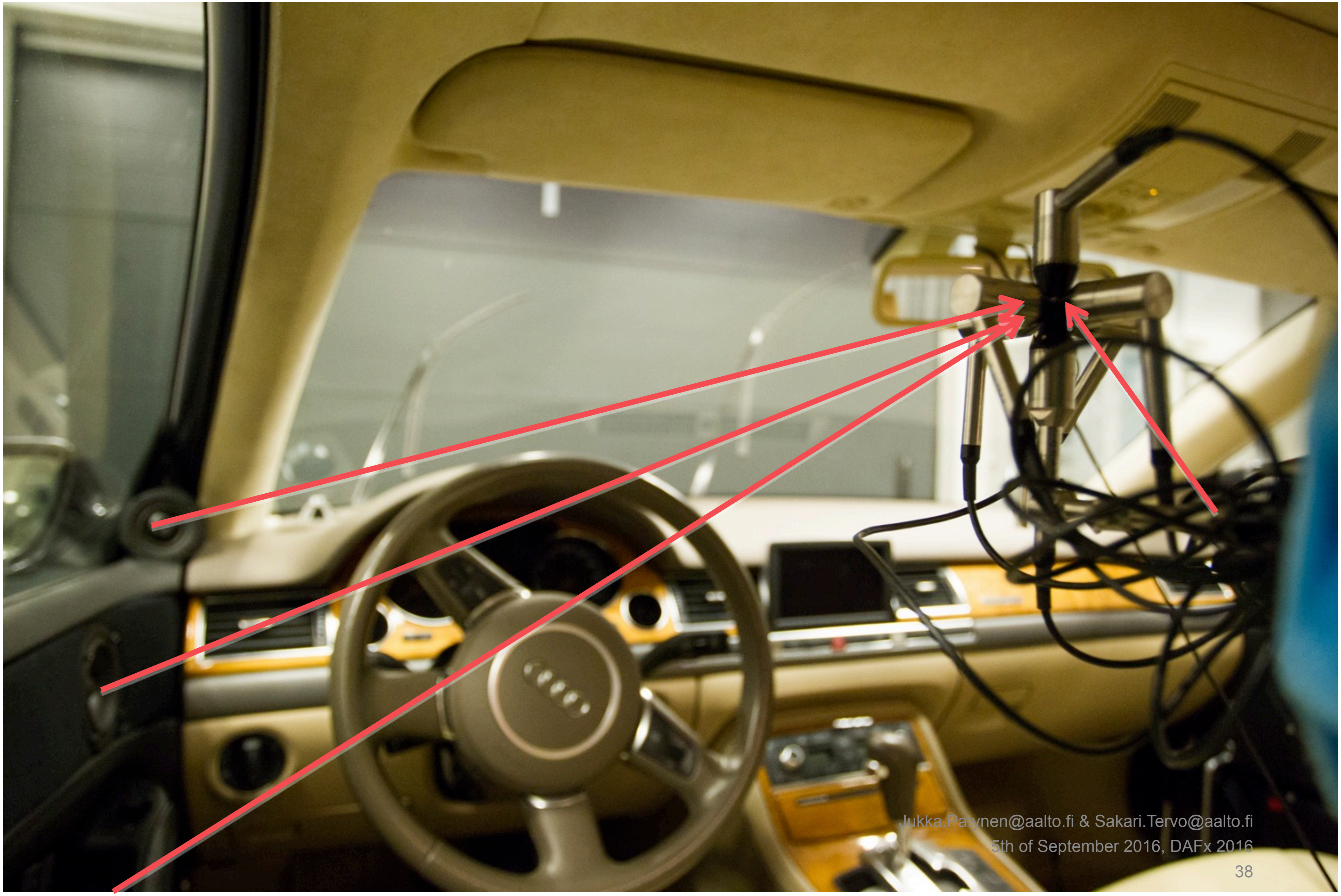

Example: car audio system

- **Earlier method: binaural room/car scanning**
- **Does not provide data for spatial analysis**
- **Not extendable to loudspeaker reproduction**
- **Bias from fixed HRTFs**

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Concert spaces

- **Bring your own sources**
- **Standard: handful of source positions**
- **In performance: 70+ natural instruments**
- **Measurement repeatability**
- **Practicality**

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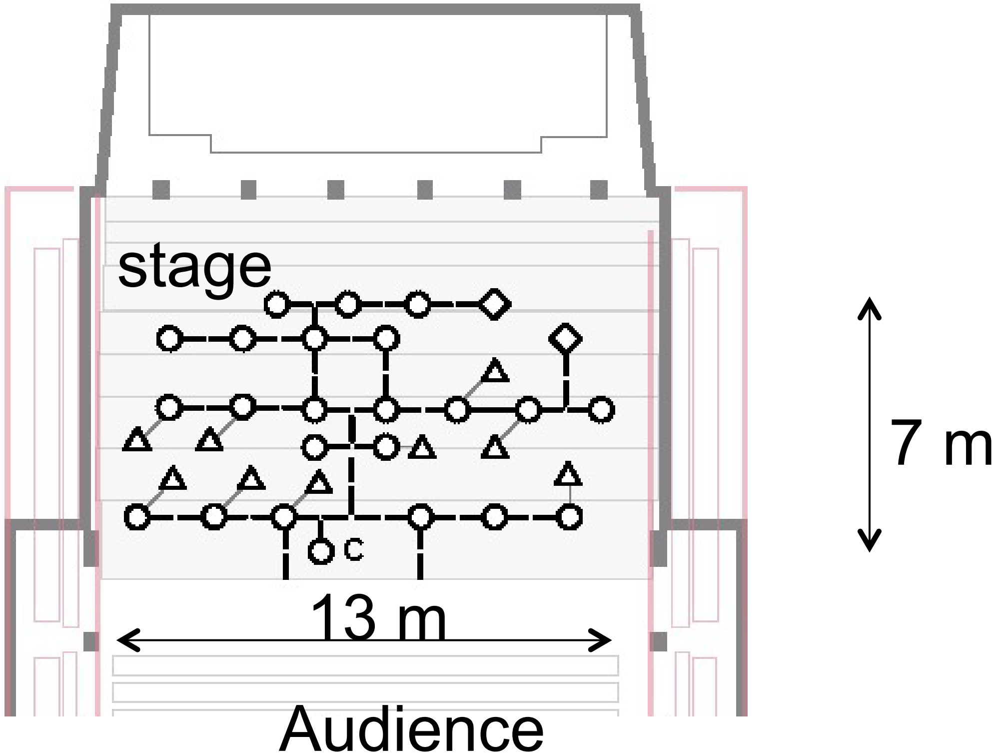
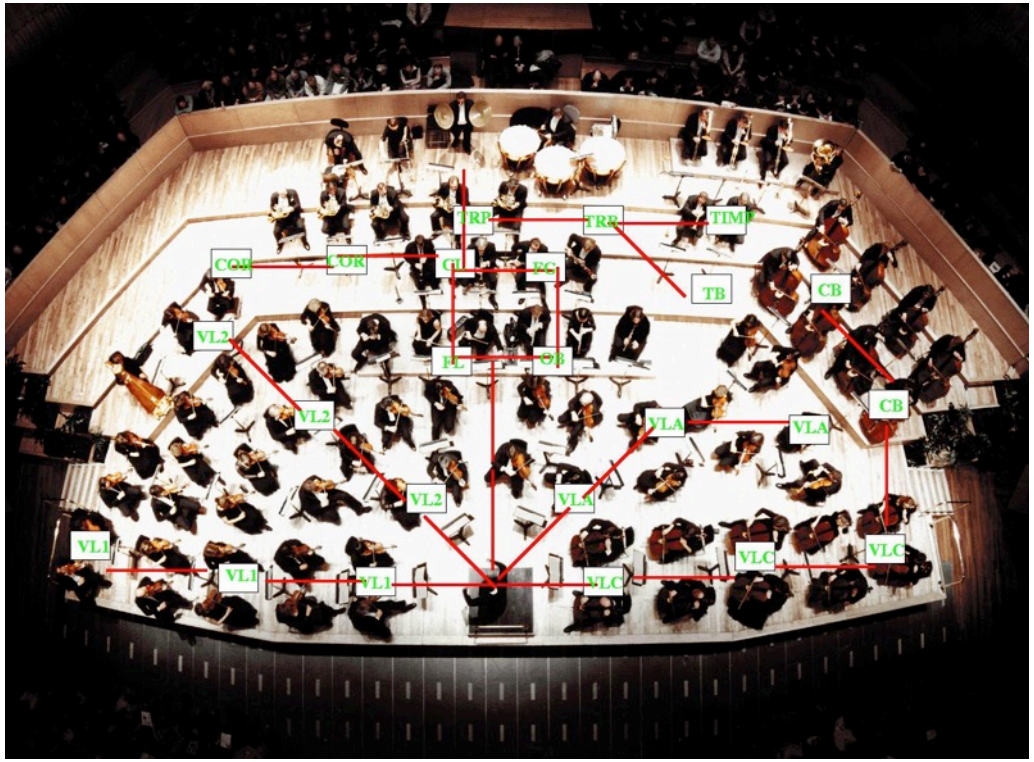
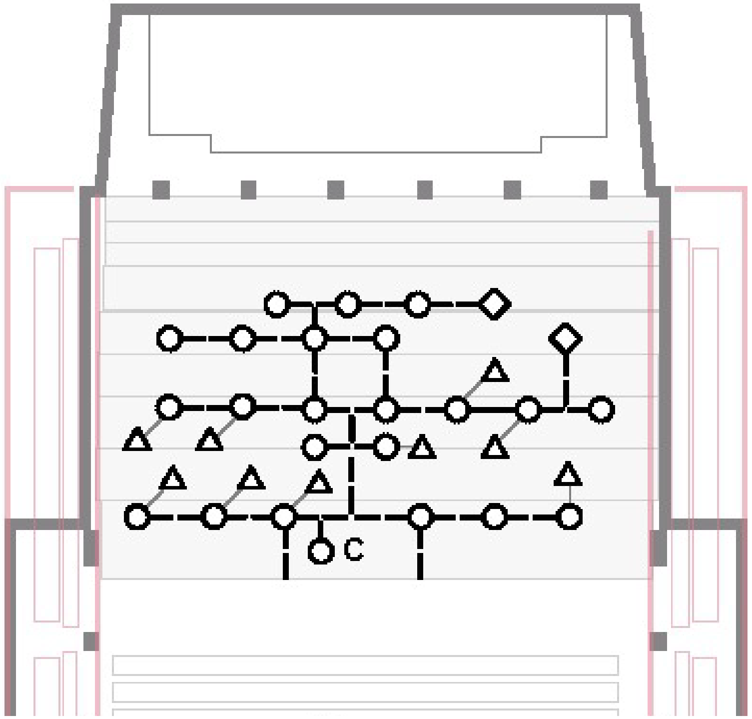
Concert spaces

- The “loudspeaker orchestra”
- 34 loudspeakers connected to 24 signal channels



Loudspeaker orchestra design





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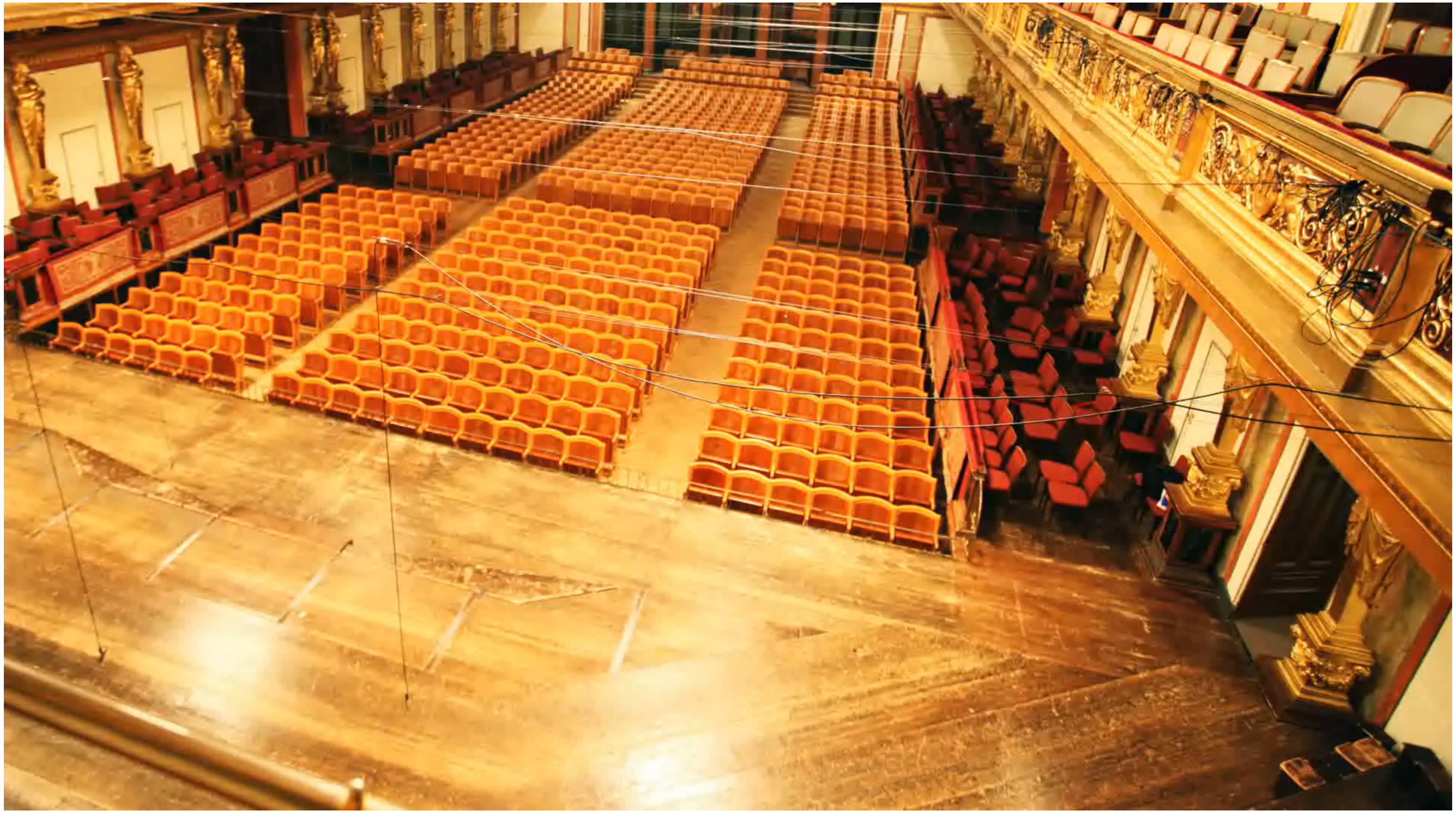
Concert hall A

Concert hall B



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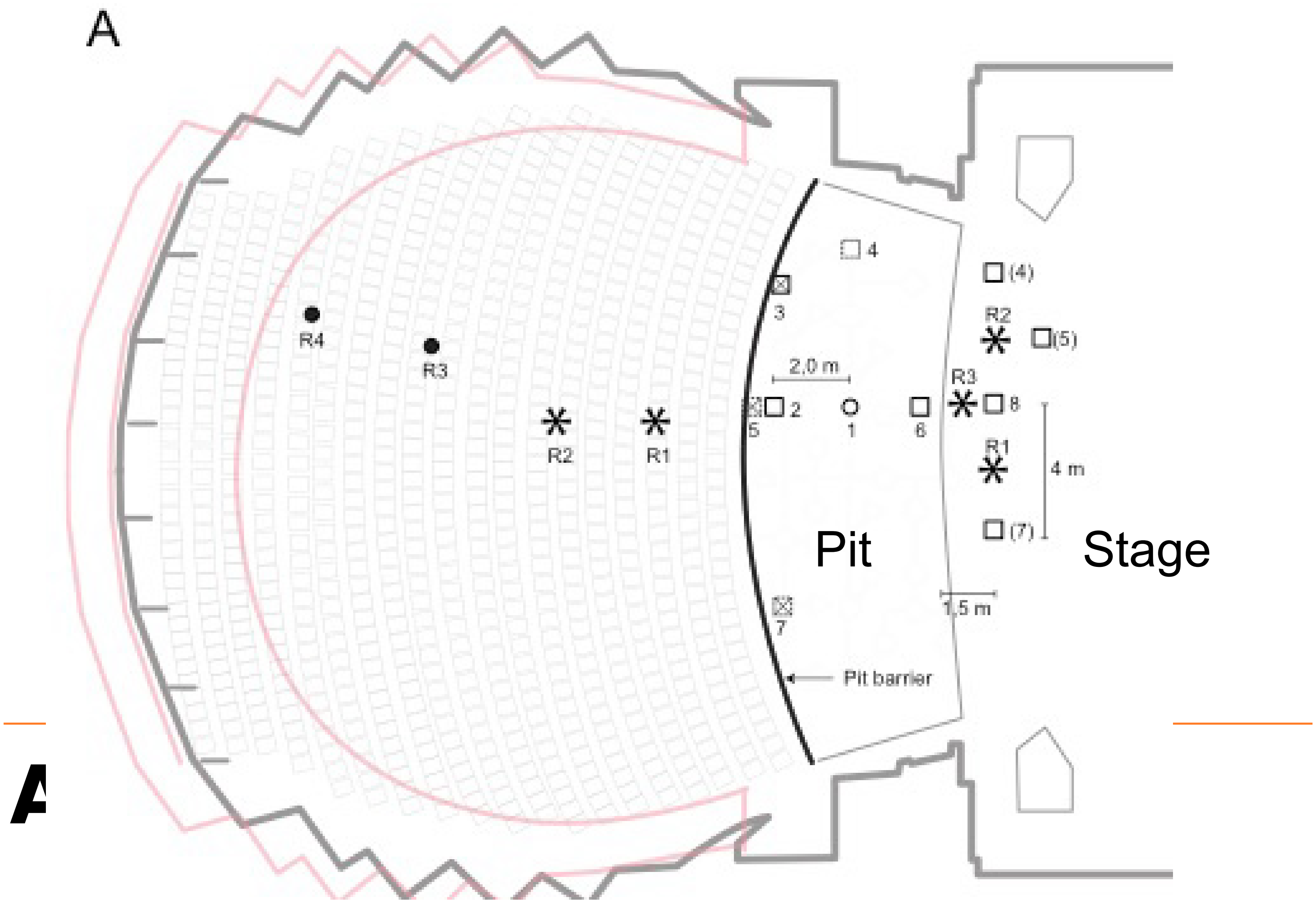
RÖNTGEN

Adaptation: Opera house

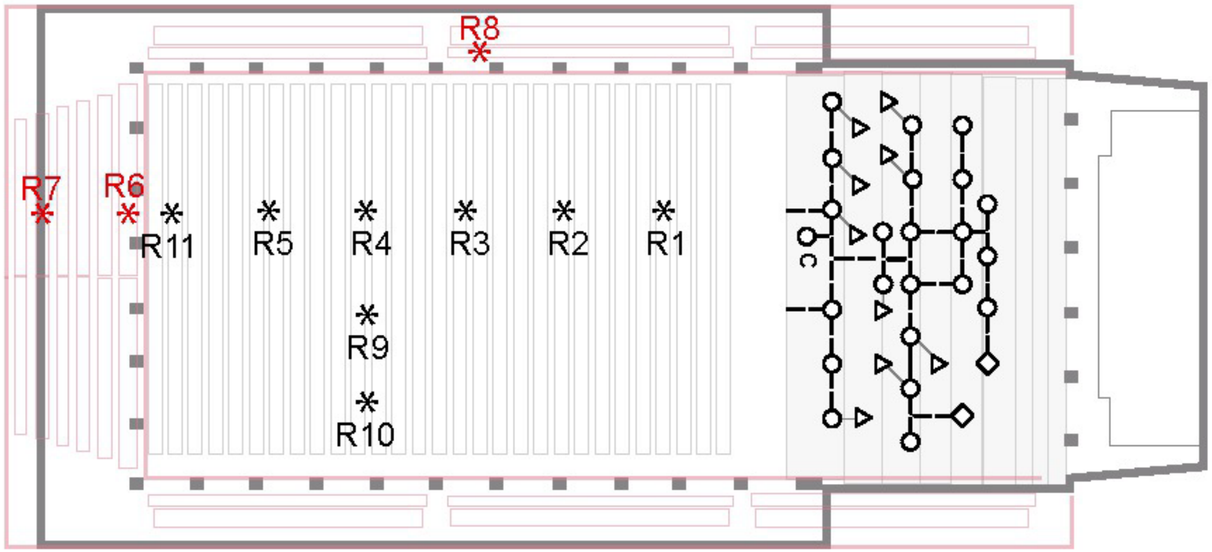


Concert spaces

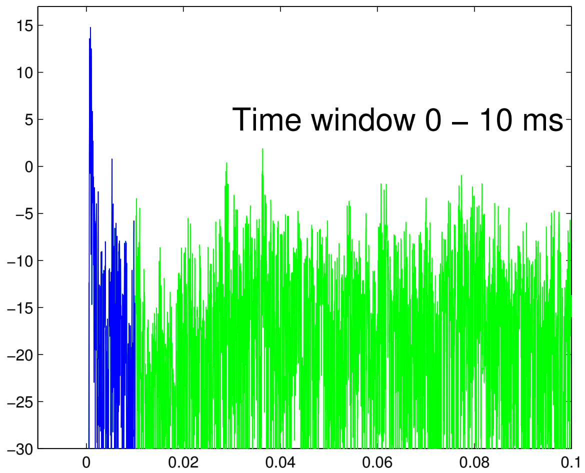
Detailed analysis in single receiver positions

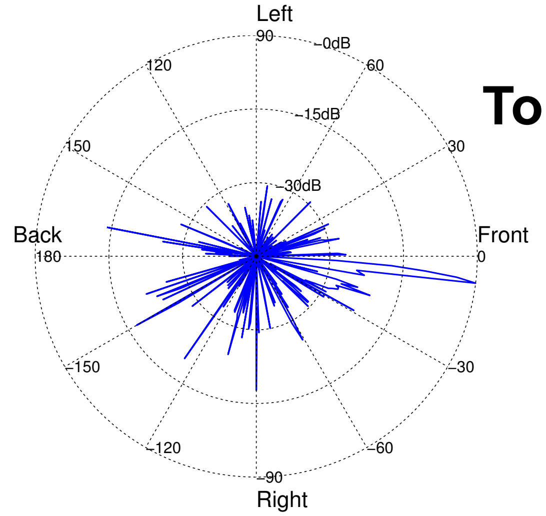
Individual listener occupies one seat

- No averaging across positions (ISO3382)

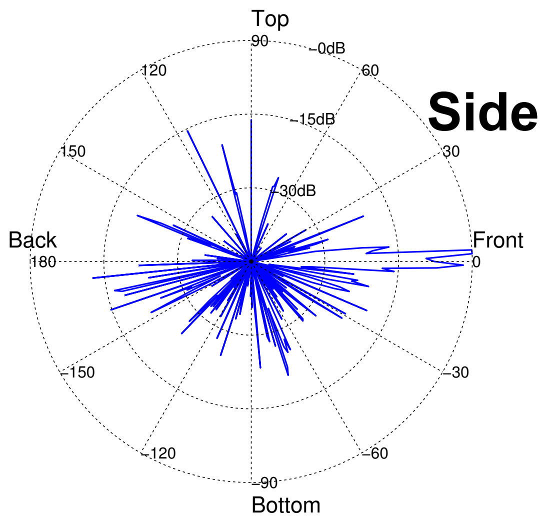


Example visualization: measurement from a single source + SDM

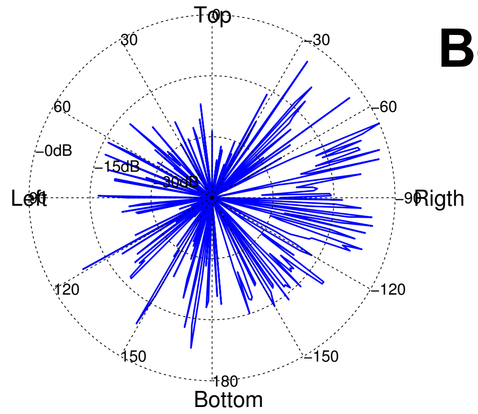




Top view



Side view



Behind view

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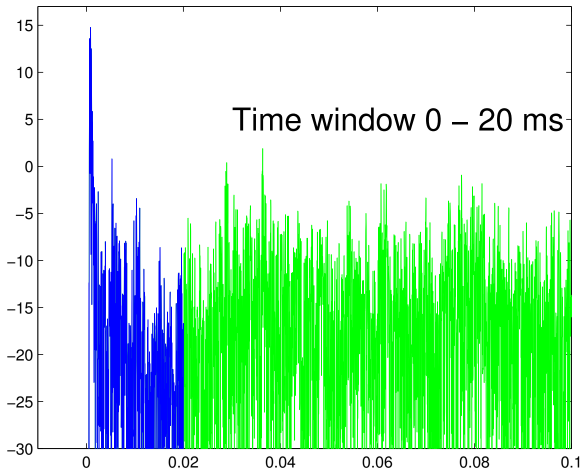
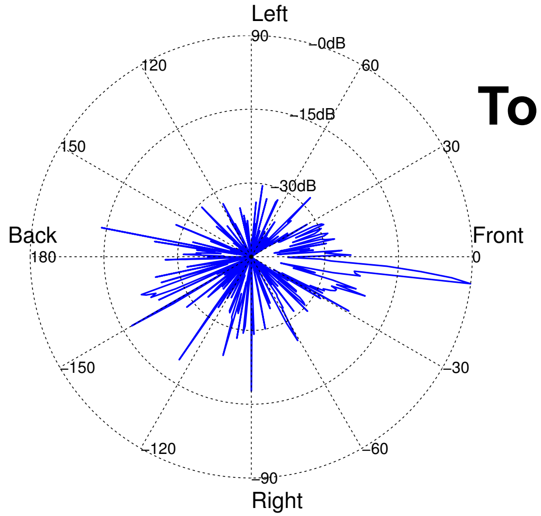
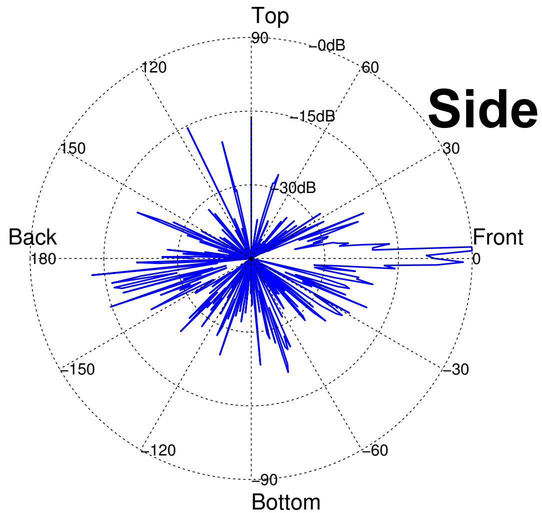
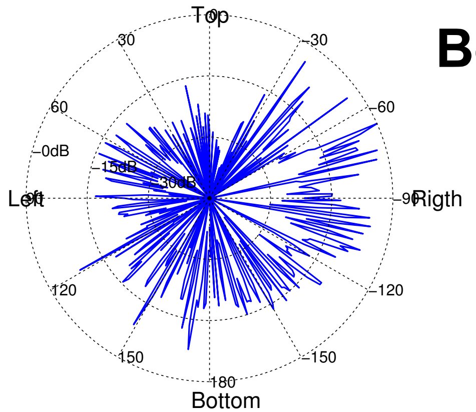




Top view



Side view



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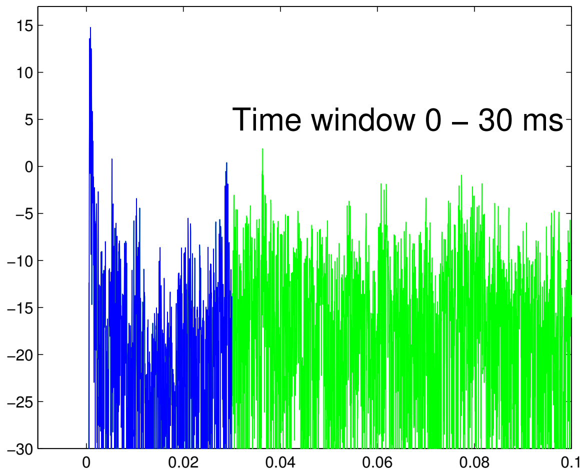
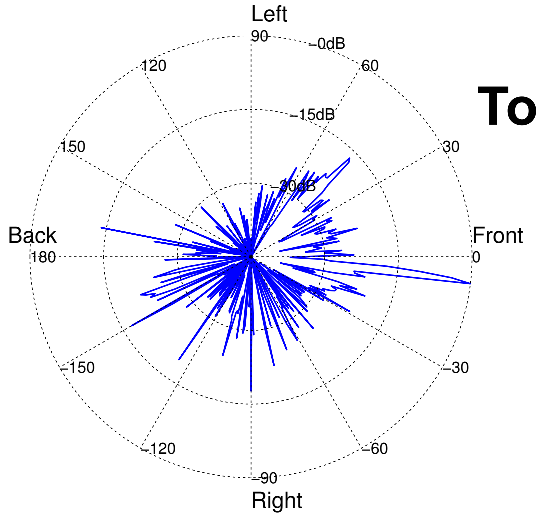
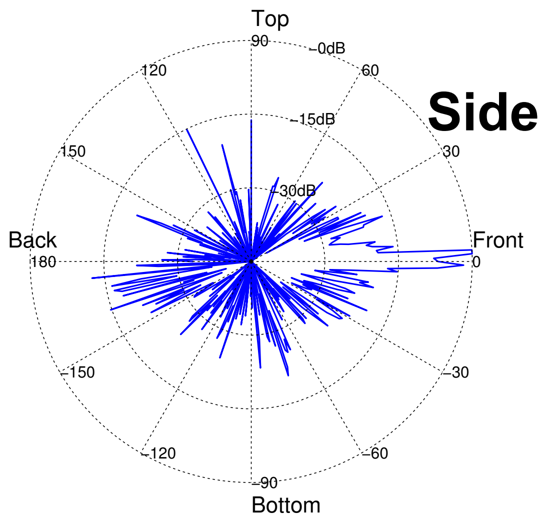




Top view



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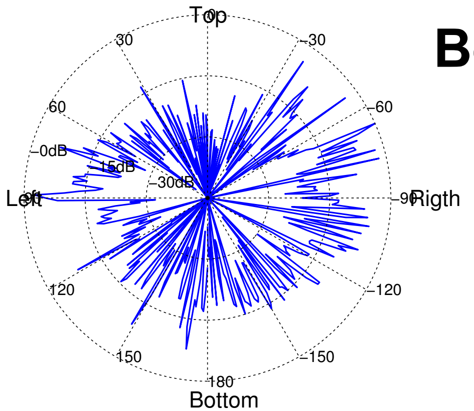

Behind view

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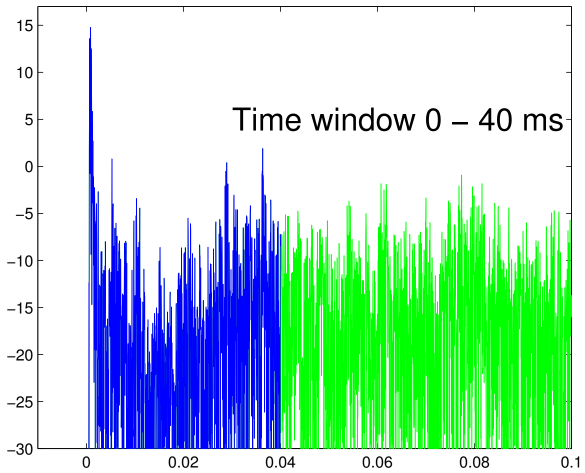

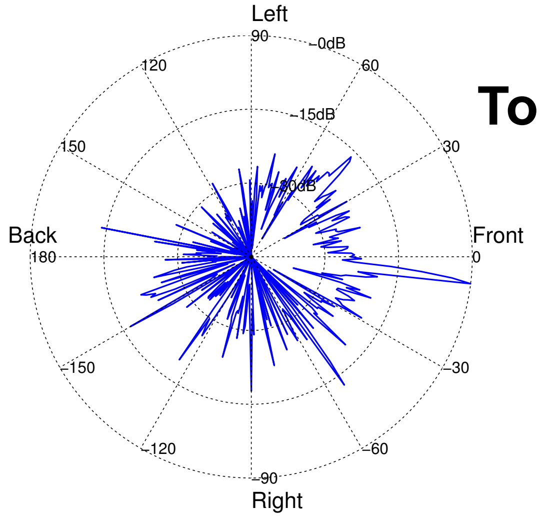

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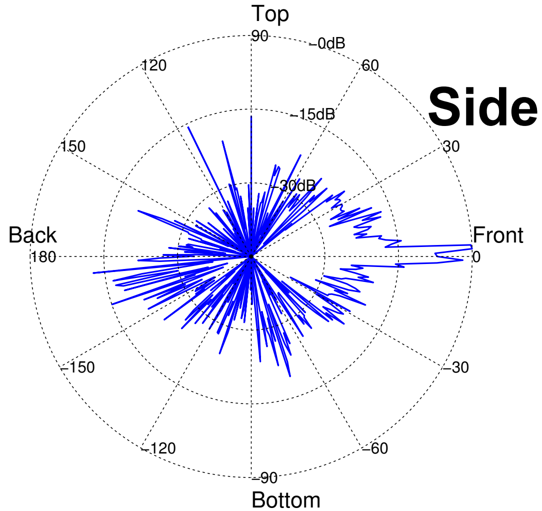
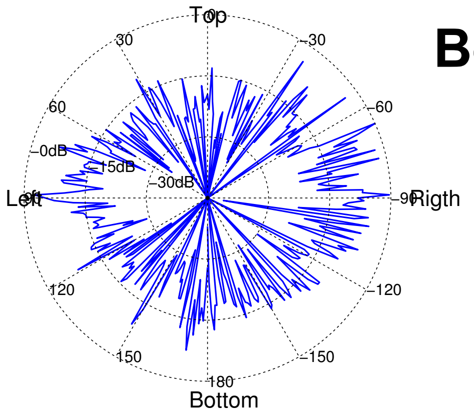


Side view



Behind view

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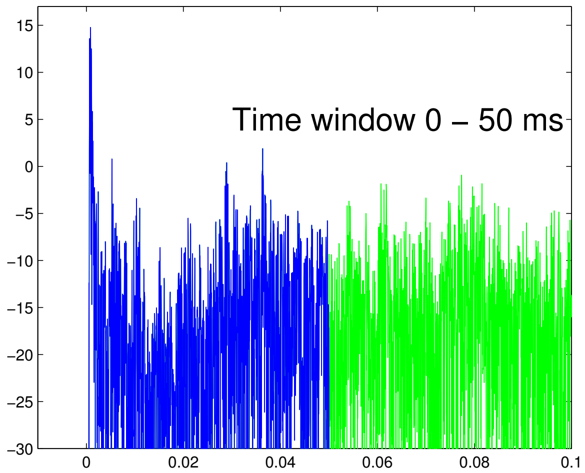
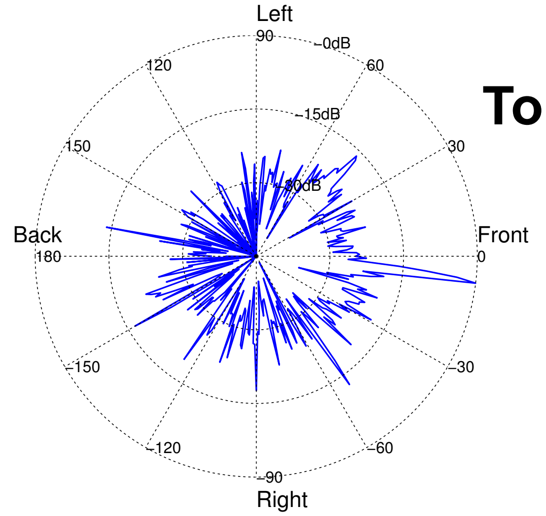
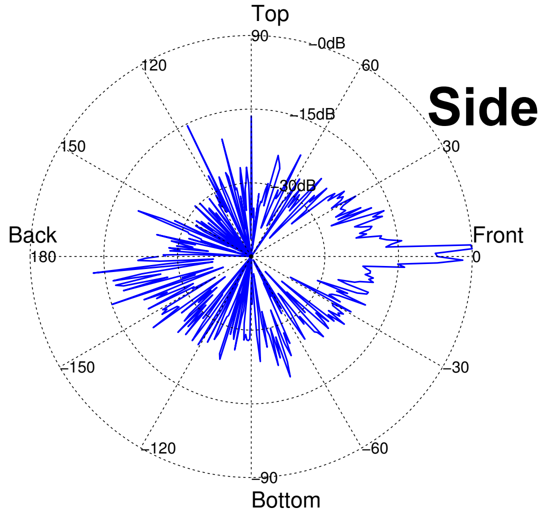
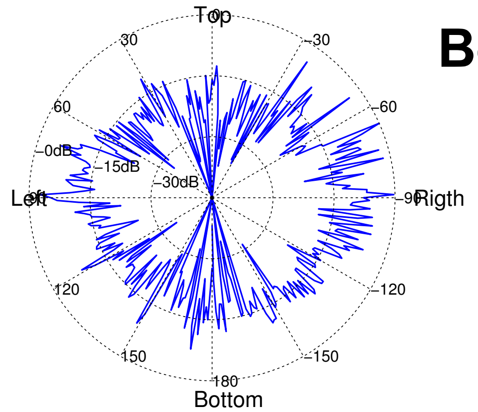




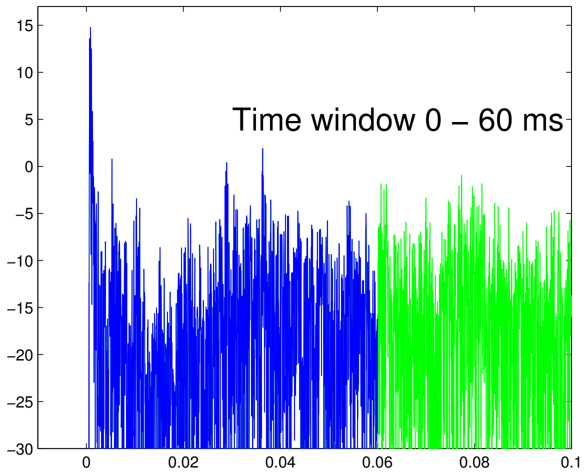
Top view

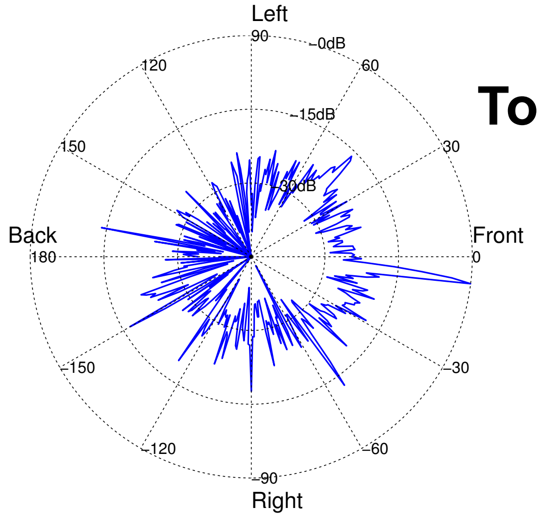


Side view

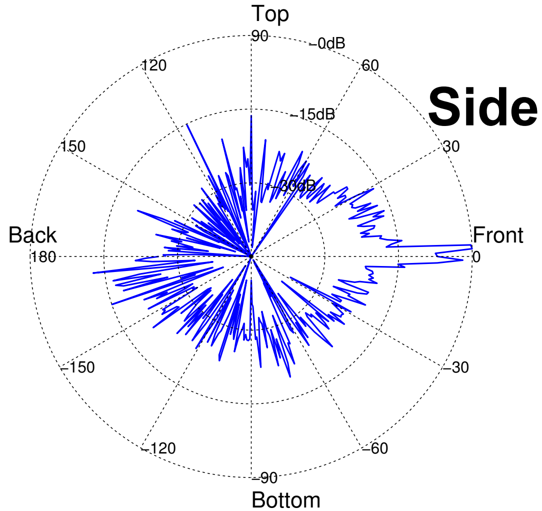


Behind view

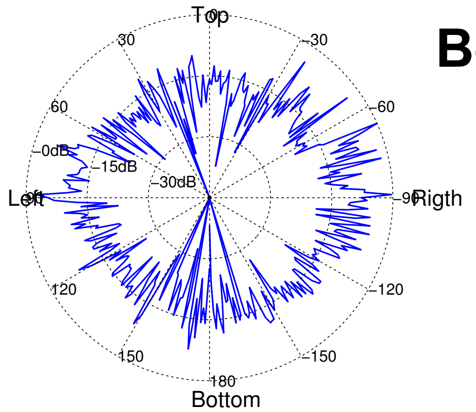




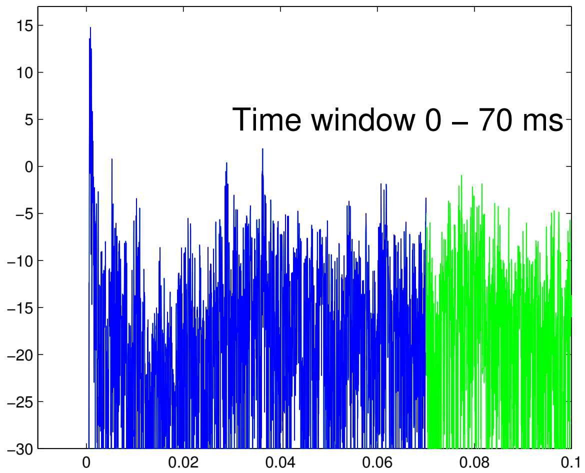
Top view

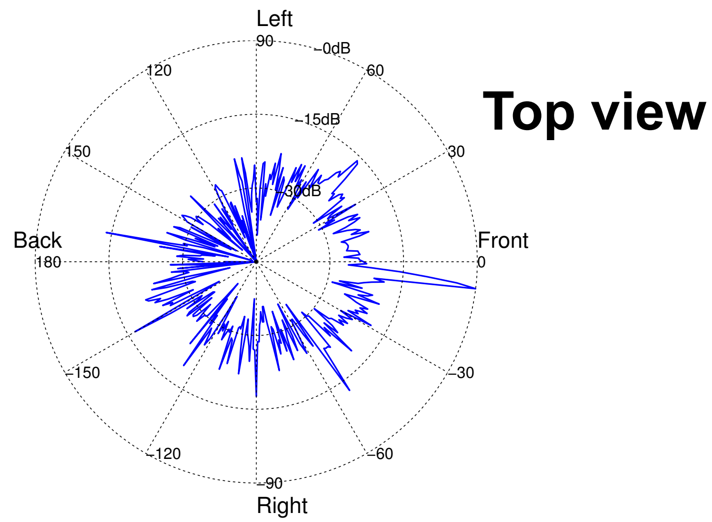


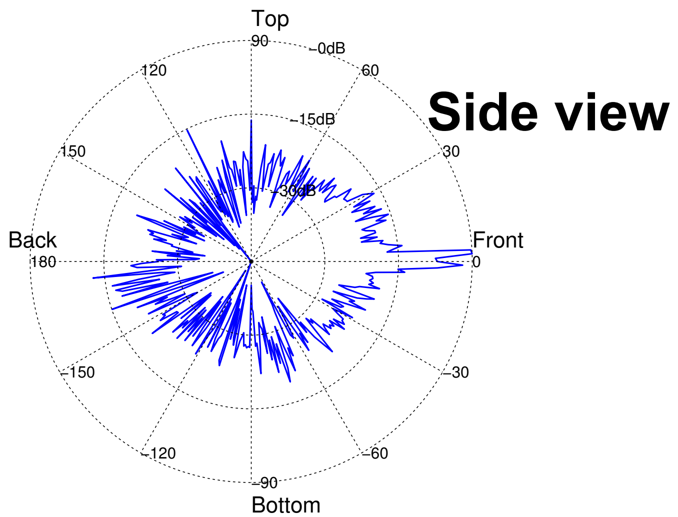
Side view

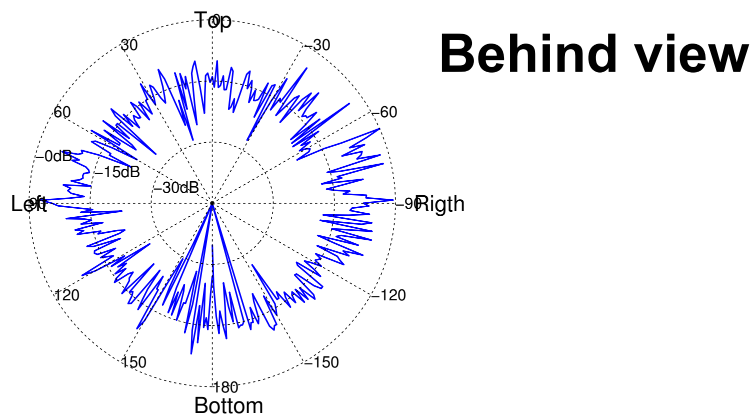


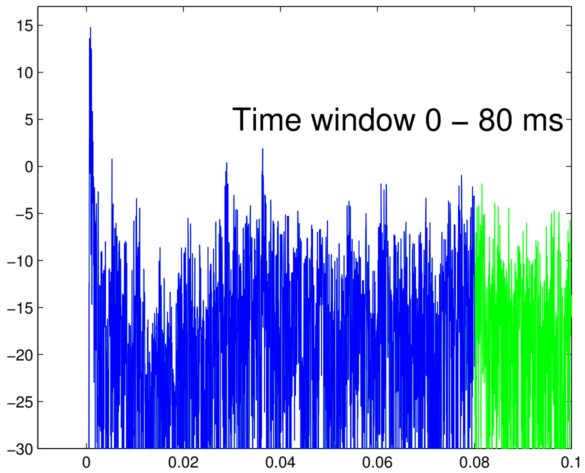
Behind view

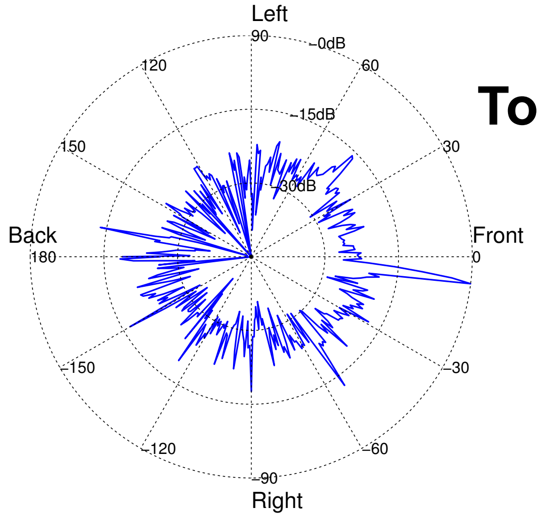

Time window 0 – 70 ms
15
10
5
0
−5
−10
−15
−20
−25
−30
0
0.02
0.04
0.06
0.08
0.1


Left
Right
Back
Front
Top view
−0dB
−15dB
−30dB

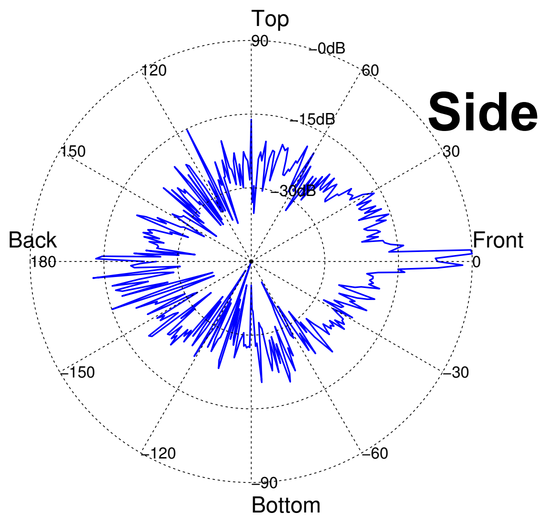

Top
Bottom
Back
Front
Side view
−0dB
−15dB
−30dB


Top
Bottom
Left
Rigth
Behind view
−0dB
−15dB
−30dB

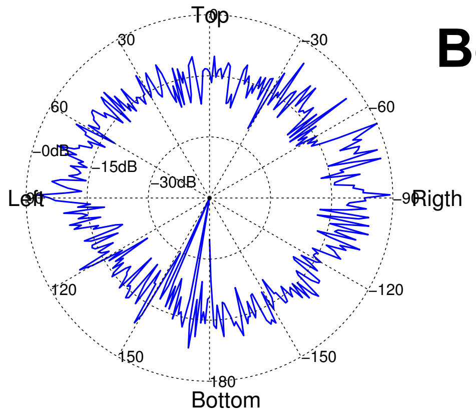




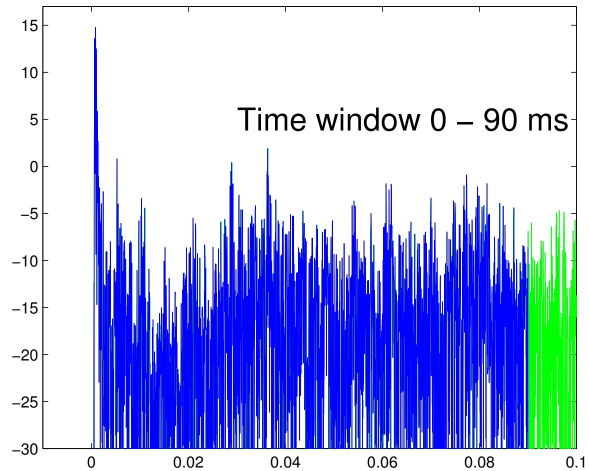
Top view

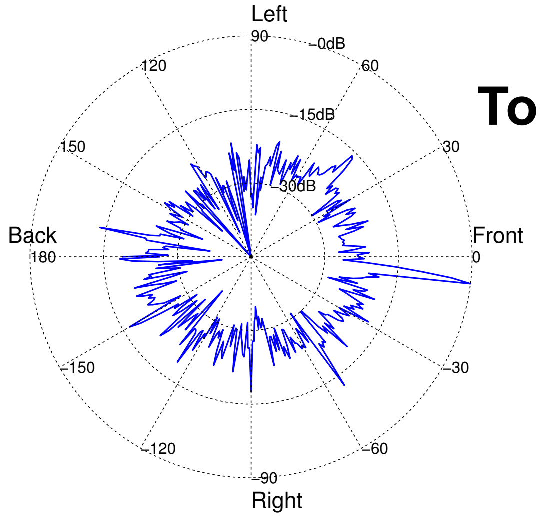


Side view

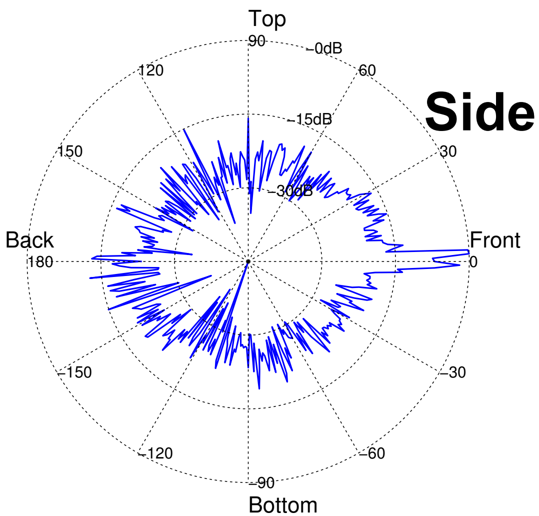


Behind view

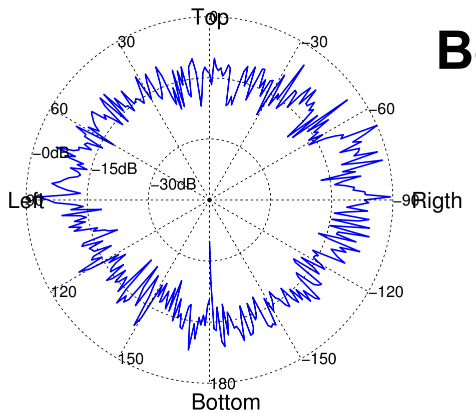




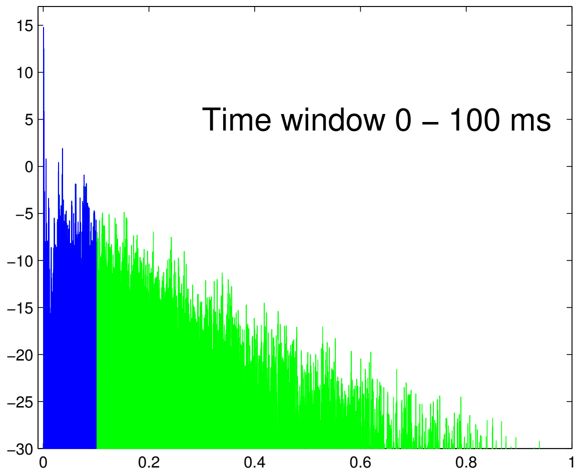
Top view

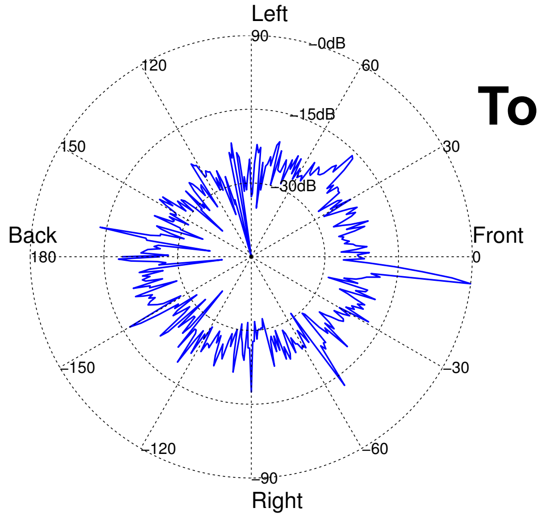


Side view

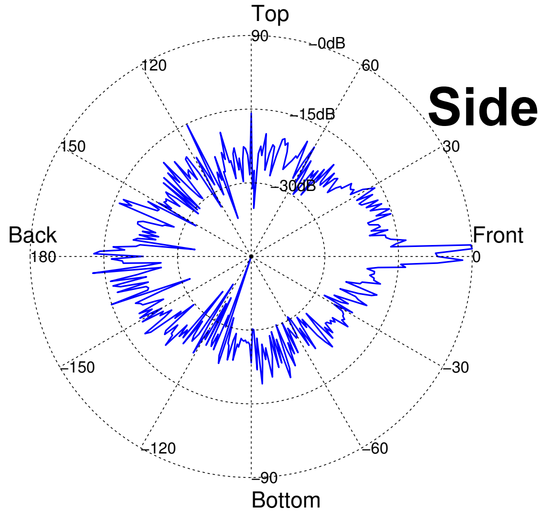


Behind view

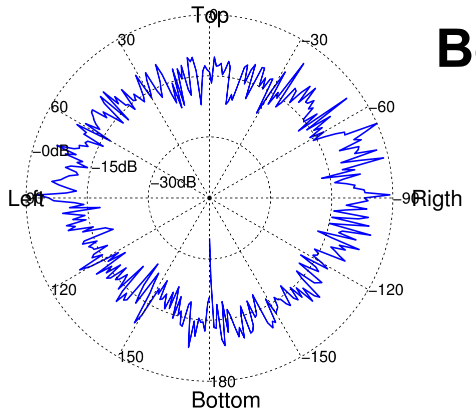




Top view



Side view



Behind view

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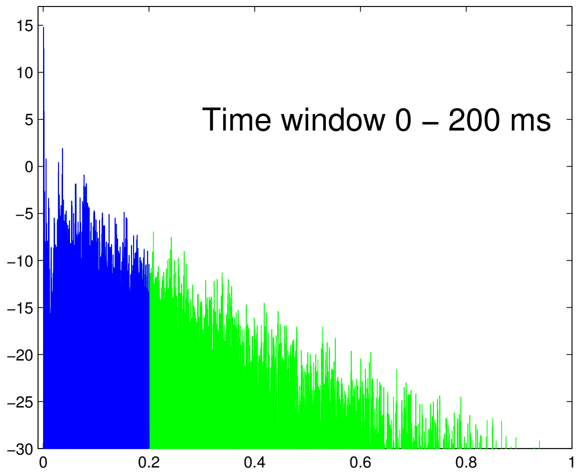
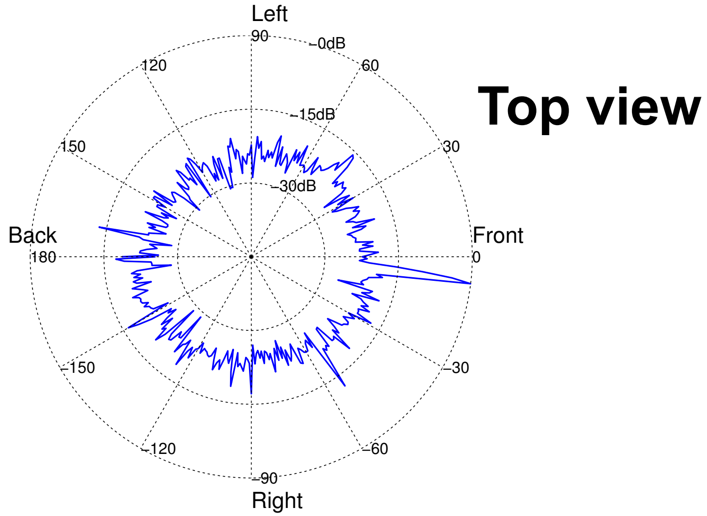
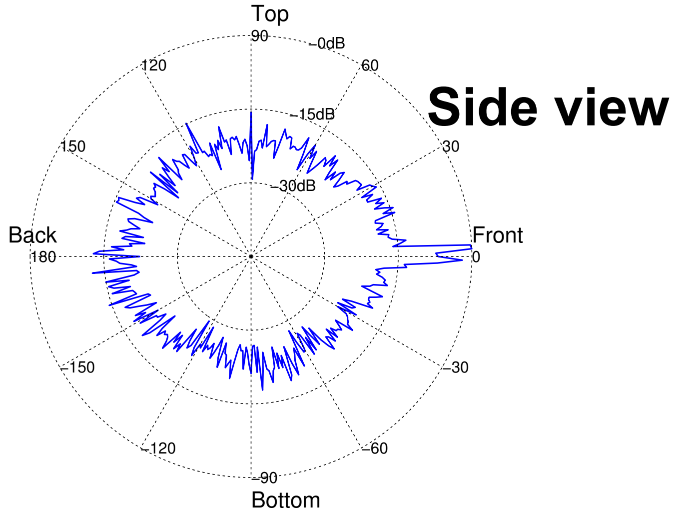
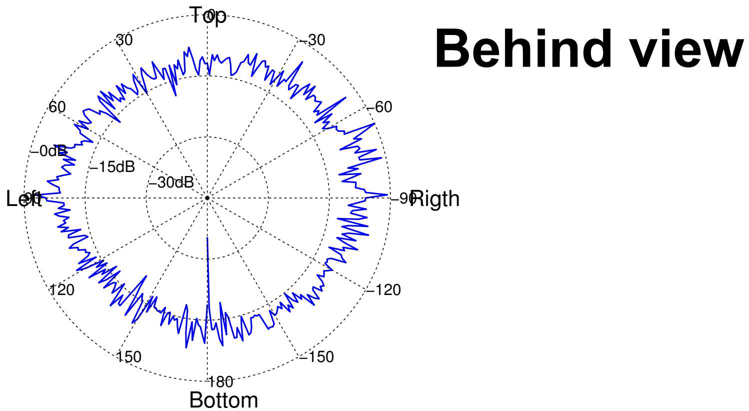
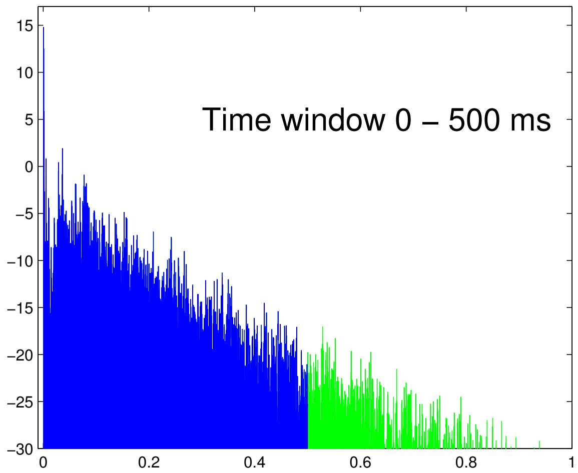
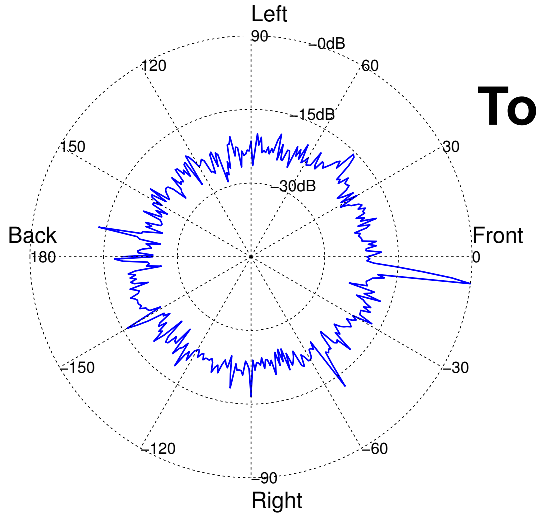

Time window 0 – 200 ms


Left
Front
Back
Right
Top view

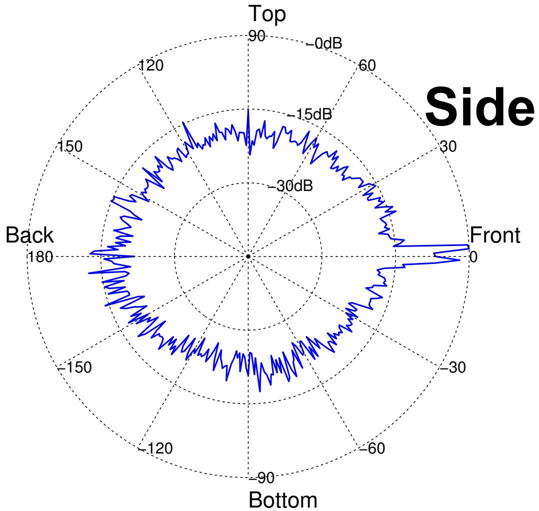

Top
Front
Back
Bottom
Side view


Top
Left
Rigth
Bottom
Behind view

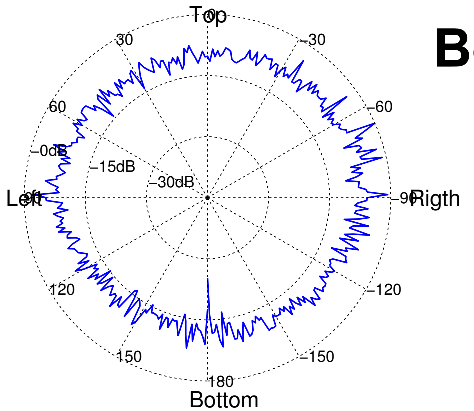




Top view

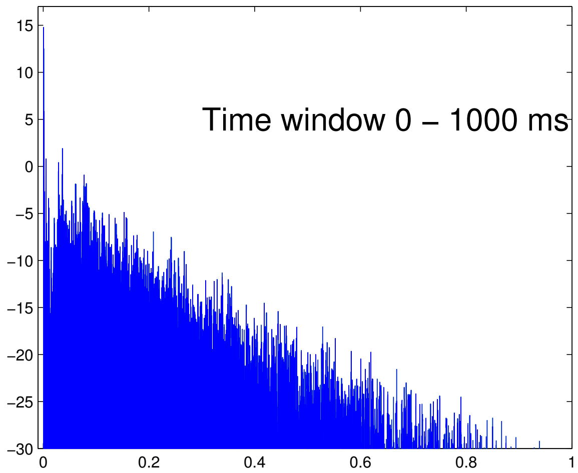


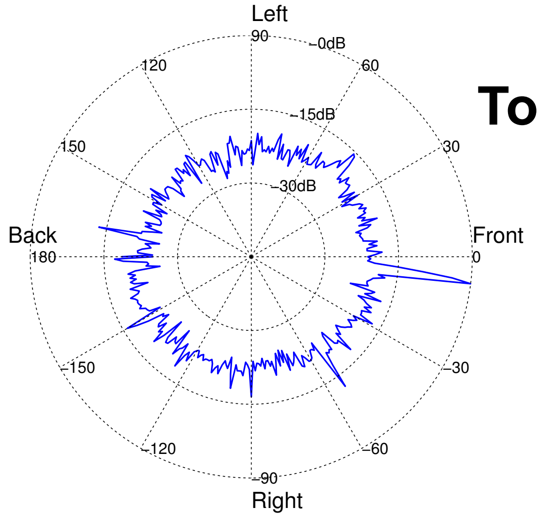
Side view



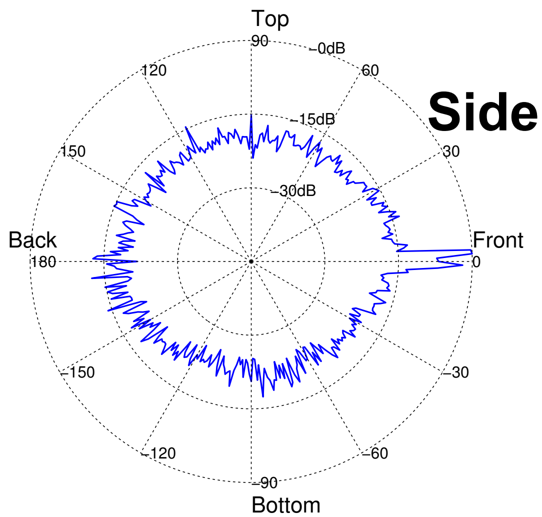
Behind view

Jukka.Patynen@aalto.fi & Sakari.Tervo@aalto.fi

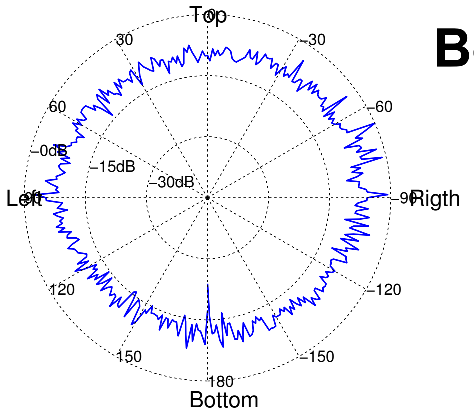




Top view

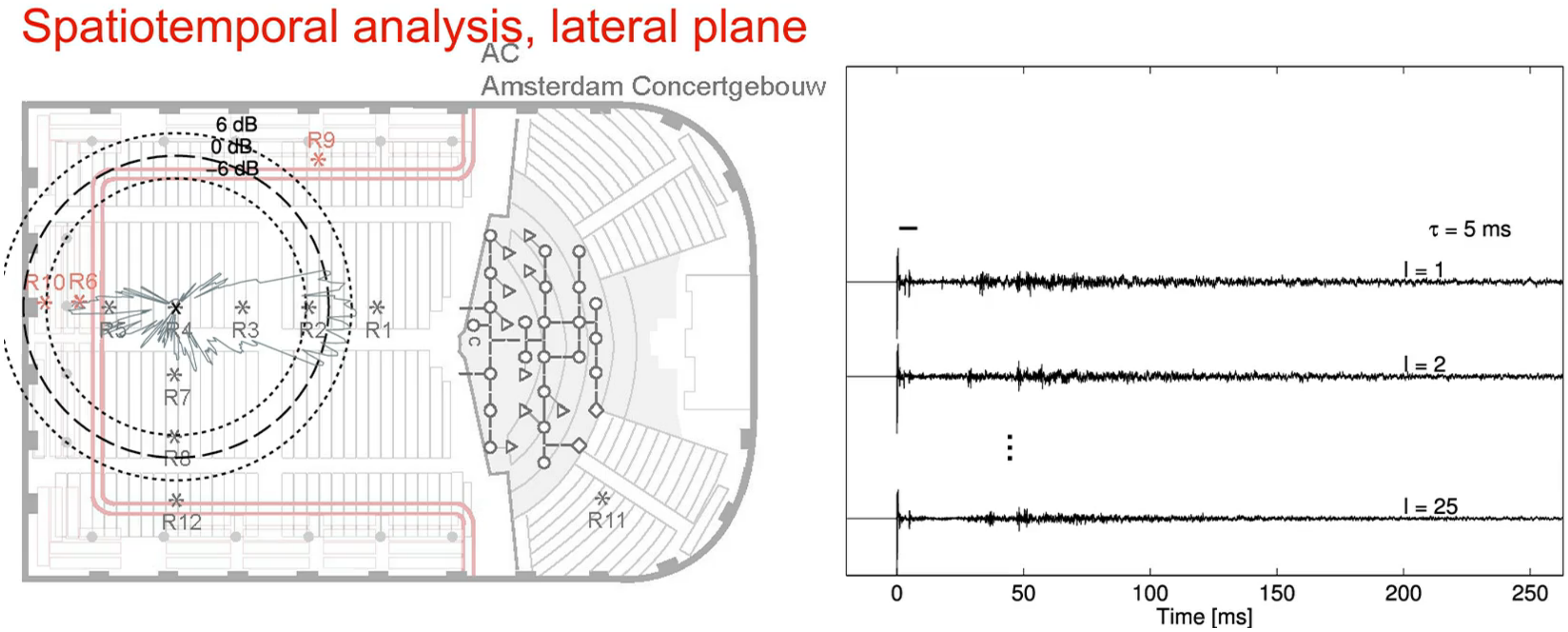


Side view



Behind view

Spatiotemporal analysis example, concert hall, 24 sources together



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Spatiotemporal visualization

- **Analyze the spatial distribution of sound energy cumulating over time**
- **Forward or backward integration**
- **Forward integration ~ Hearing integration**
- **Backward integration ~ Emphasis on room reverberation**

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Visualization of concert hall analysis

More details:

J. Pätynen et al. (2013): “Analysis of concert hall acoustics via visualization of time-frequency and spatiotemporal responses”, JASA.

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Part 4:
Applications

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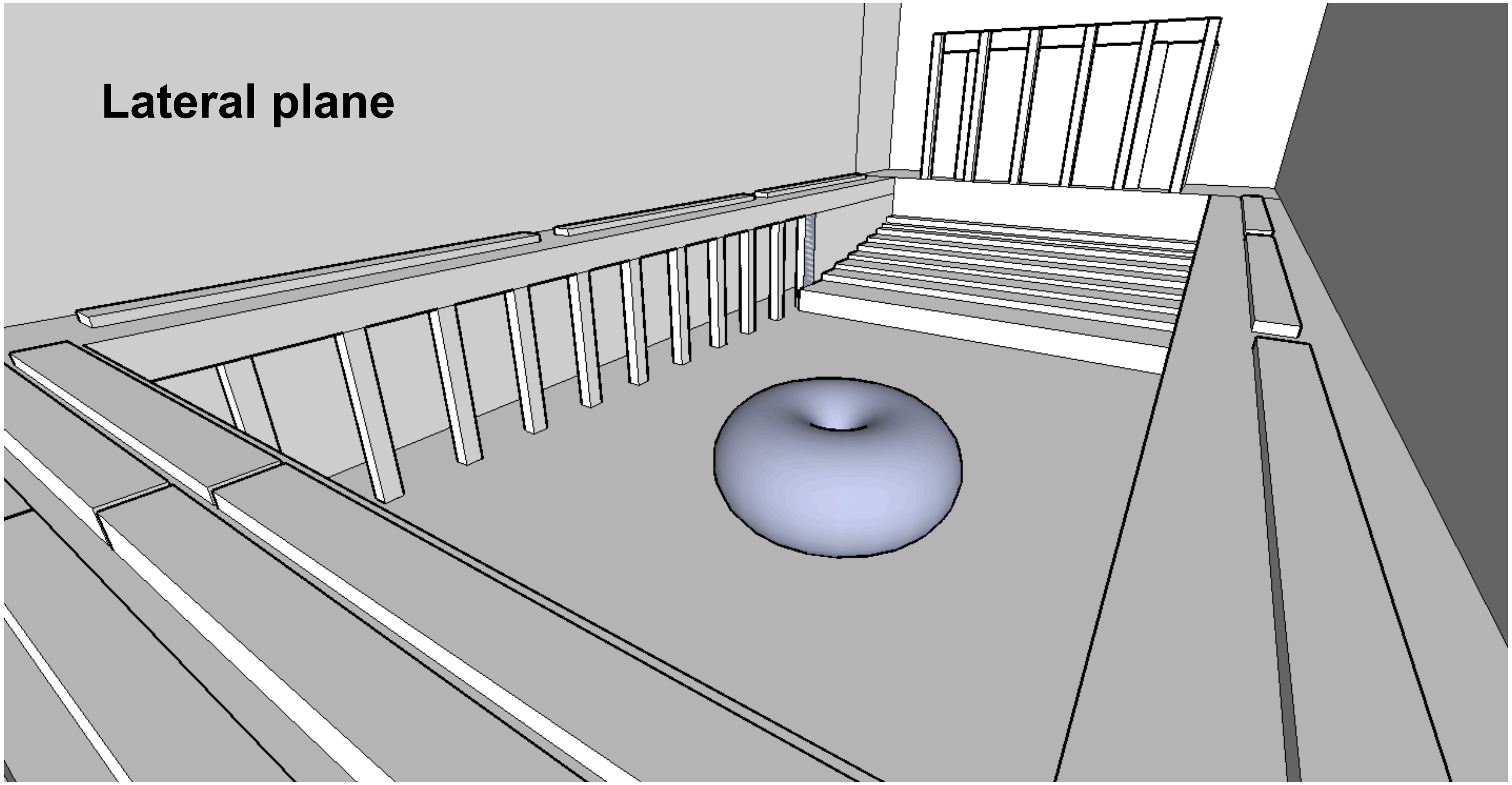
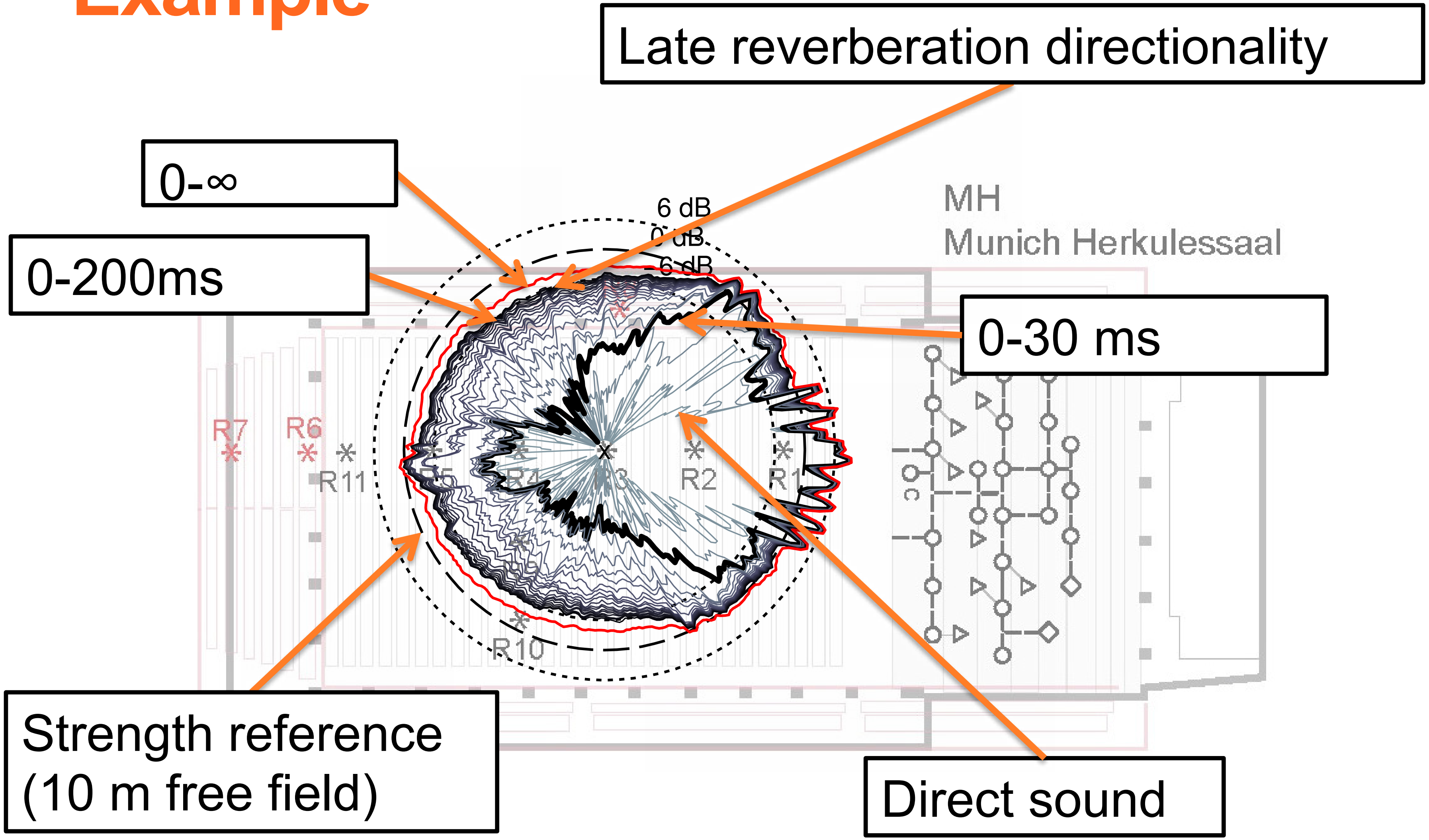
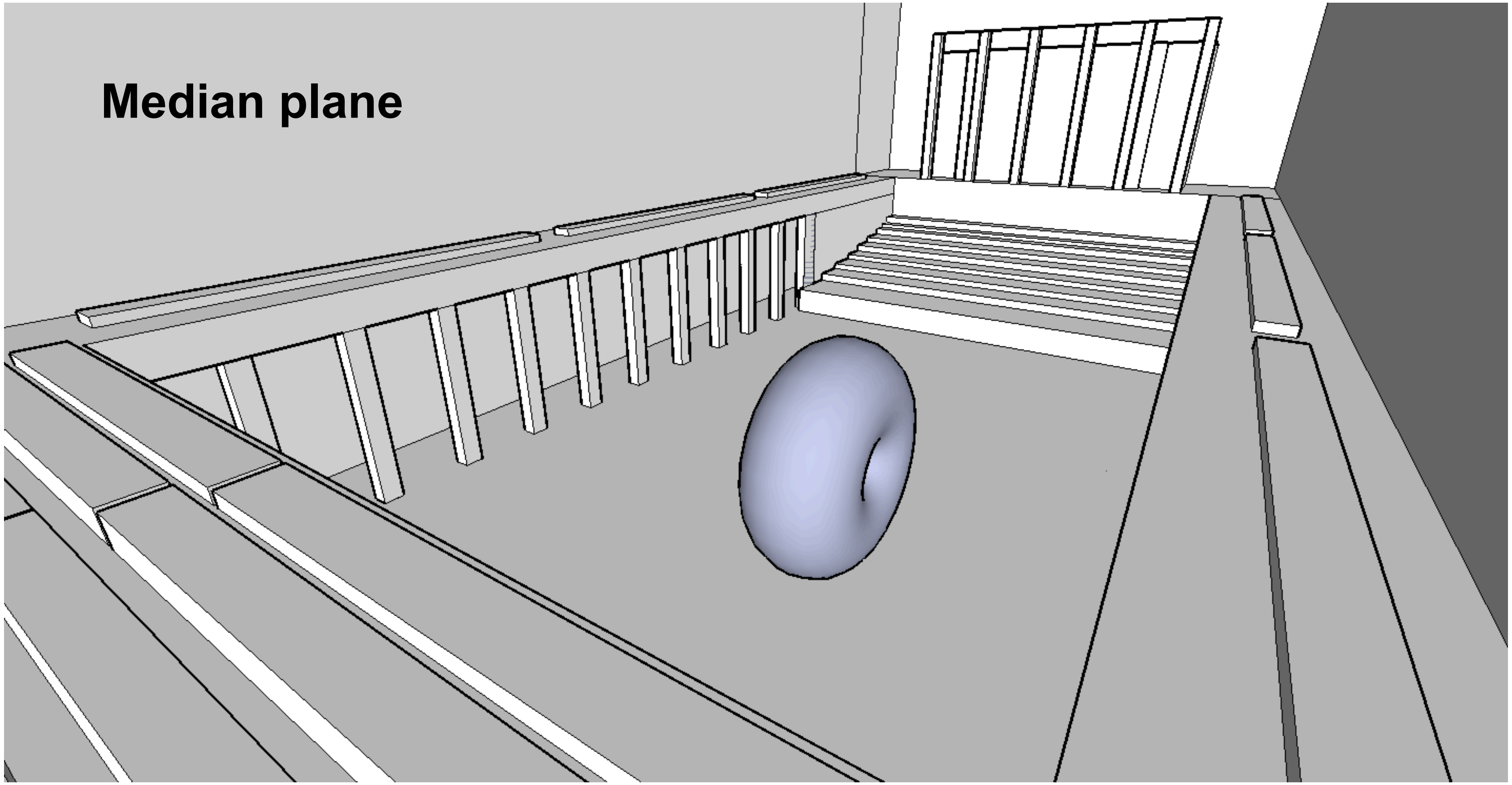
Directional weighting, w.r.t. ISO3382



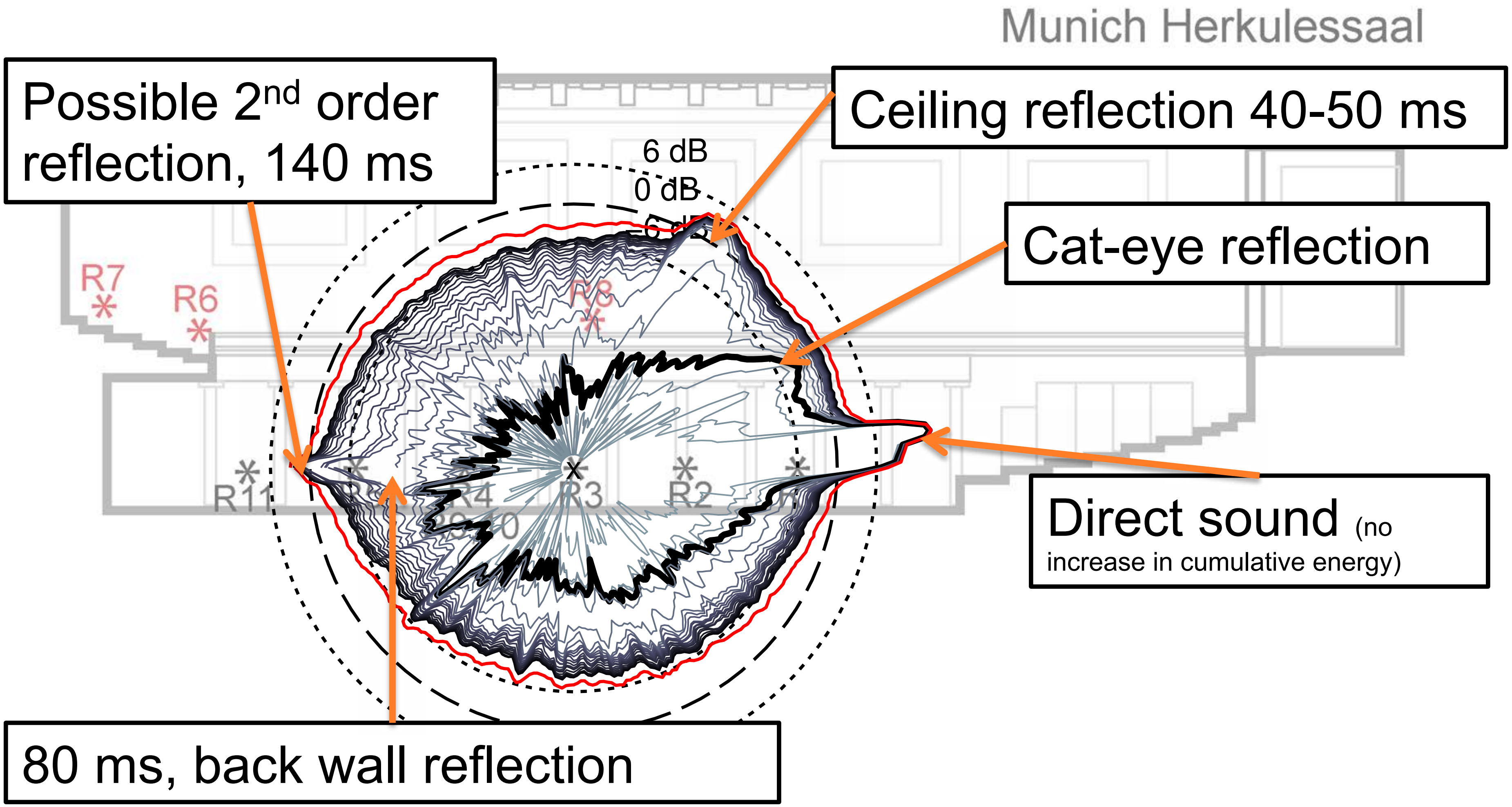
Example


Late reverberation directionality
0-∞
0-200ms
0-30 ms
Strength reference
(10 m free field)
Direct sound
6 dB
0 dB
-6 dB
MH
Munich Herkulessaal
R7
R6
R11
R2
R1
R10

Directional weighting, w.r.t. ISO3382

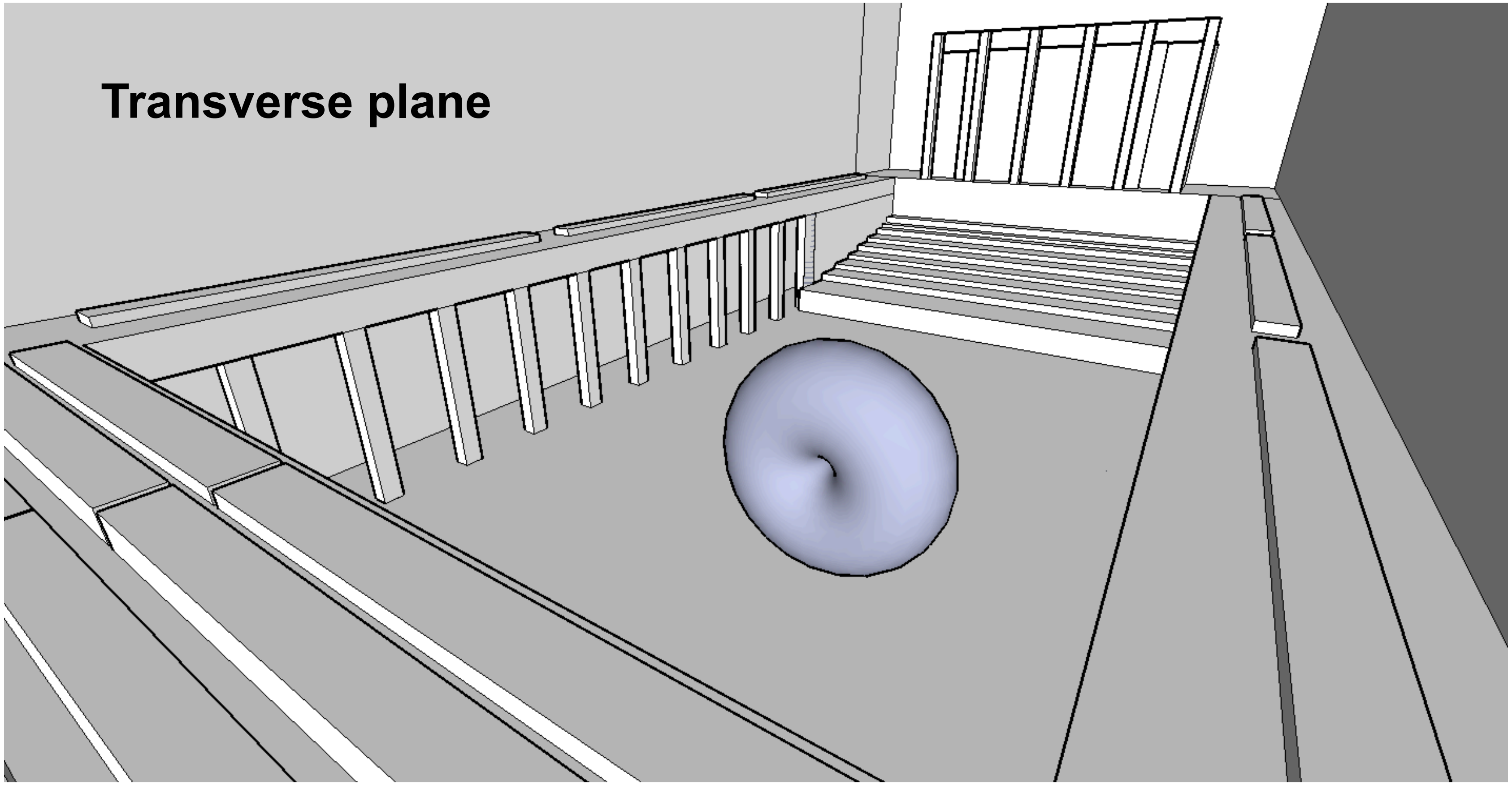


Example



Munich Herkulessaal
Possible 2nd order reflection, 140 ms
Ceiling reflection 40-50 ms
Cat-eye reflection
Direct sound (no increase in cumulative energy)
80 ms, back wall reflection
6 dB
0 dB
R7
R6
R11
R3
R2

Directional weighting, w.r.t. ISO3382



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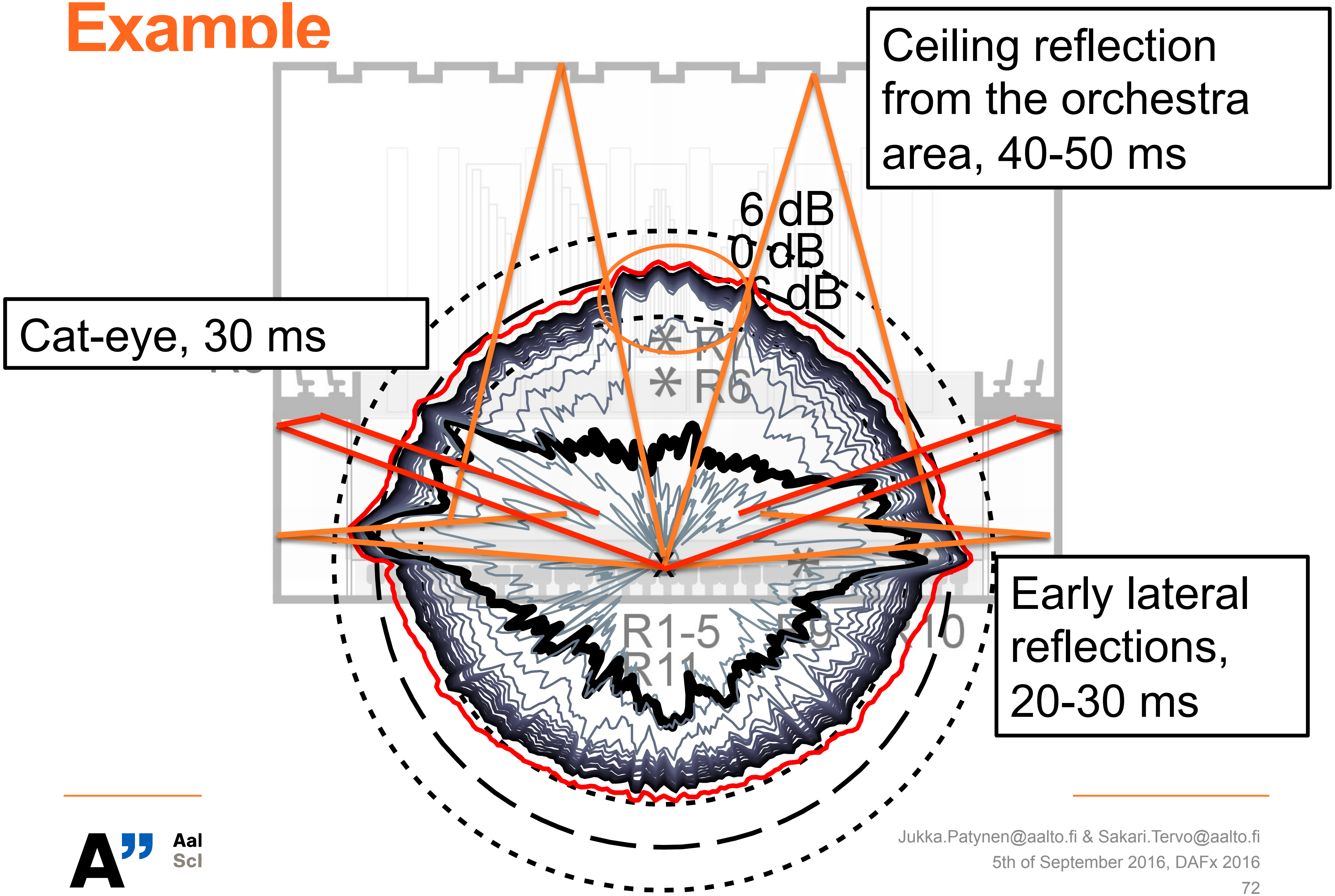
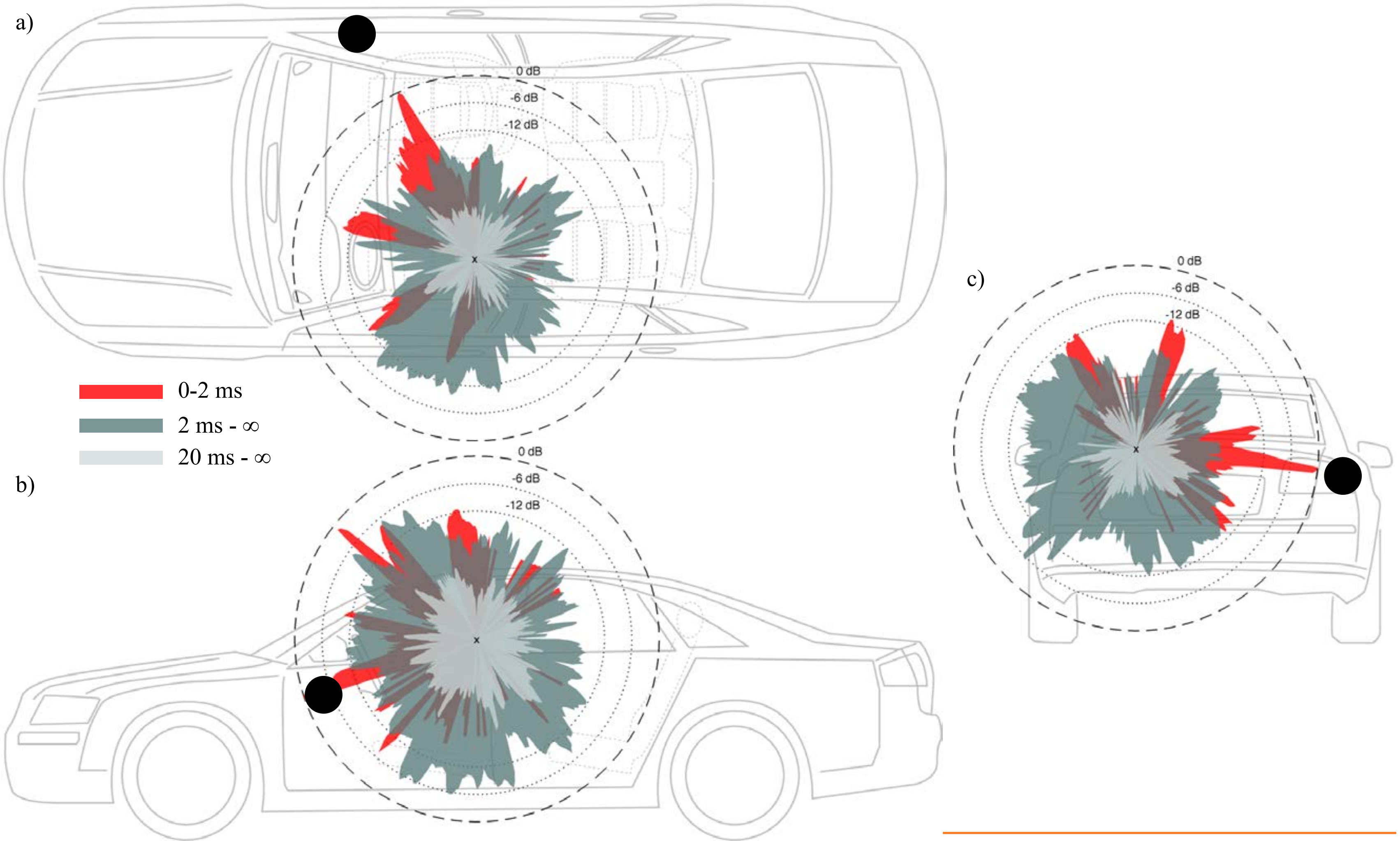
Example

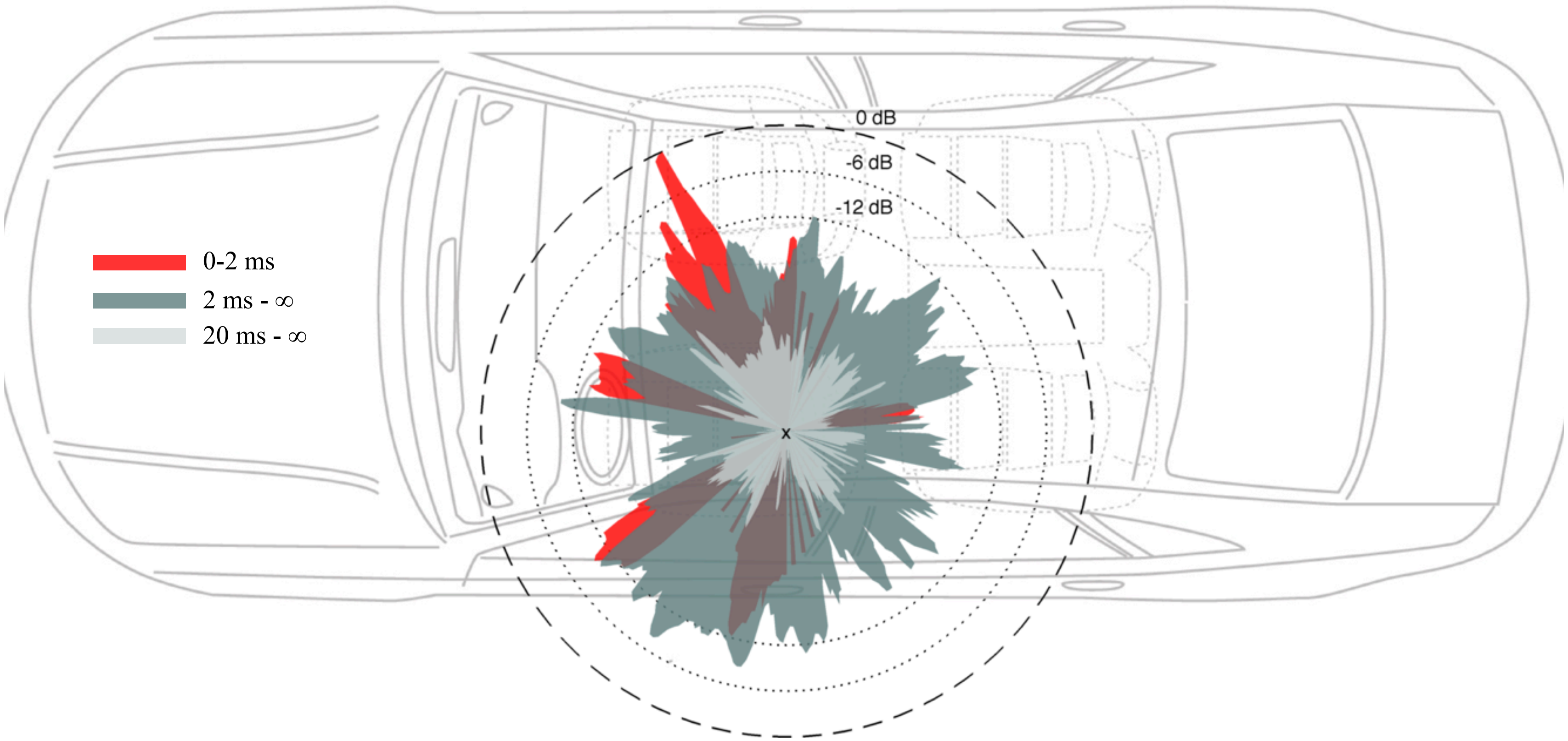

Ceiling reflection from the orchestra area, 40-50 ms
Cat-eye, 30 ms
Early lateral reflections, 20-30 ms
6 dB
0 dB
-6 dB
R7
R6
R1-5
R11
R9
R10

Car audio system



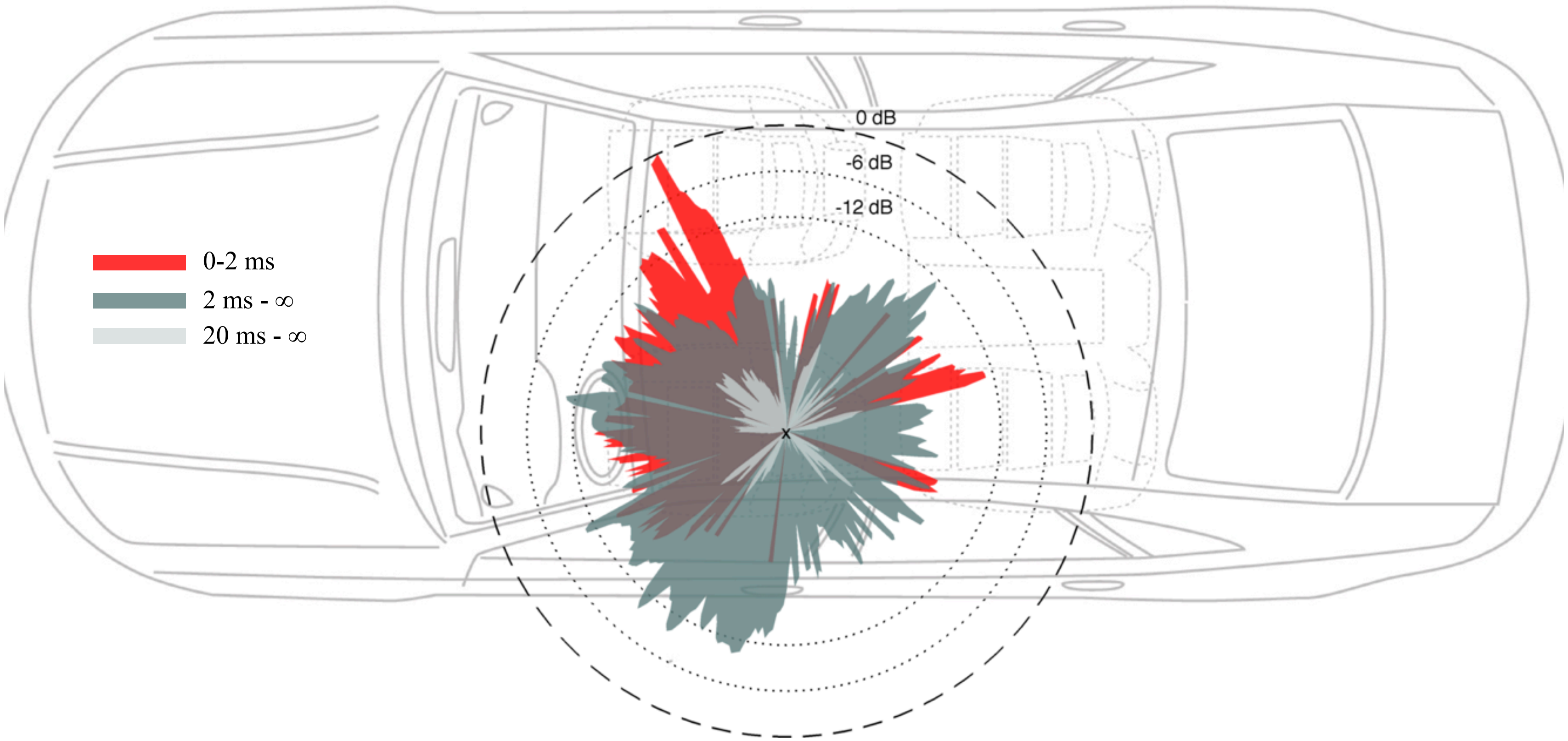
Car audio system

Normal condition



Car audio system

Side windows opened

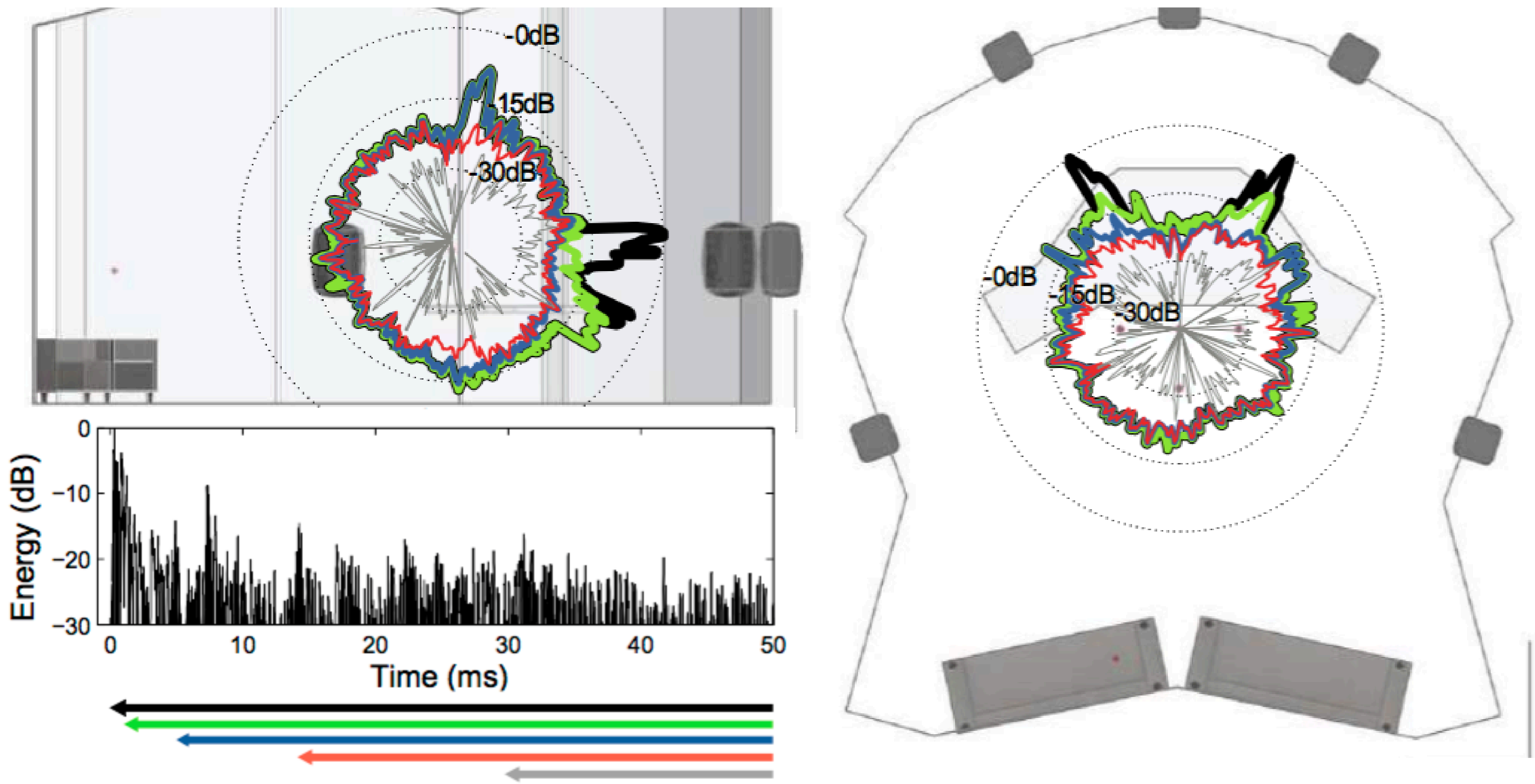


Analysis and reproduction of car audio system

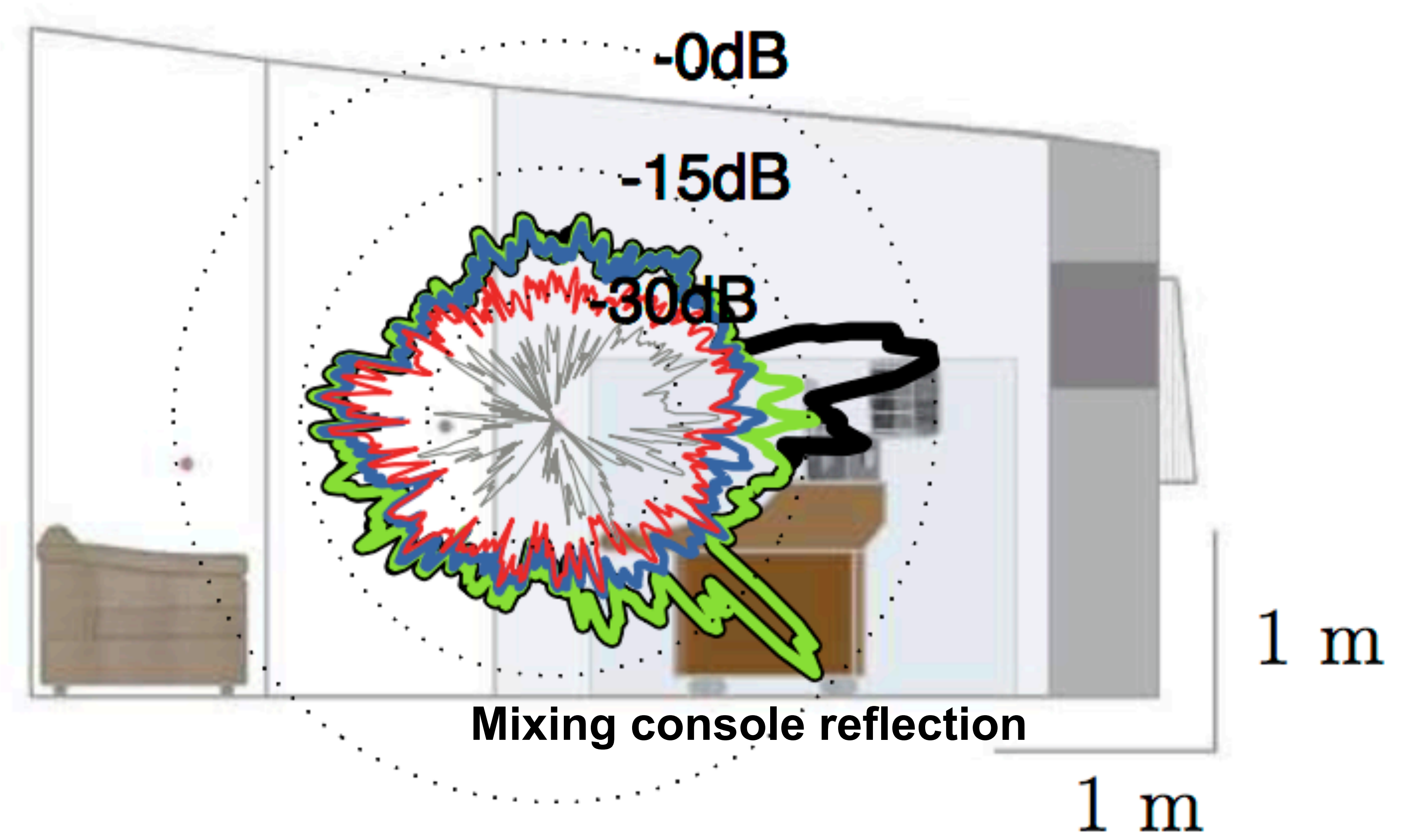
More details:

S. Tervo et al. (2015): "Spatial analysis and synthesis of car audio system and car cabin acoustics", JAES.

Studio control rooms



Studio control rooms



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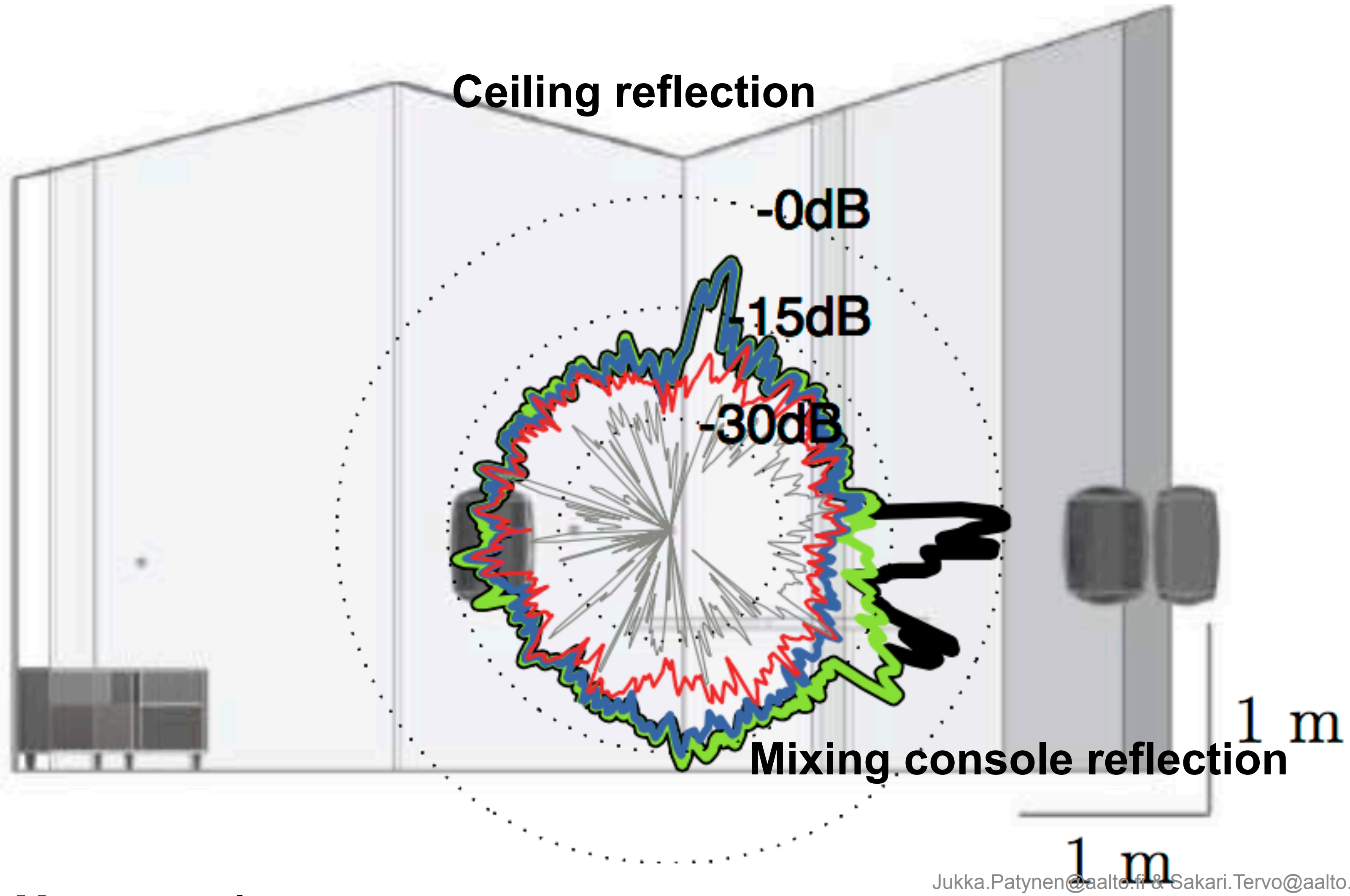
Studio control rooms



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Studio control rooms

Much more details:

P. Laukkanen (2014): "Evaluation of Studio Control Room Acoustics with Spatial Impulse Responses and Auralization", Master's thesis.

Next: concert space details

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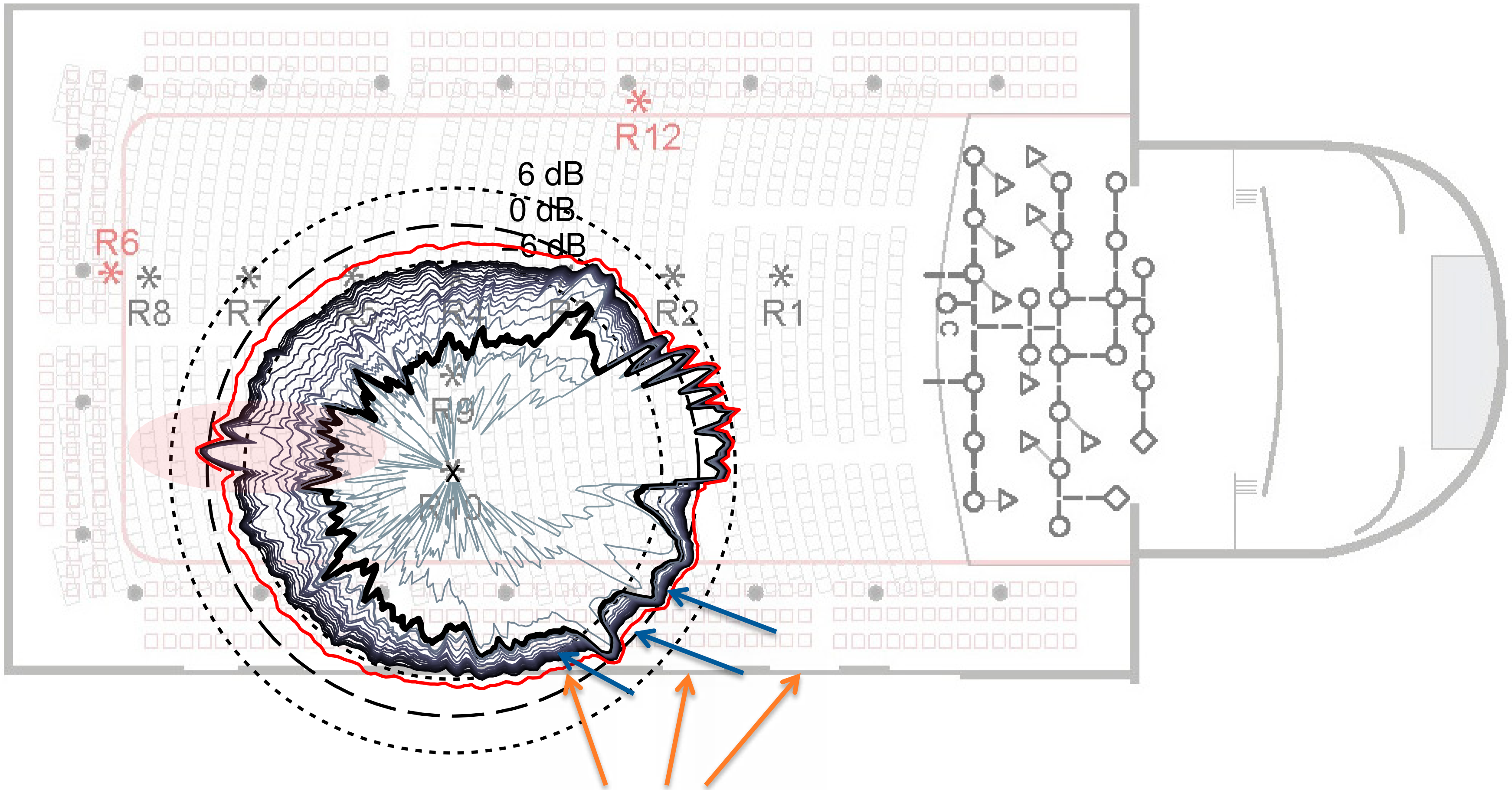
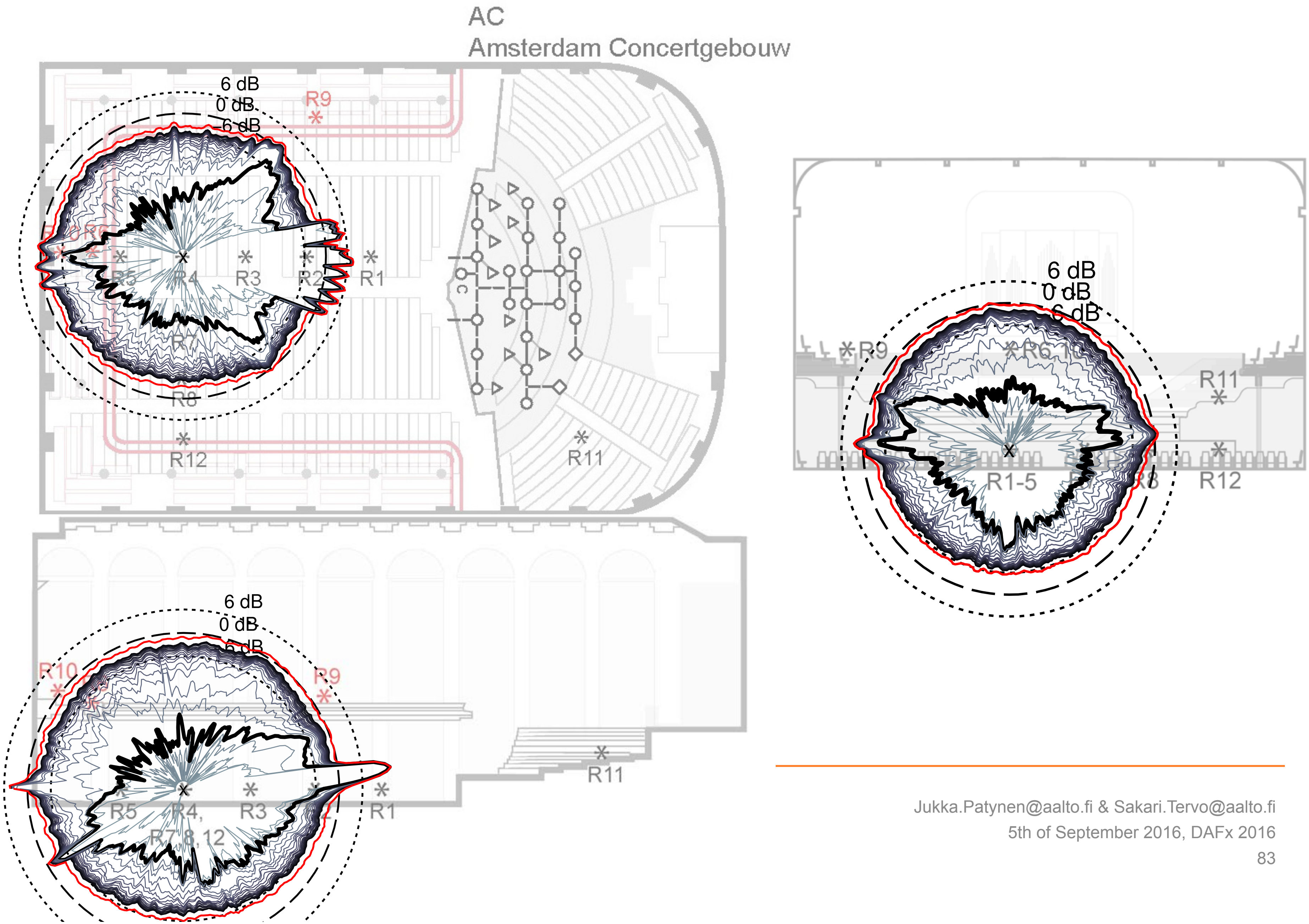
Concert halls, wall materials

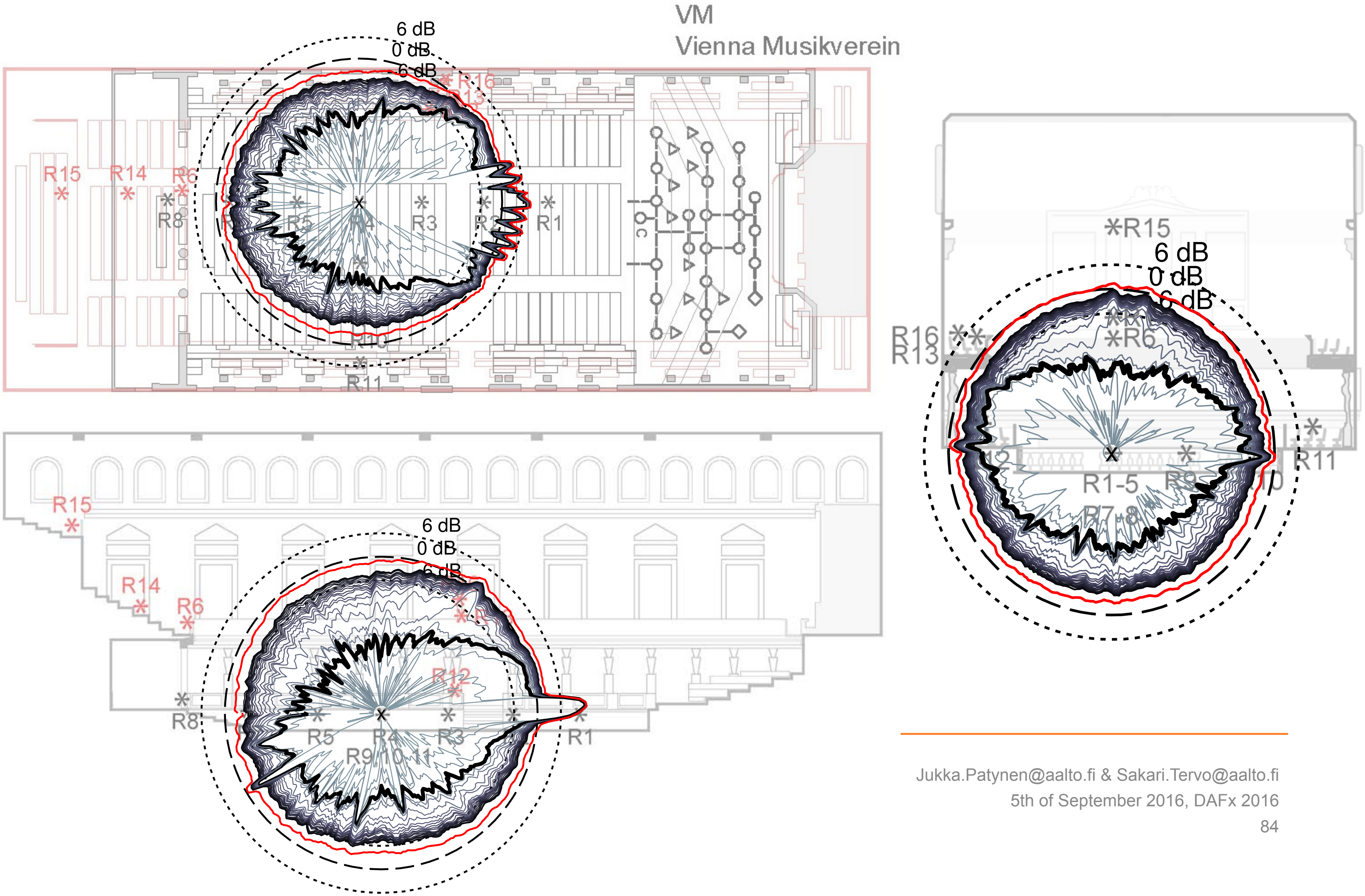


Windows with absorbing drapes

Concert hall examples, shoebox



Concert hall examples, shoebox



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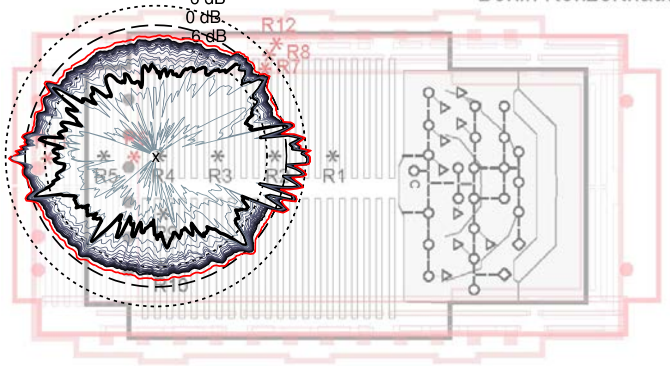
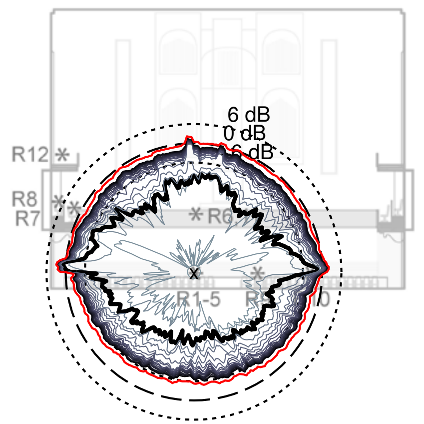
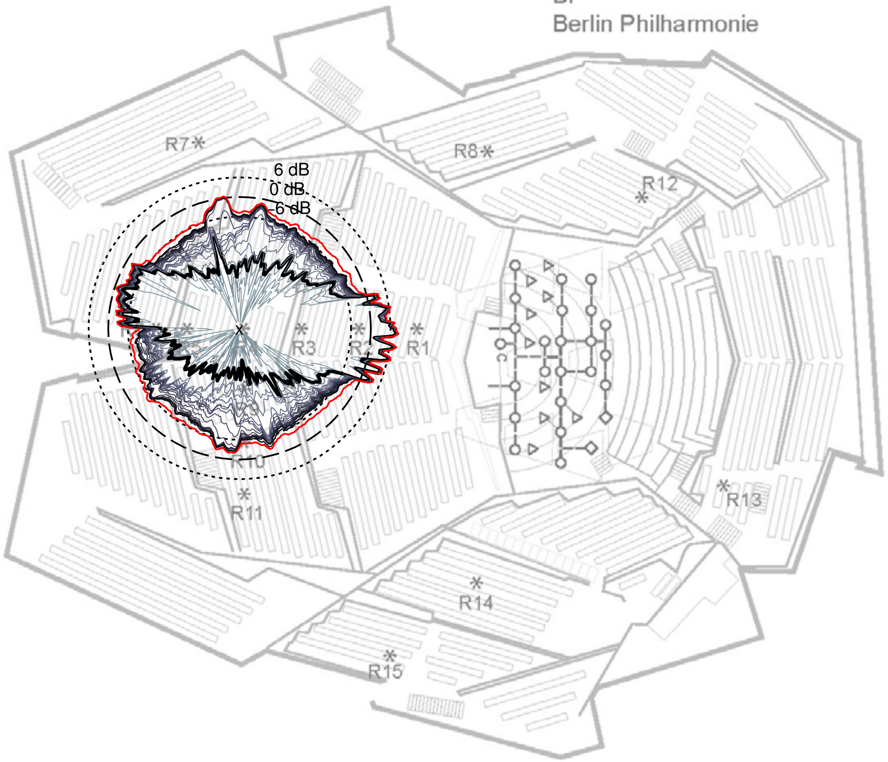
Concert hall examples, identical distance

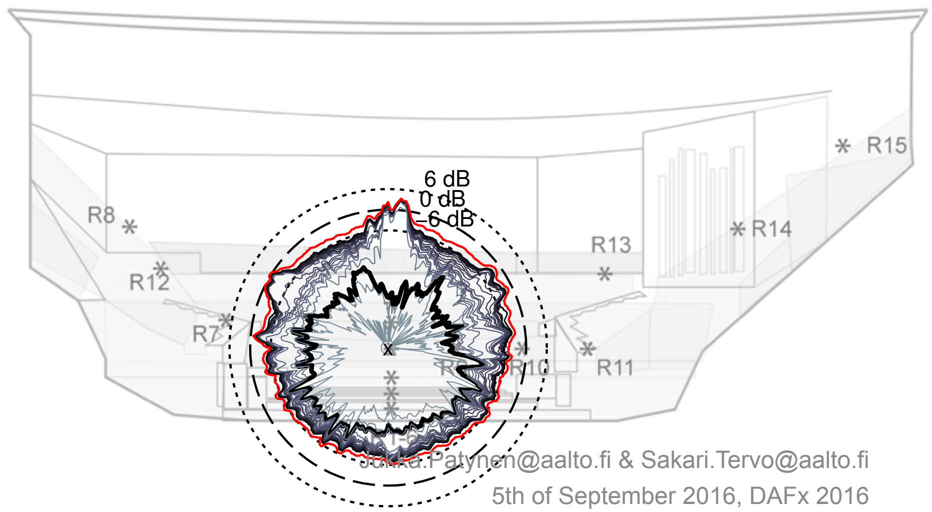
BK
Berlin Konzerthaus



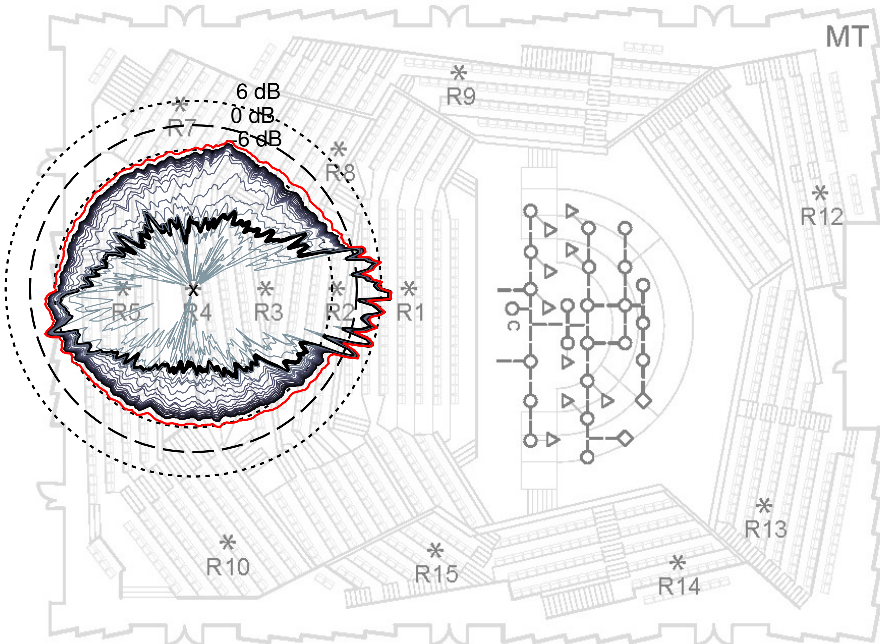


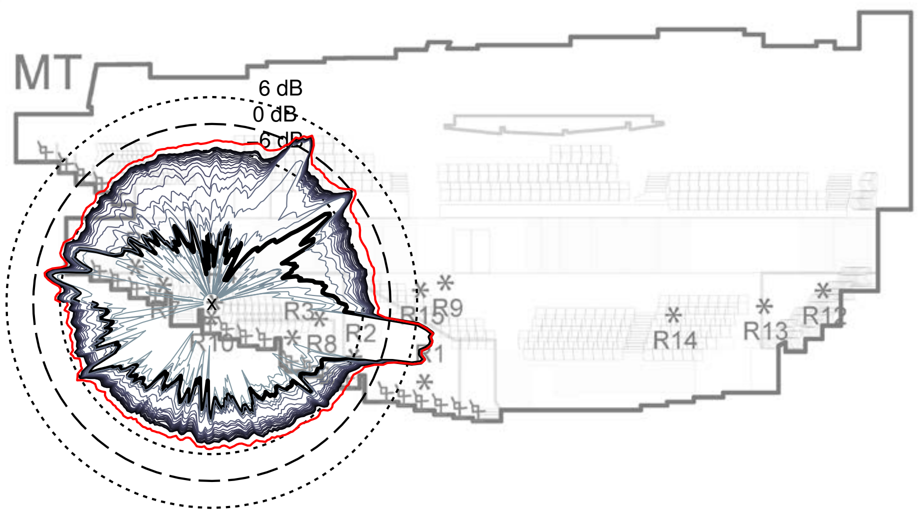
BP
Berlin Philharmonie



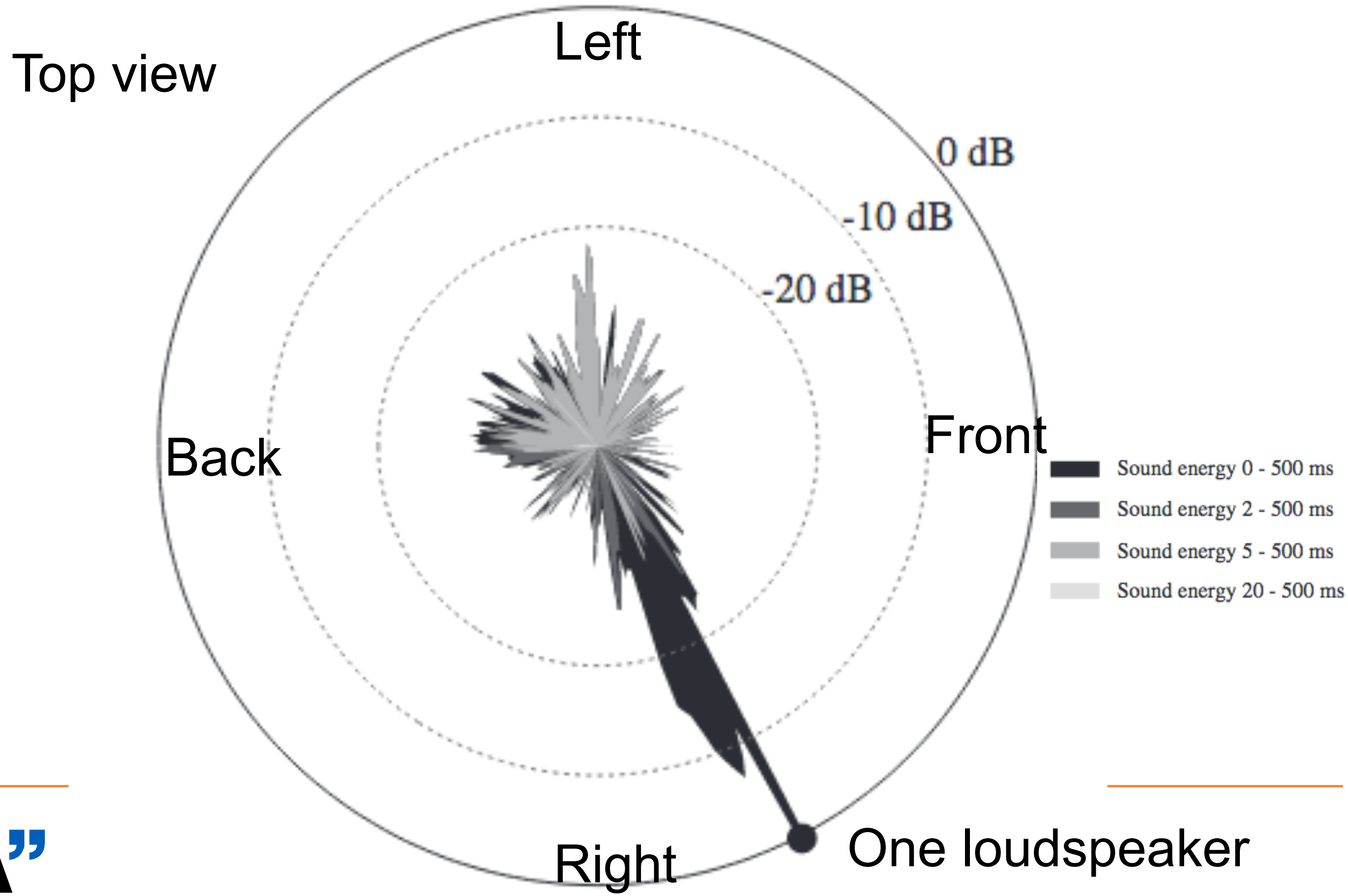


Concert hall examples, vineyard



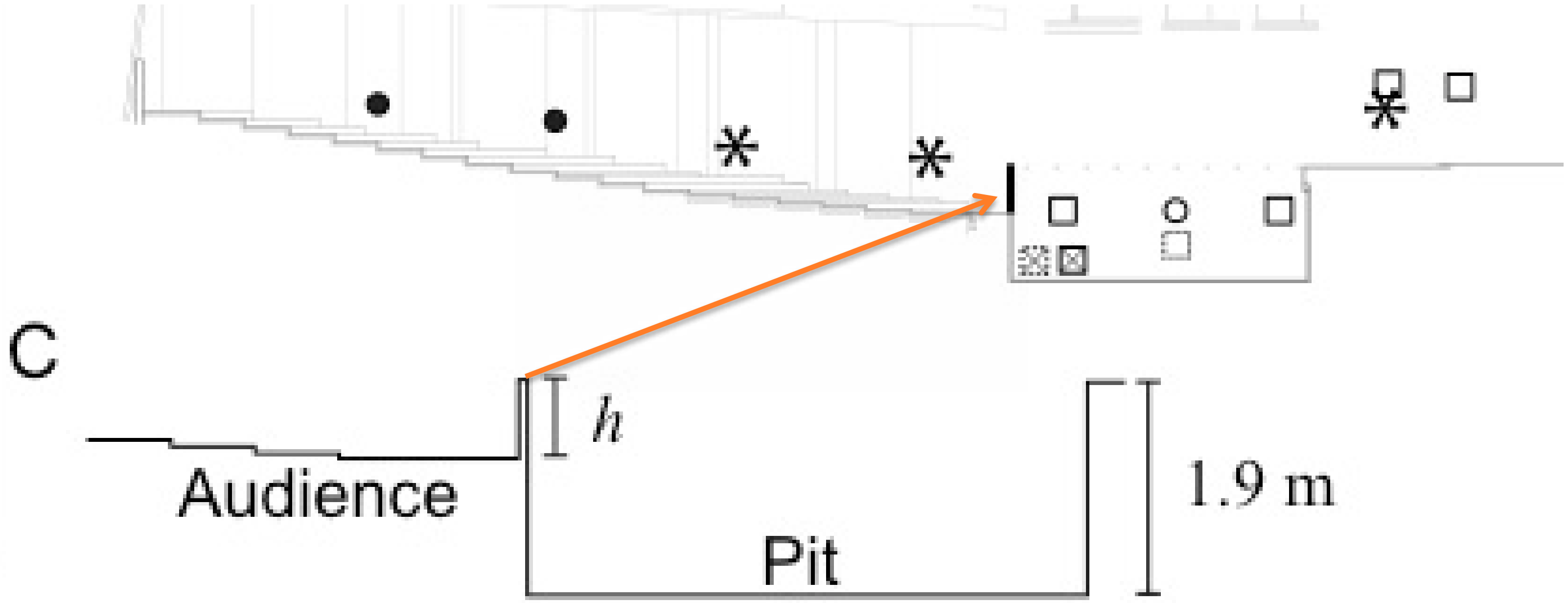


Listening room acoustics



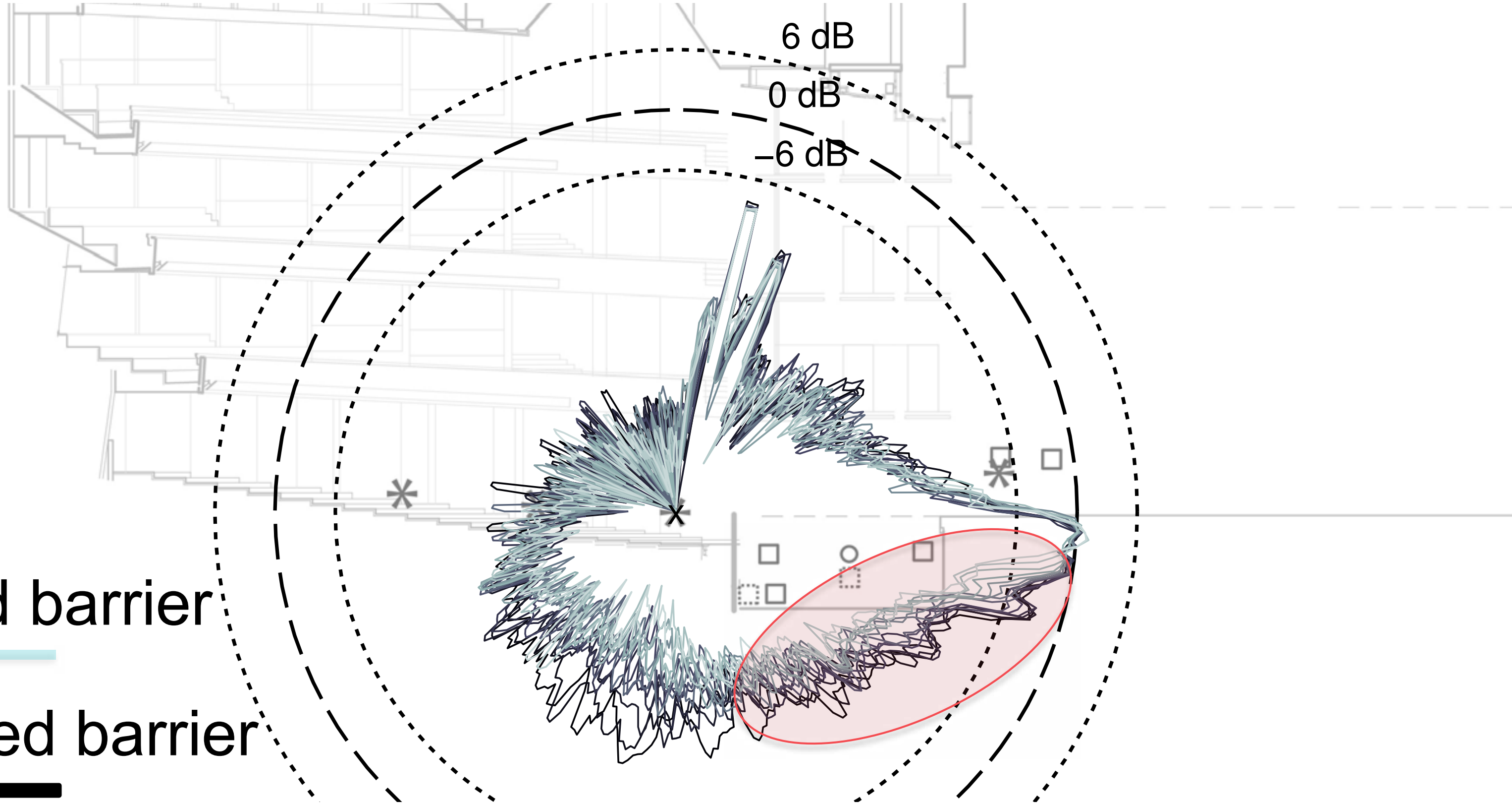
Opera house: pit barrier

- Other variables for overlaid plots
- Variation of physical property
- Adjustable opera pit barrier height



Opera house: pit barrier

Early sound (50 ms), sources in the pit



Raised barrier

Lowered barrier

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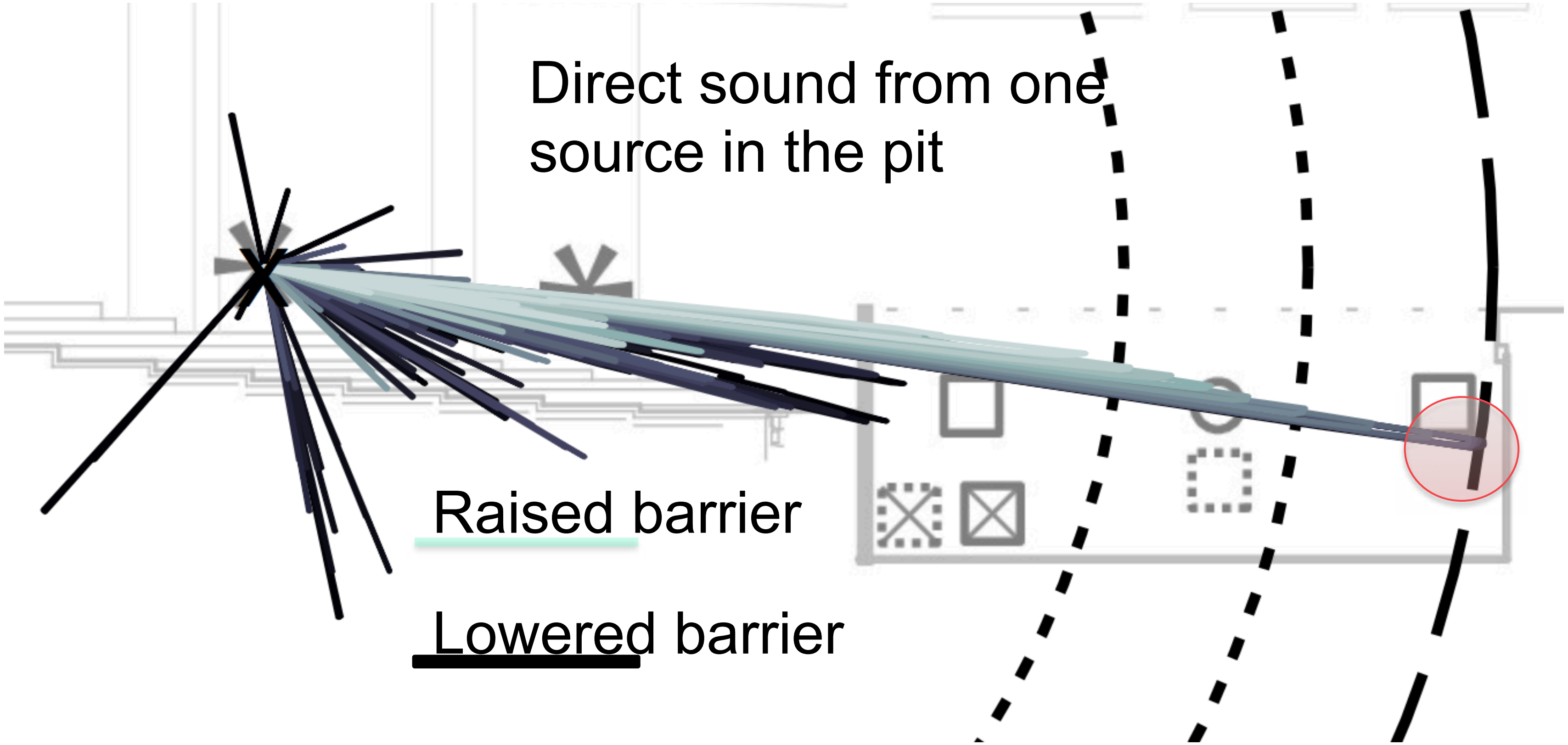
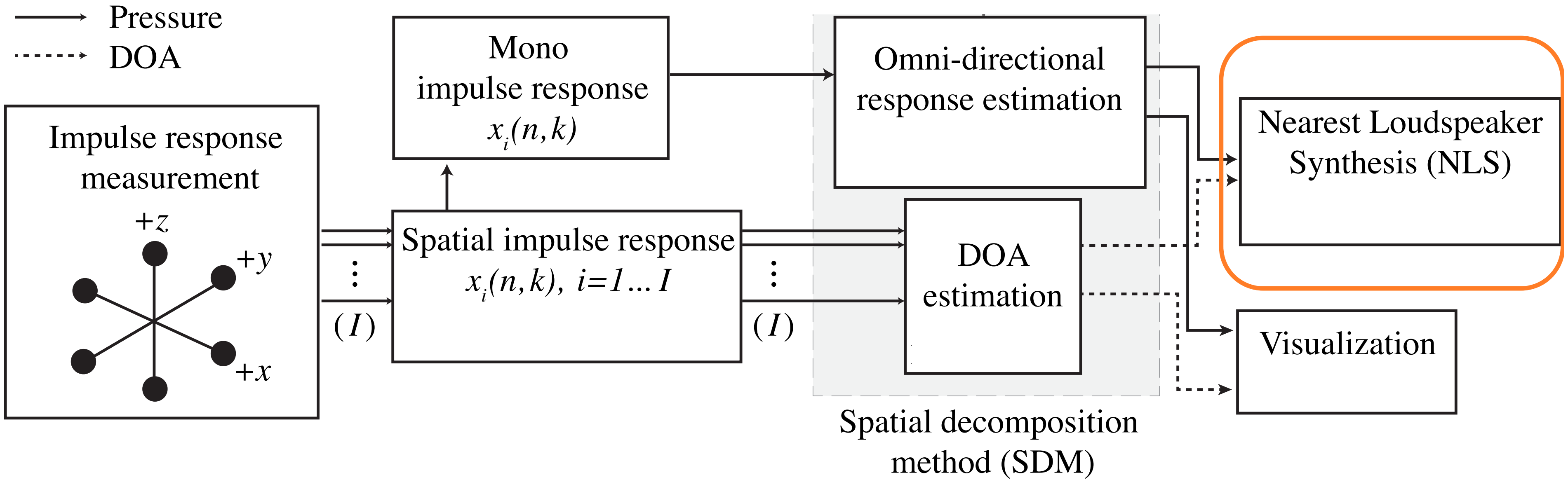
Opera house: pit barrier



Apply the same analysis results for auralization



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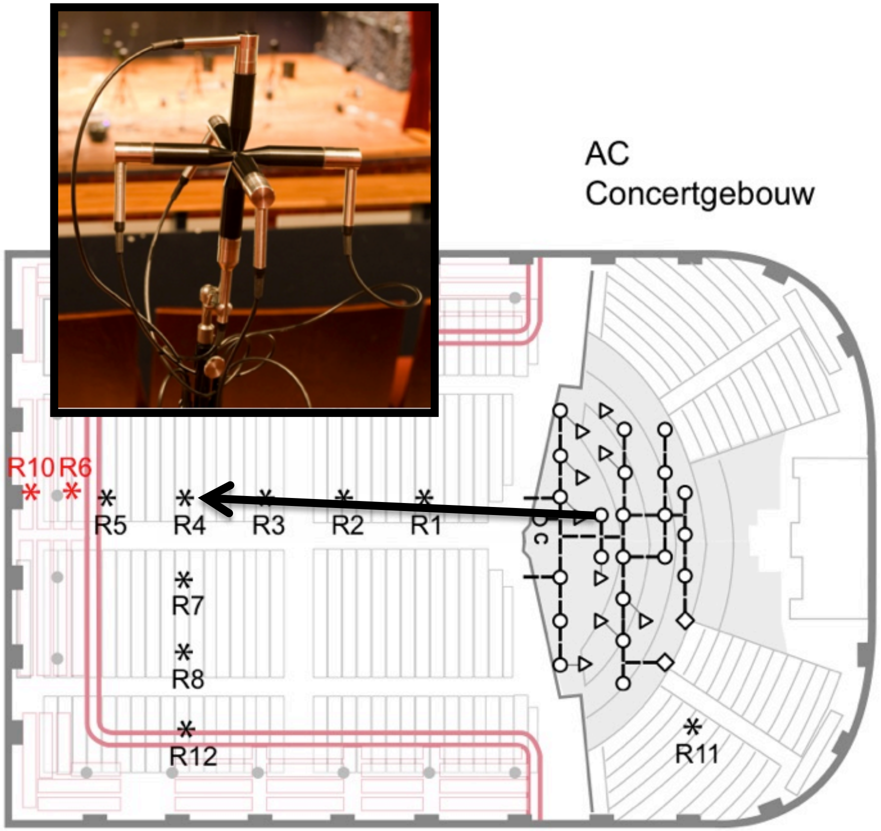
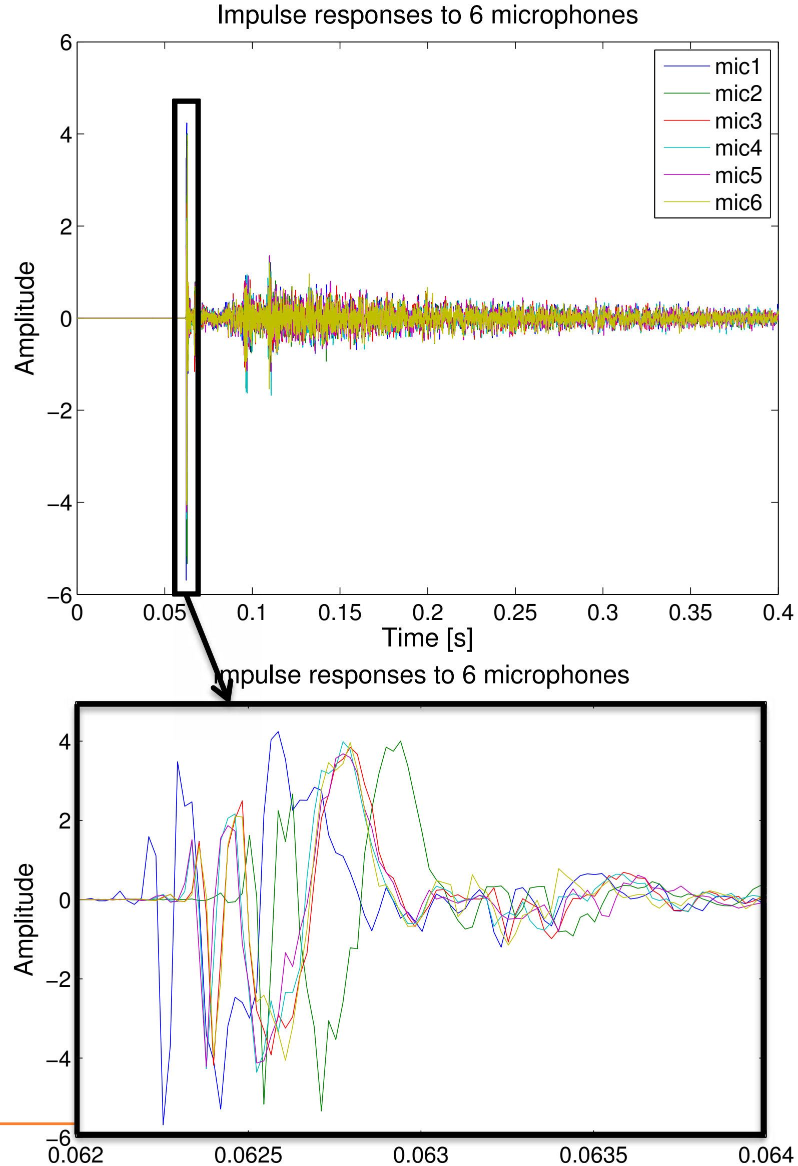
SDM for reproduction





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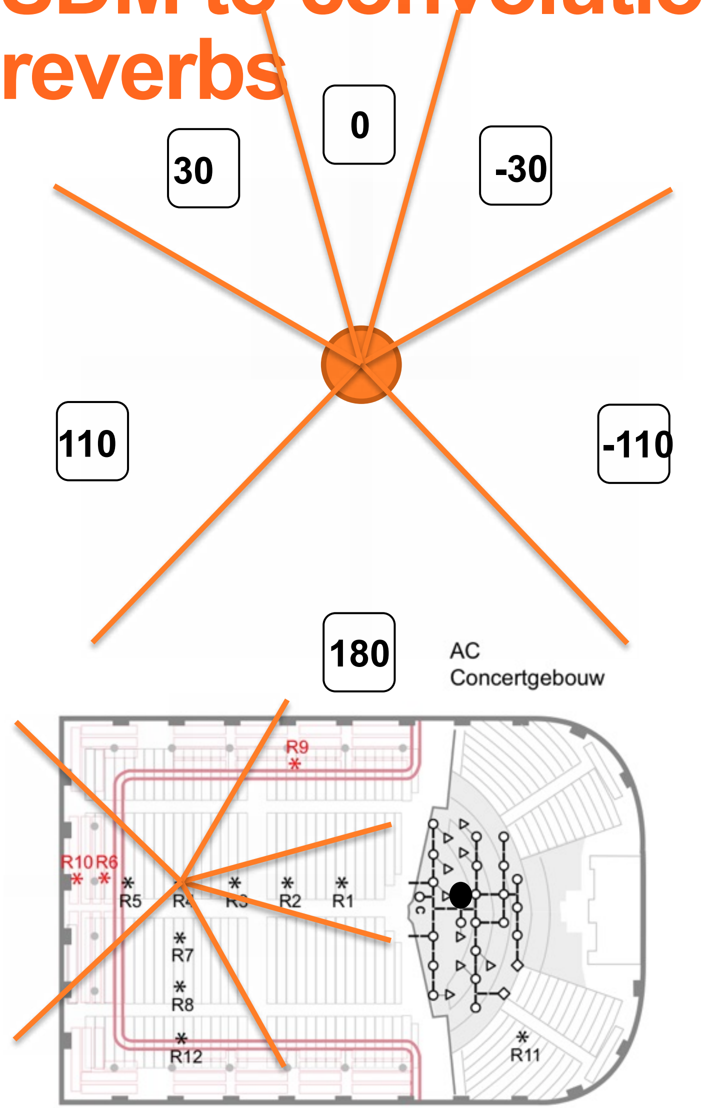
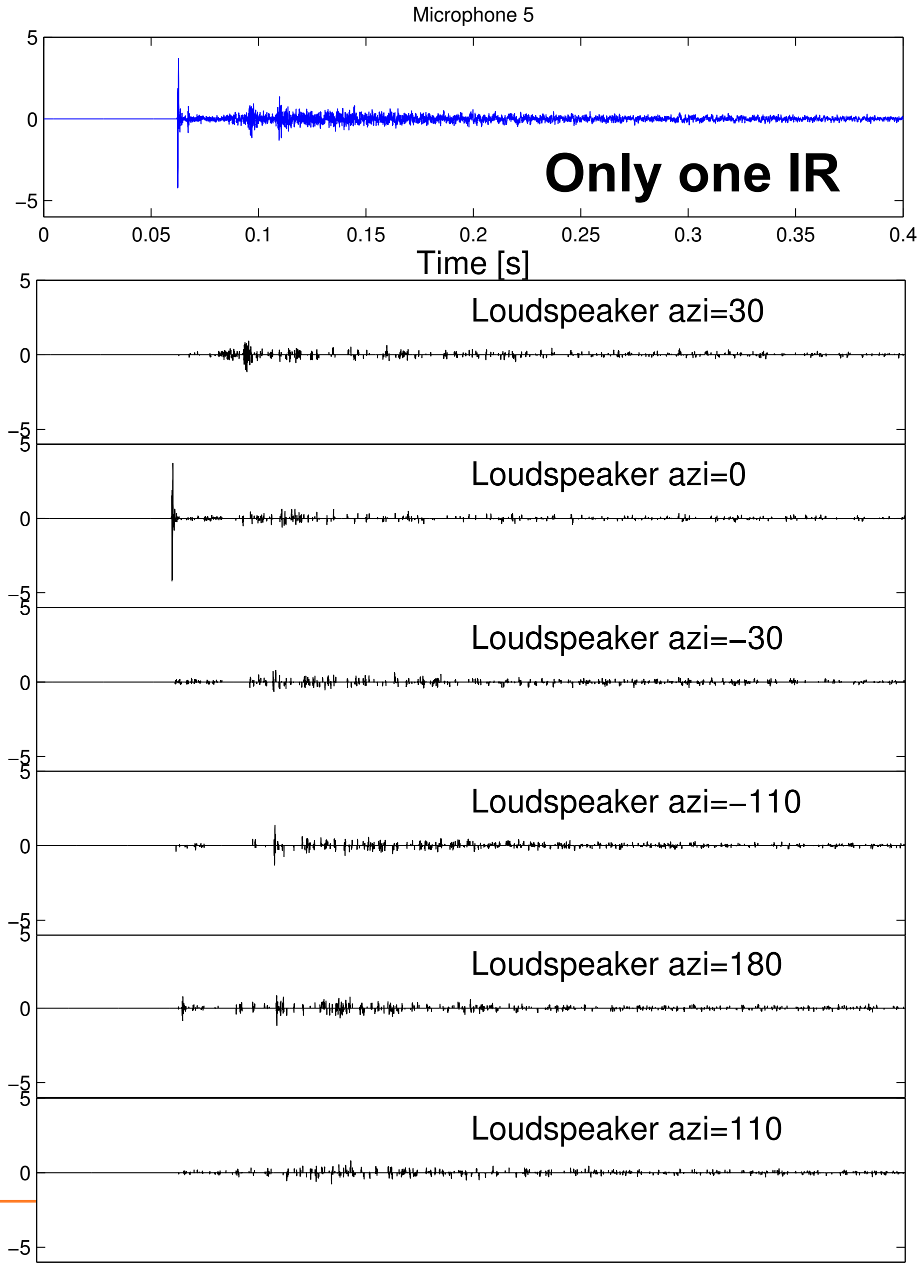
SDM to convolution reverbs





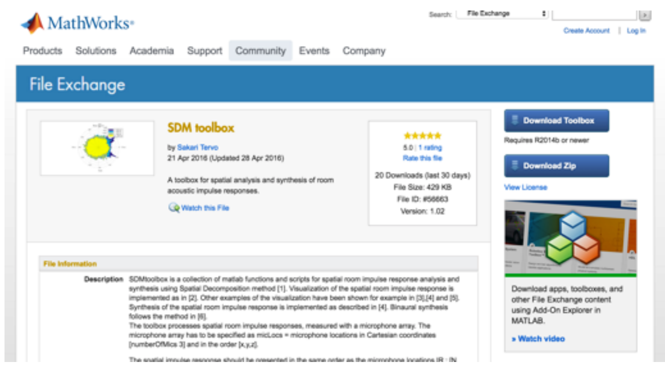
With 24 ch, no amplitude panning: Pätynen et al. AES55, 2014

Part 5: Matlab toolbox demo

URL: https://www.mathworks.com/matlabcentral/fileexchange/56663-sdm-toolbox

SDM Toolbox freely available in Matlab File Exchange

- **Provides all functions for analysis and synthesis**
- **4 core functions:**
  - `SDMPar.m` Directional analysis, currently omnidirectional mics
  - `spatioTemporalVisualization.m`
  - `timeFrequencyVisualization.m`
  - `synthesizeSDMCoeffs.m` Nearest loudspeaker synthesis for auralization



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Recap, direction estimation

- Room-acoustic events as plane waves inside the array
- Signal time-differences calculated from cross-corelations
- Provides metadata for omnidirectional pressure

Recap, spatiotemporal analysis

- **Directional histogram of arriving energy**
- **Cumulation of spatial energy over time windows**
- **Use-case dependent direction of integration and selected time window resolution**

Take-home message

A small microphone array and a simple model provide highly useful information on the spatial room acoustics, and can be achieved even with a low-cost equipment.

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Key references

- **SDM:** Tervo et al.: "Spatial decomposition method for room impulse responses", *JAES* 61(1/2), 16, 2013.
- **Spatiotemporal visualization:** Pätynen et al.: "Analysis of concert hall acoustics via visualizations of time-frequency and spatiotemporal responses", *JASA* 133(2), 2013.
- **Car audio:** Tervo et al.: "Spatial analysis and synthesis of car audio system and car cabin acoustics", *JAES* 63(11), 2015.
- **Concert hall perception:** Lokki et al.: "Concert hall acoustics: Repertoire, listening position, and individual taste of the listeners influence the qualitative attributes and preferences", *JASA* 140(1), 2016.

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DAFx 16

Thank you!

Questions and discussion

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