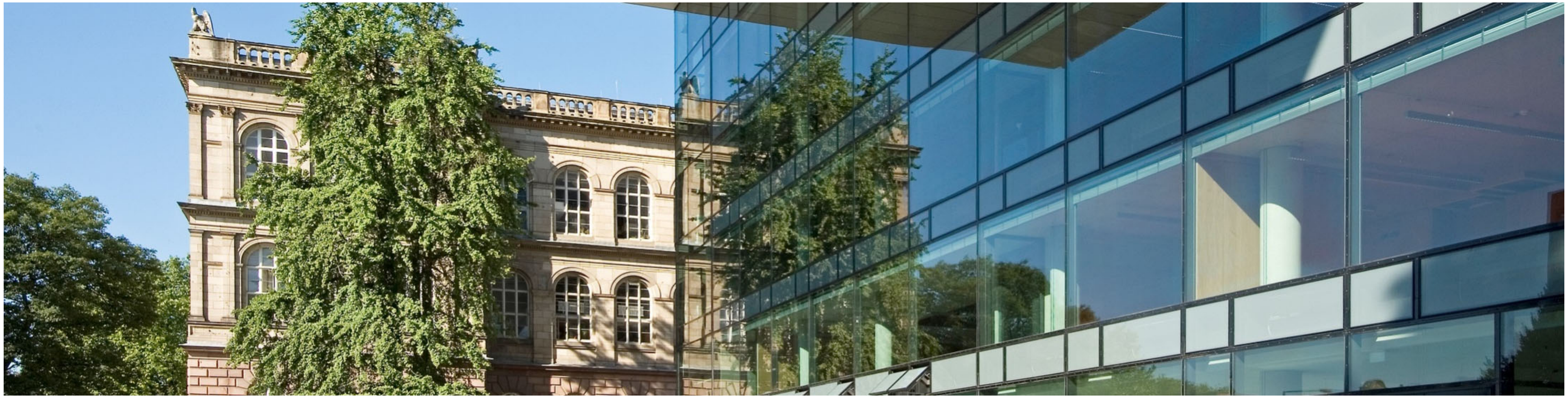

Was leisten raumakustische Simulationen?

Stand der Technik und Ausblick

Michael Vorländer

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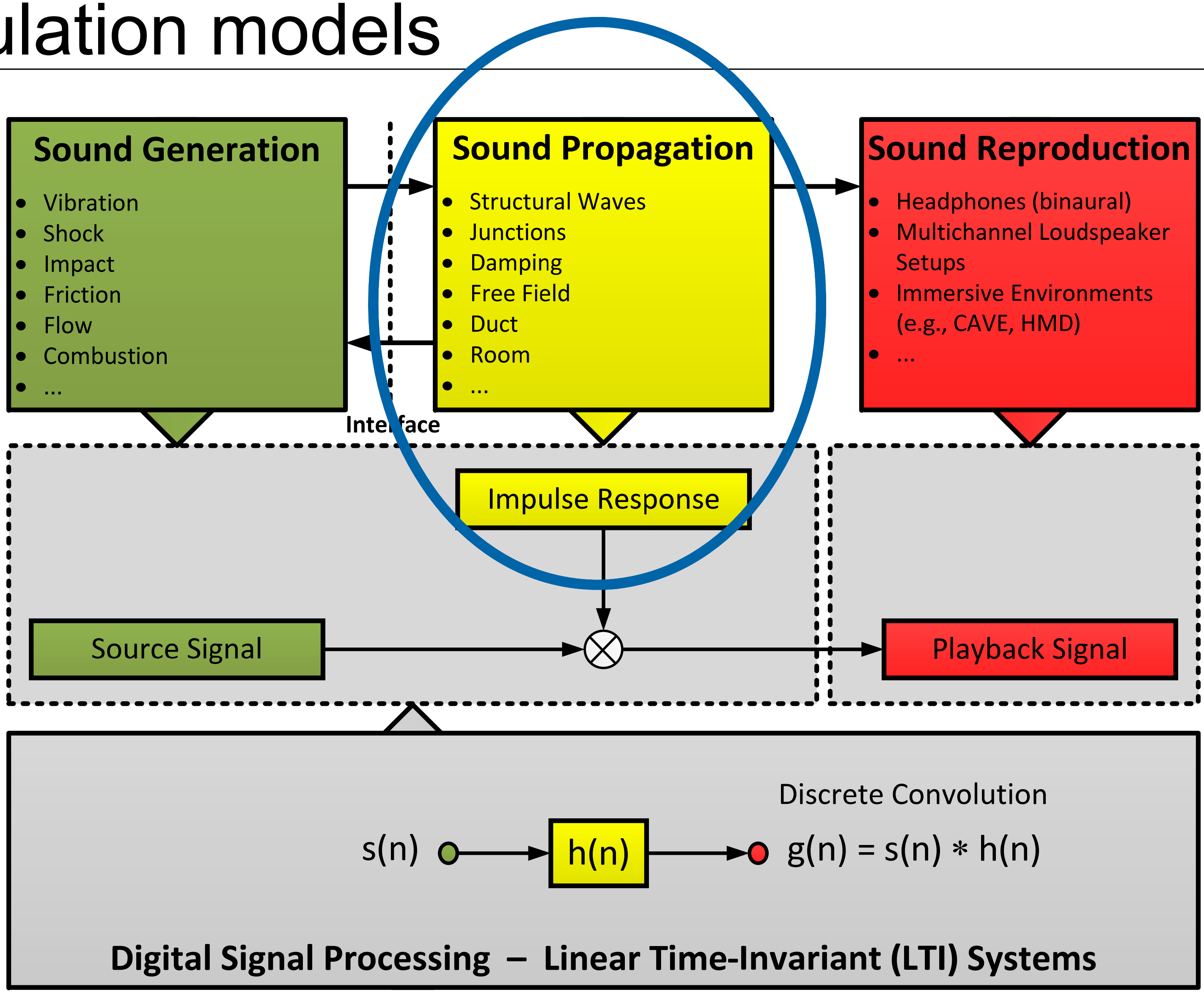
RWTH Aachen

IHTA Institute for Hearing Technology and Acoustics | RWTH AACHEN UNIVERSITY

Content

- Fundamentals of simulation algorithms
- State of the art
- Uncertainties
- Auralization round robin
- Conclusion and Outlook

Simulation models



Standard methods of acoustic simulation

- „Exact“ solution of wave acoustics
  - Helmholtz equation + boundary conditions
  - numerical methods
  - Frequency domain → IFFT → Time domain
  - or time domain BE/FE or FDTD

- Geometrical acoustics (approximations)
  - Image sources, edge diffraction models
  - Ray Tracing
  - Radiosity
  - Diffusion equation

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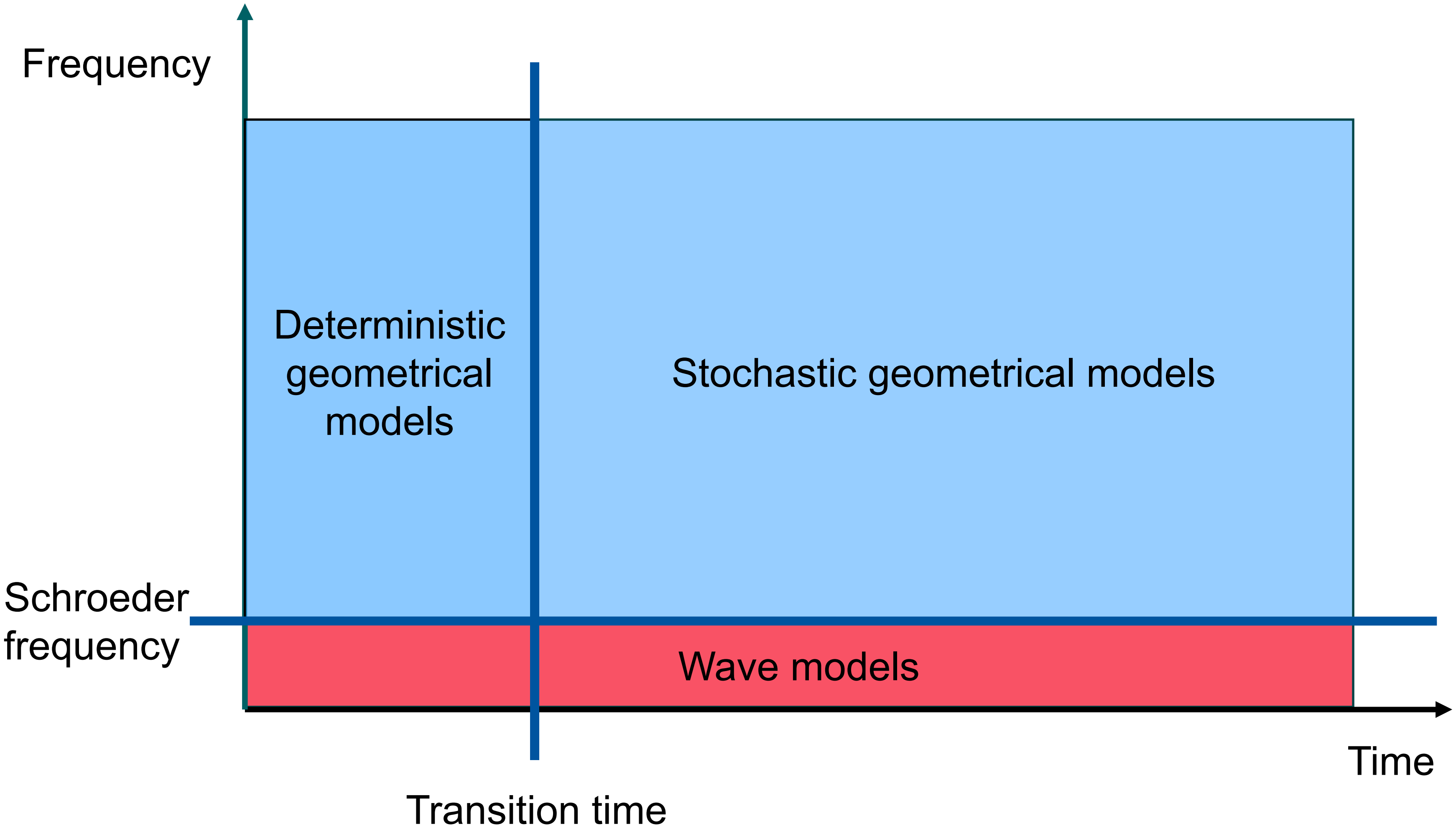
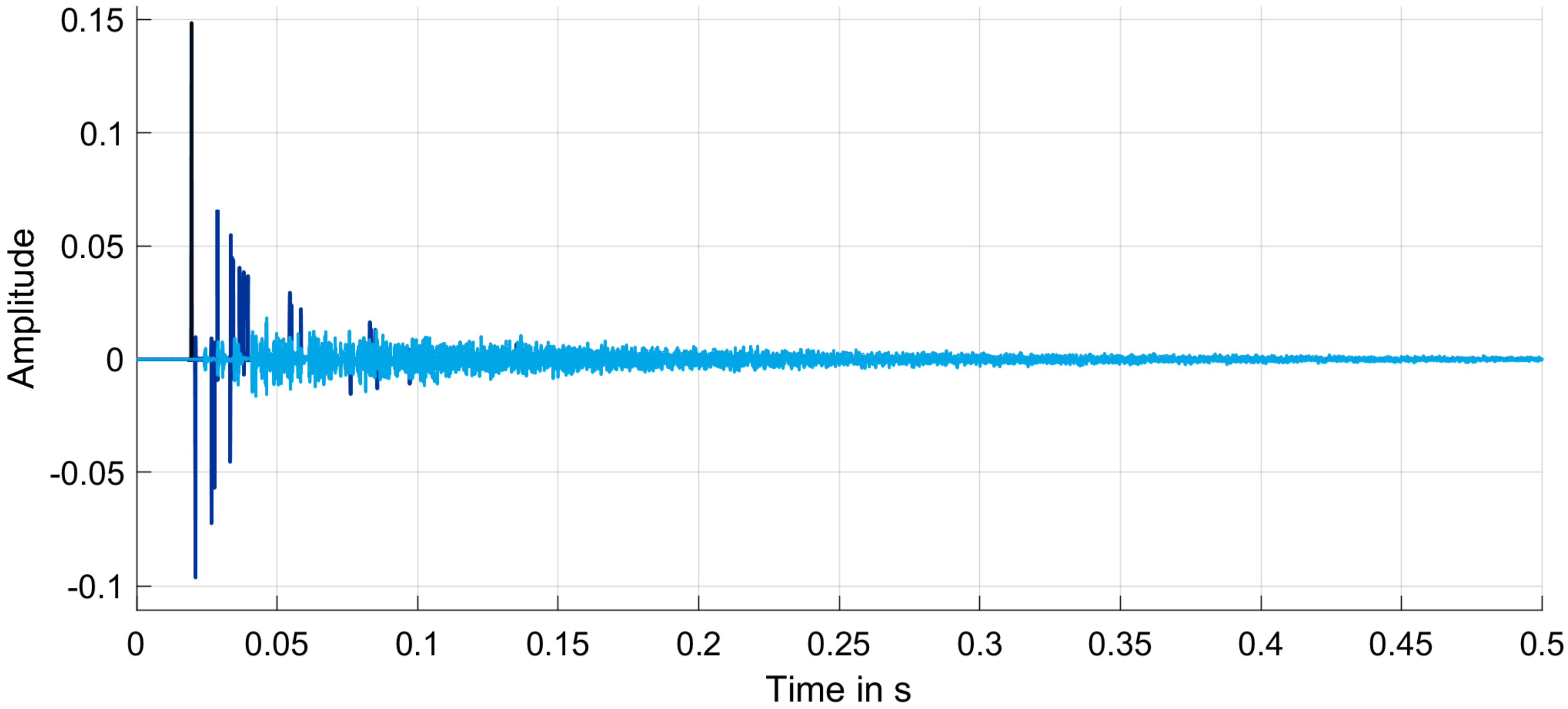
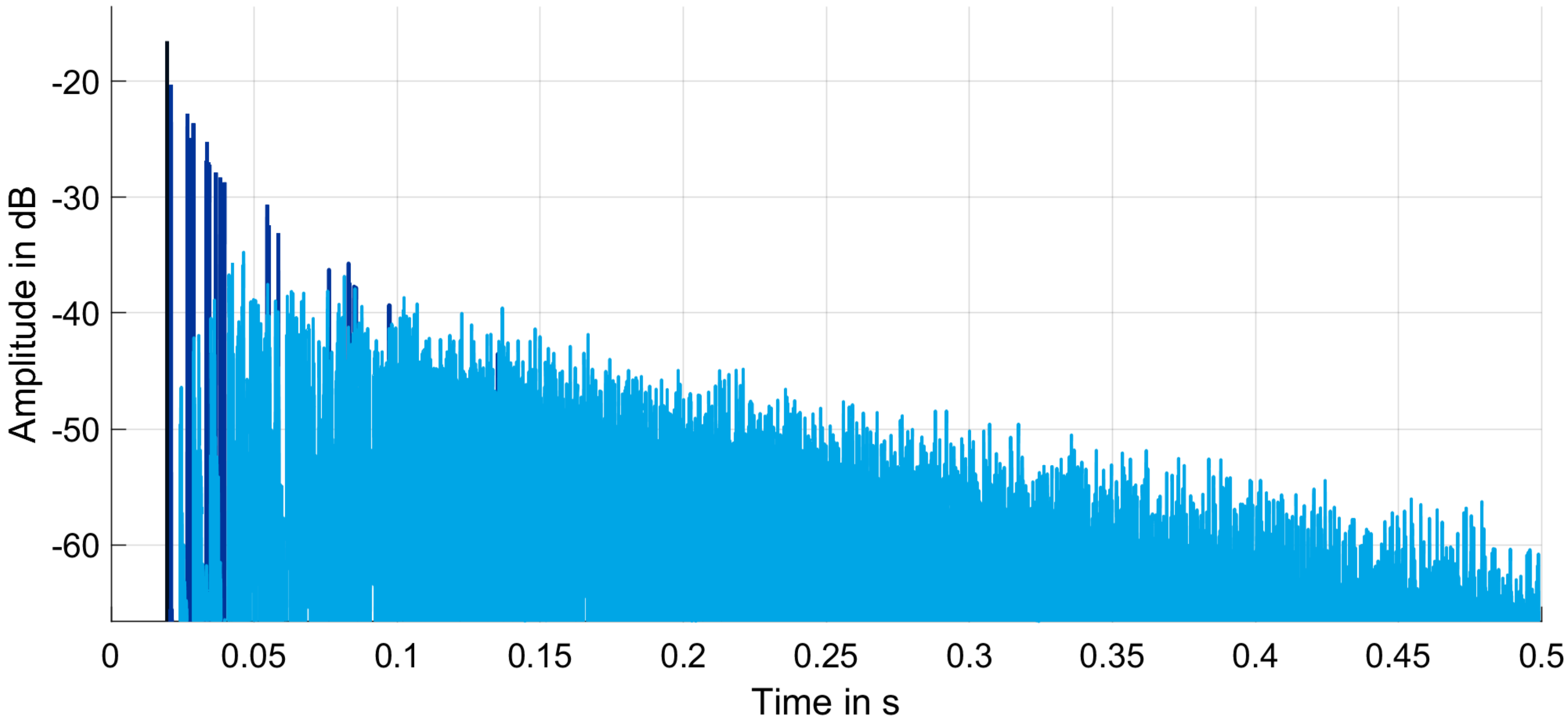
State of the art: hybrid methods



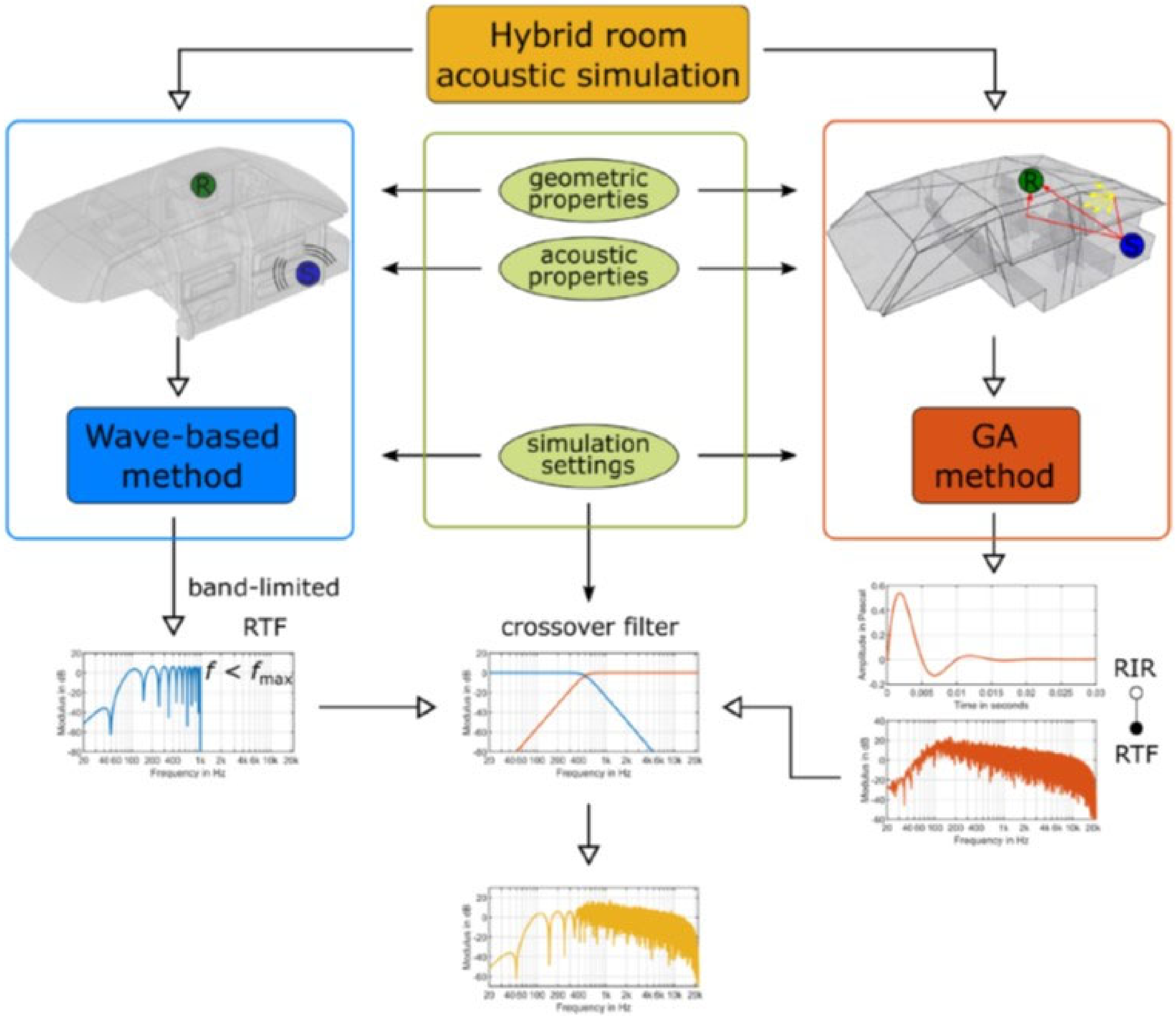
Room Impulse Response (RIR) - geometrical



Room Impulse Response (RIR) - geometrical



Hybrid methods – geometrical/wave



Marc Aretz: Combined Wave And Ray Based Room Acoustic Simulations Of Small Rooms. Dissertation RWTH Aachen, 2012

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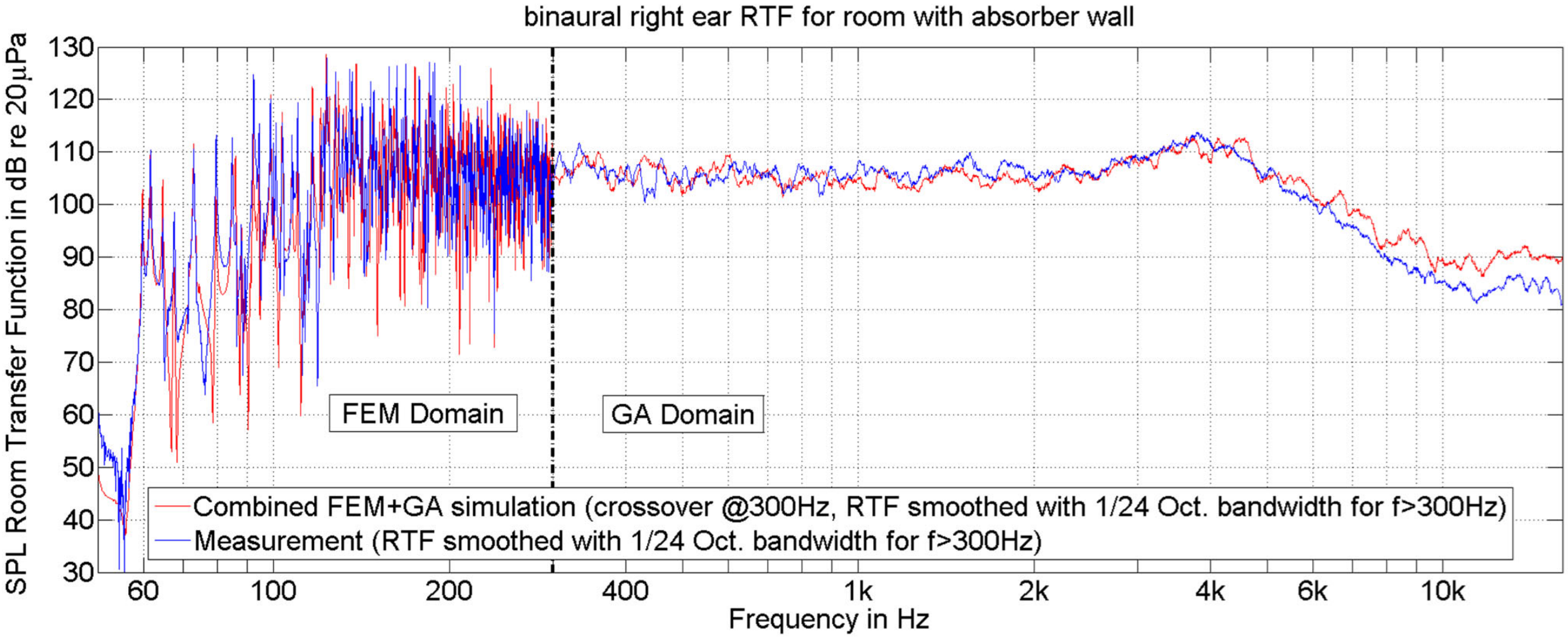
Results: Spectrum

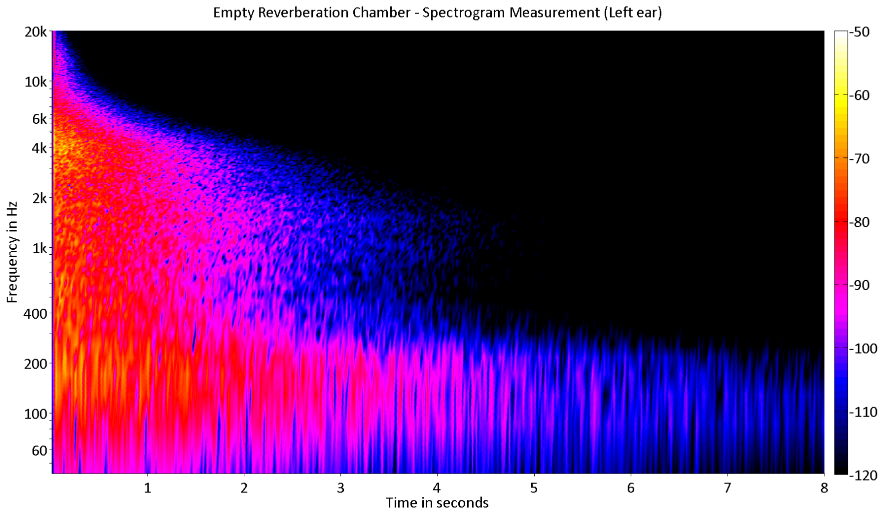
- Reverberation chamber with absorber wall
- Dummy head's right ear



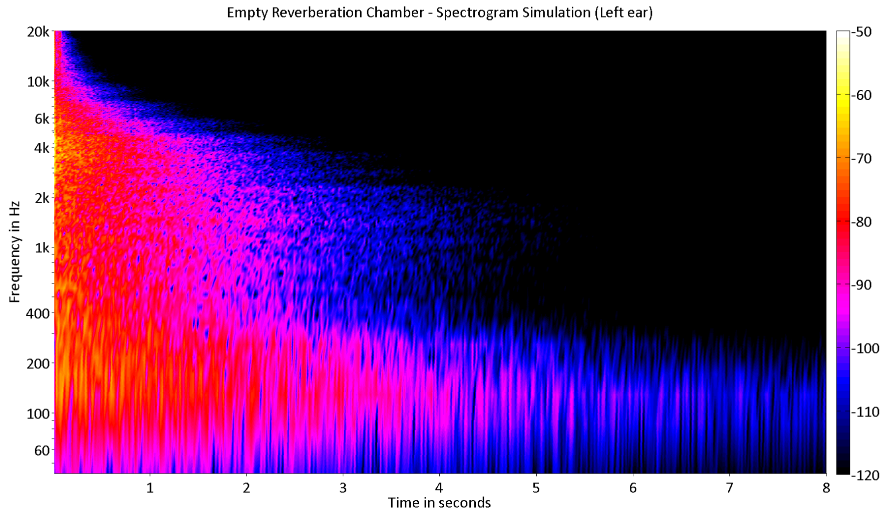
S. Pelzer, M. Aretz, M. Vorländer: Quality assessment of room acoustic simulation tools by comparing binaural measurements and simulations in an optimized test scenario. Proc. Forum Acusticum 2011, Aalborg, Denmark

Results: Spectrograms

- Empty reverberation chamber
- Dummy head's left ear



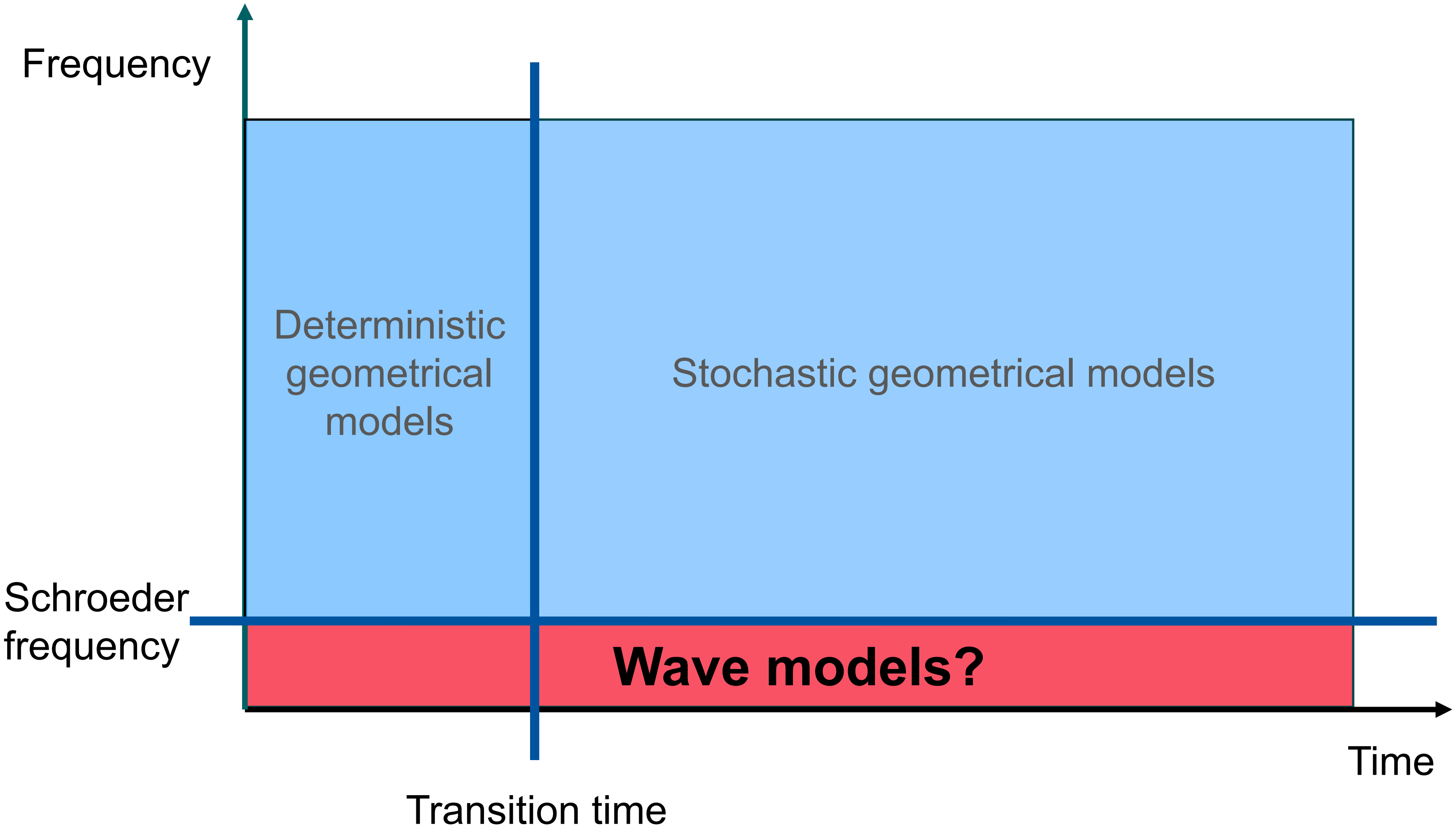
- Measurement



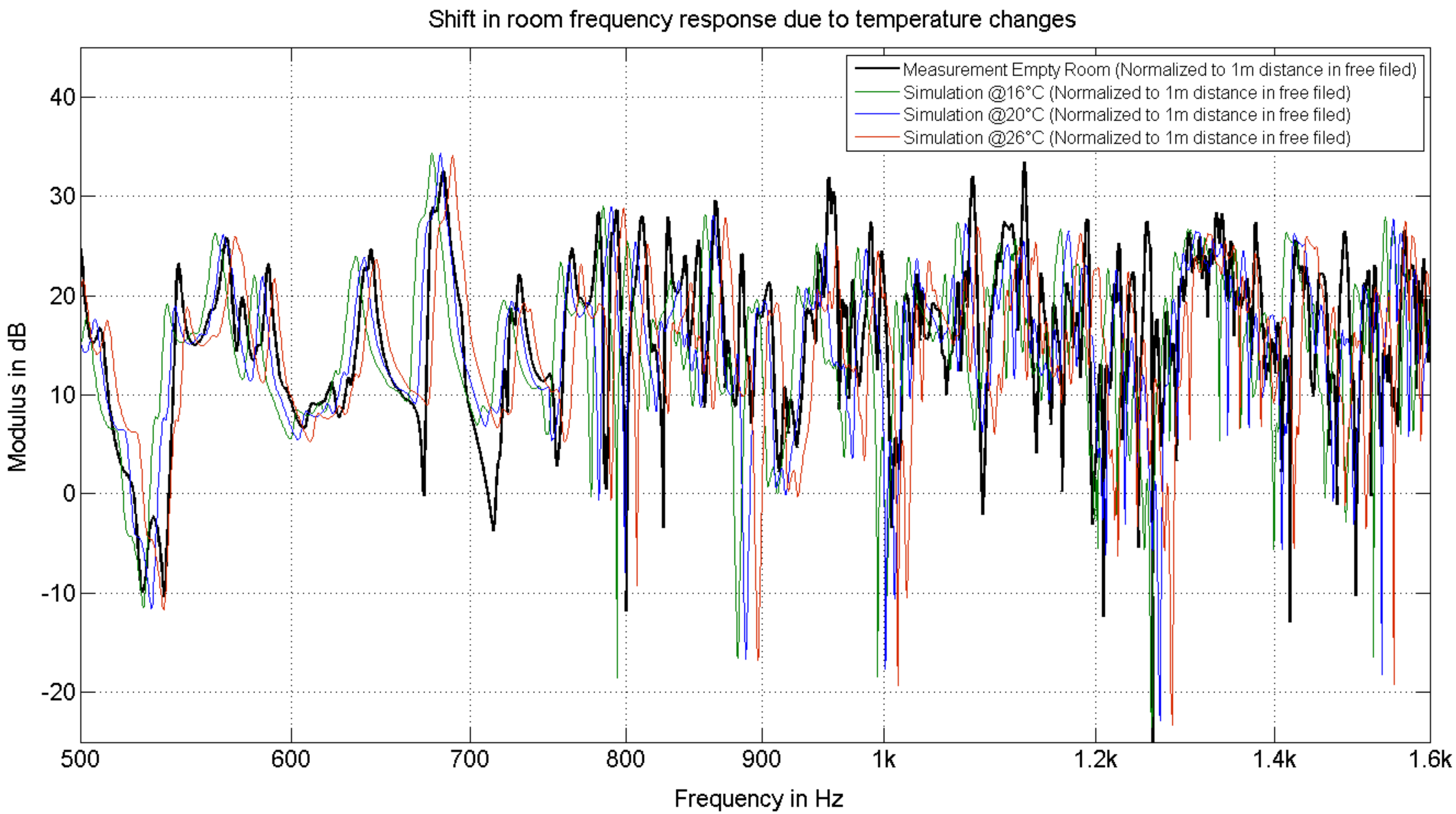
- Simulation (GA+FEM)

S. Pelzer, M. Aretz, M. Vorländer: Quality assessment of room acoustic simulation tools by comparing binaural measurements and simulations in an optimized test scenario. Proc. Forum Acusticum 2011, Aalborg, Denmark

Hybrid methods

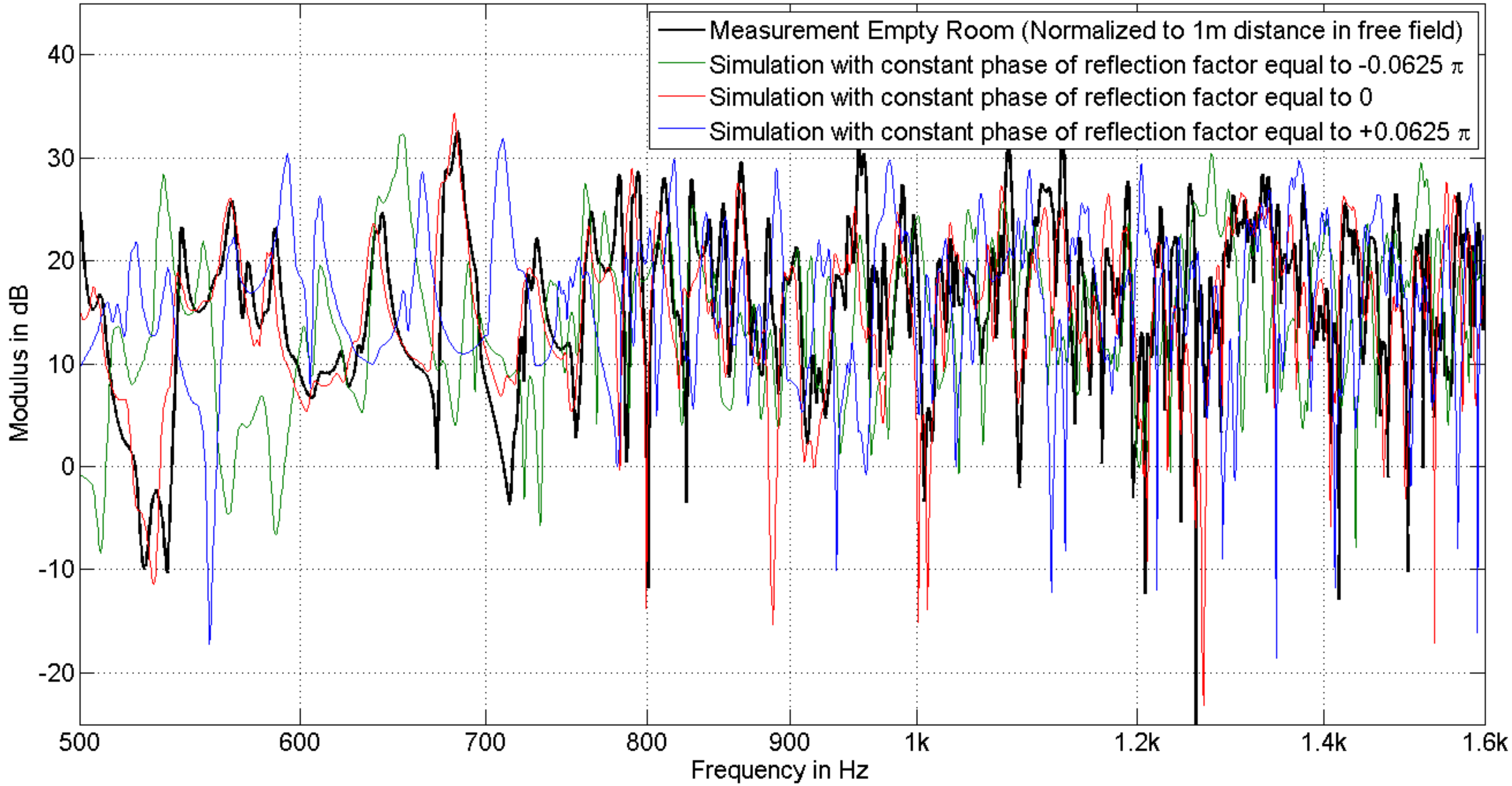


Uncertainties - exact temperature ?



M. Vorländer: Prediction tools in acoustics-Can we trust the PC? Proc. BNAM 2010, Bergen, Norway

Uncertainties - exact phase of $\underline{R}$?



M. Vorländer: Prediction tools in acoustics-Can we trust the PC? Proc. BNAM 2010, Bergen, Norway

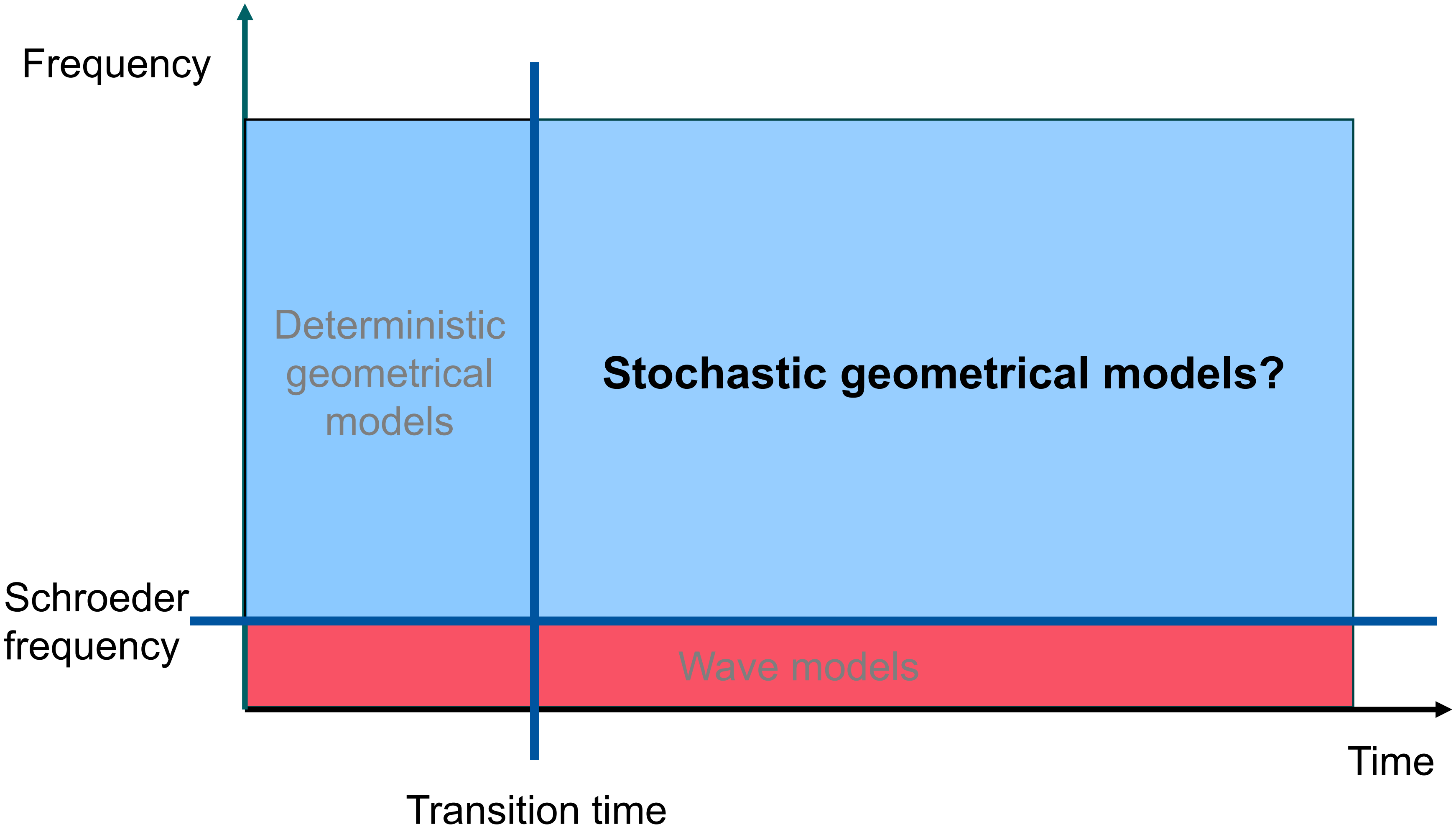
Uncertainties of input data

it does not always make sense
to use „exact“ wave models!!

what about geometrical acoustics?

other errors! → stochastic effects!

Hybrid methods



Uncertainties – inside of “Ray Tracing” ?

„image source finder“

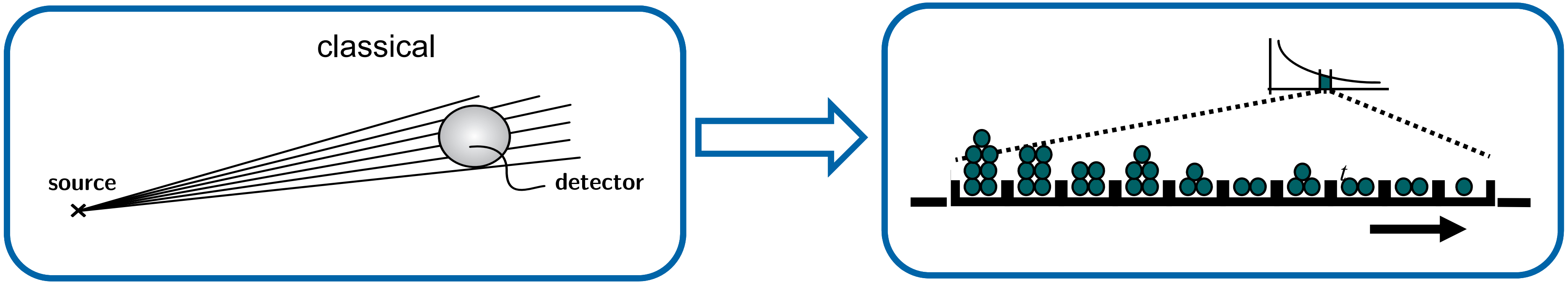
cone tracing

beam tracing

classical

Uncertainties – inside of classical “Ray Tracing” ?

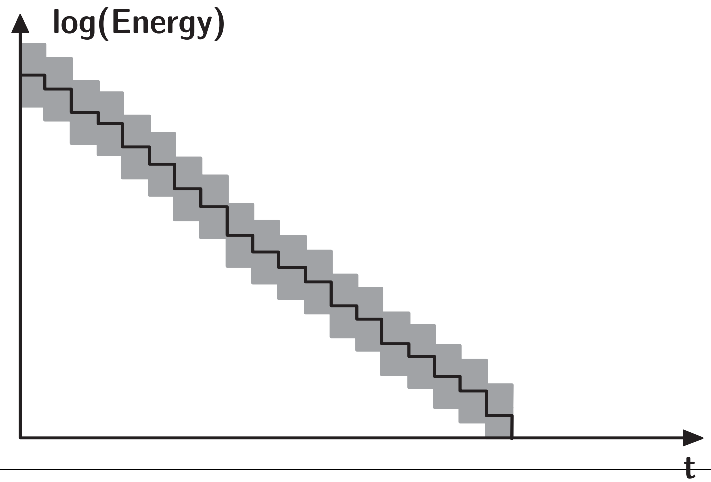
(for late reverberation)



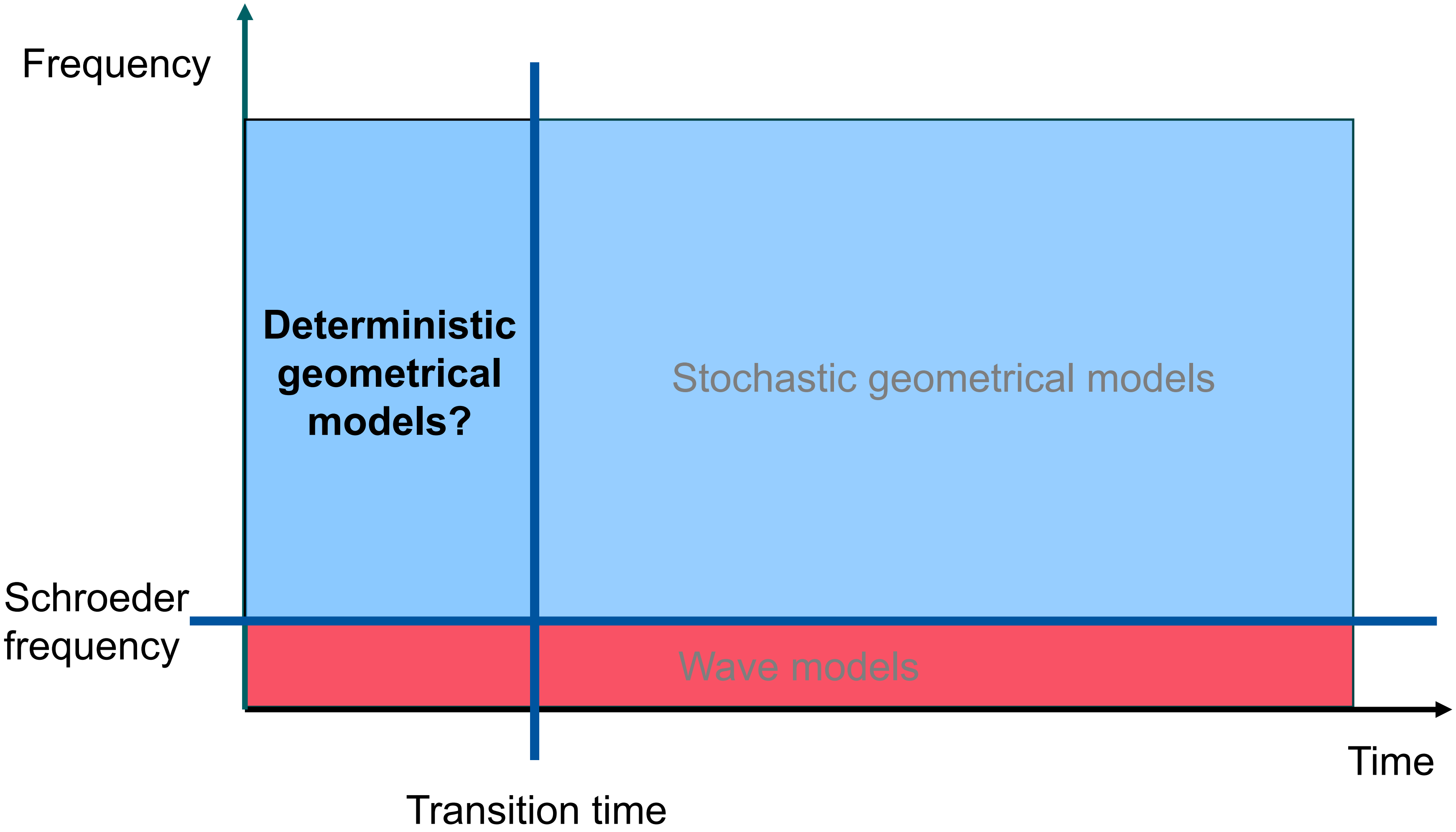
Statistics of counts $P(k) = \frac{\langle k \rangle}{k!} e^{-\langle k \rangle}$

$$\sigma_{ETC} = 4.34 \sqrt{\frac{V}{N \pi r_d^2 c \Delta t}}$$

$$\sigma_G = 4.34 \sqrt{\frac{A}{8 \pi N r_d^2}}$$



Hybrid methods



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Round robins on computer simulation

- Choose a room
- Each participant: Simulation on the basis of user-defined input data
  → comparison of the results
- Measurements
  → comparison of the results, matching the model
- Repetition with fixed input data
  → comparison of the results

Lessons learned, towards a round robin IV

- User estimate too low absorption coefficients
- Scattering is important, just using image sources is not correct
- Wave effects at grazing incidence above the audience are important

rr 1 (1995)

- **More accurate surface material data required**
- **Wave effects….. are important (seat dip, columns, orchestra pit, …)**

rr 2 (2000)

- **Complex reflection factors / impedances**
- **Someone should launch an auralization round robin**

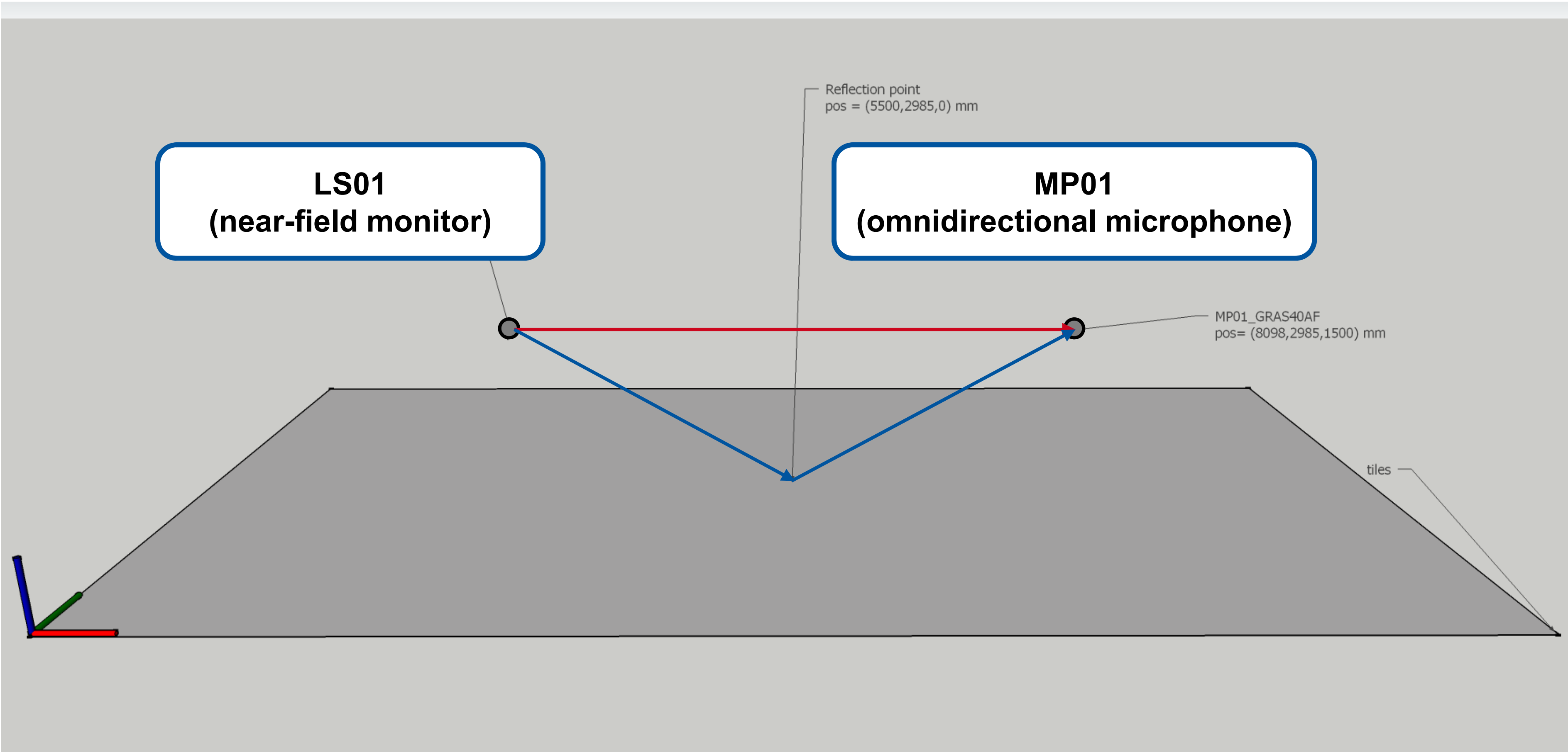
rr 3 (2005)

M. Vorländer (1995) International Round Robin on Room Acoustical Computer Simulations. Proc. 15th ICA, Trondheim, Norway 689

I. Bork (2000) A Comparison of Room Simulation Software - the 2nd Round Robin on Room Acoustical Computer Simulation. Acustica united with Acta Acustica 84, 943

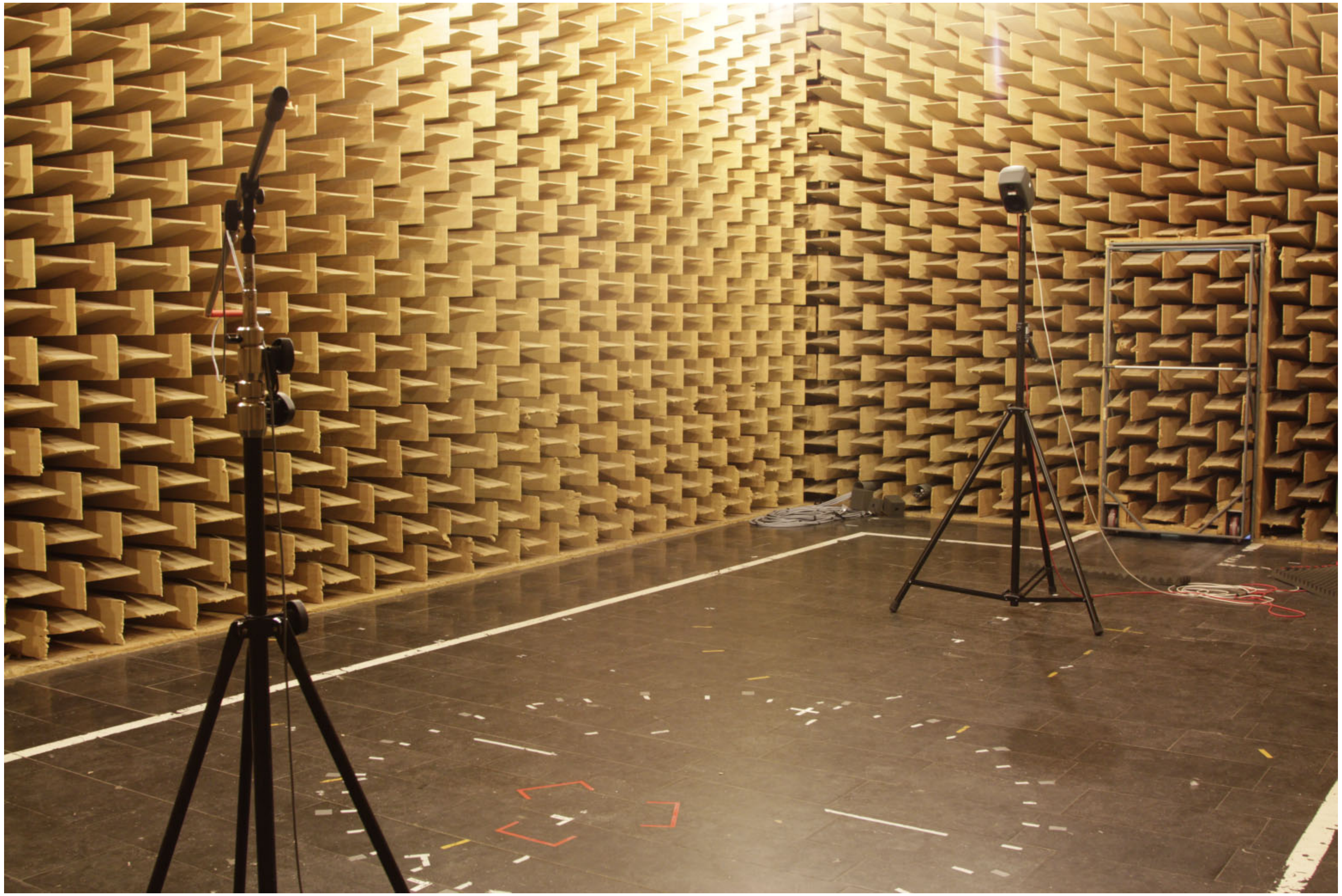
I. Bork (2005) Report on the 3rd Round Robin on Room Acoustical Computer Simulation - Part I: Measurements I. Acta Acustica united with Acustica 91, 740; Report on the 3rd Round Robin on Room Acoustical Computer Simulation - Part II: Calculations, Acta Acustica united with Acustica 91, 753

From Round Robin IV, scene1: Single reflection



F. Brinkmann, L. Aspöck, D. Ackermann, R. Opdam, M. Vorländer, S. Weinzierl (2021) A benchmark for room acoustical simulation. Concept and database. Applied Acoustics 176, 107867

Scene1: Reference measurement



F. Brinkmann, L. Aspöck, D. Ackermann, R. Opdam, M. Vorländer, S. Weinzierl (2021) A benchmark for room acoustical simulation. Concept and database. Applied Acoustics 176, 107867

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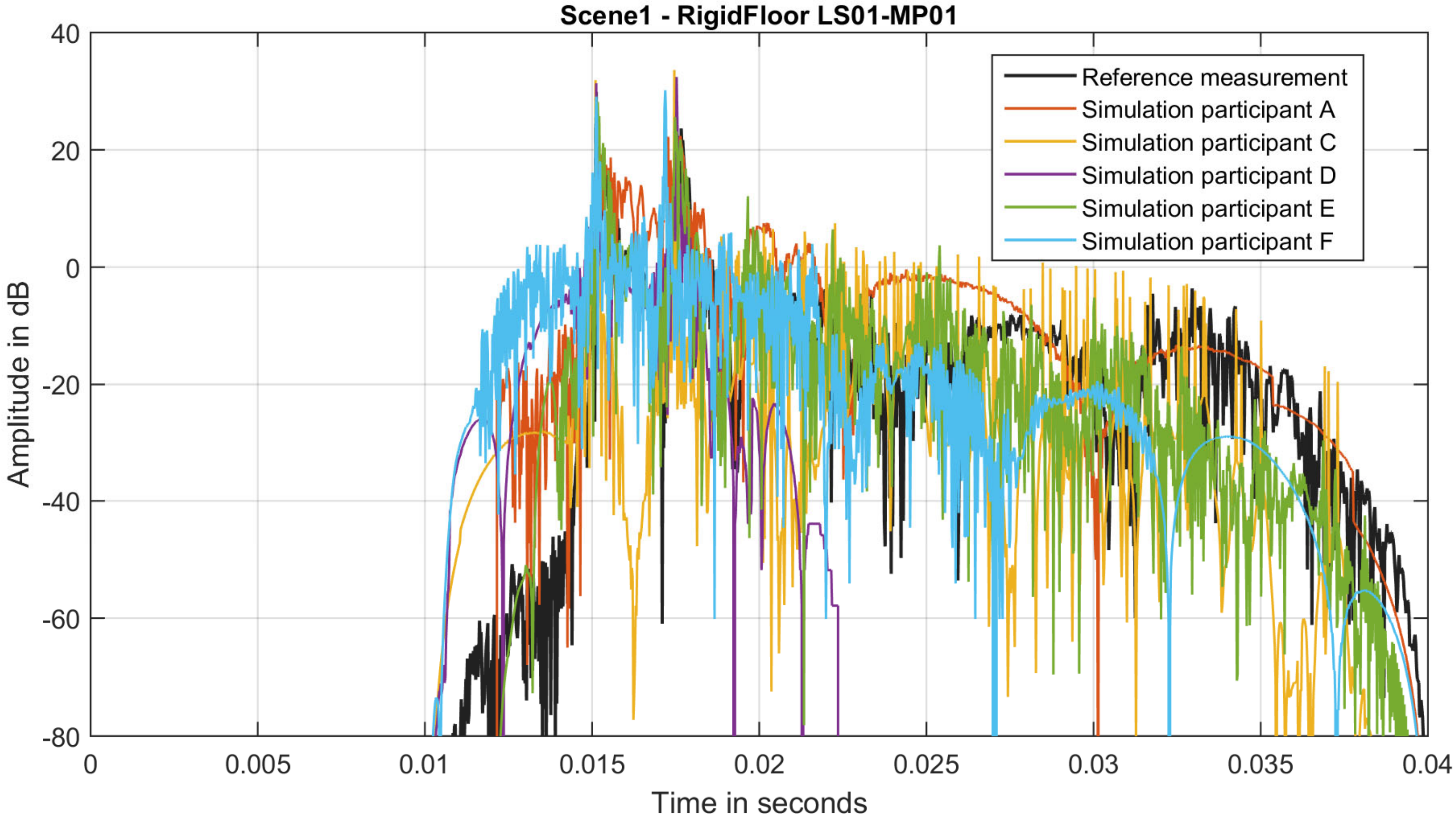
Scene1: Rigid floor reflection; time domain



F. Brinkmann, L. Aspöck, L, D. Ackermann, S. Lepa, M. Vorländer, S. Weinzierl (2019) A round robin on room acoustical simulation and auralization. J. Acoust. Soc. Am. 145 (4), 2746

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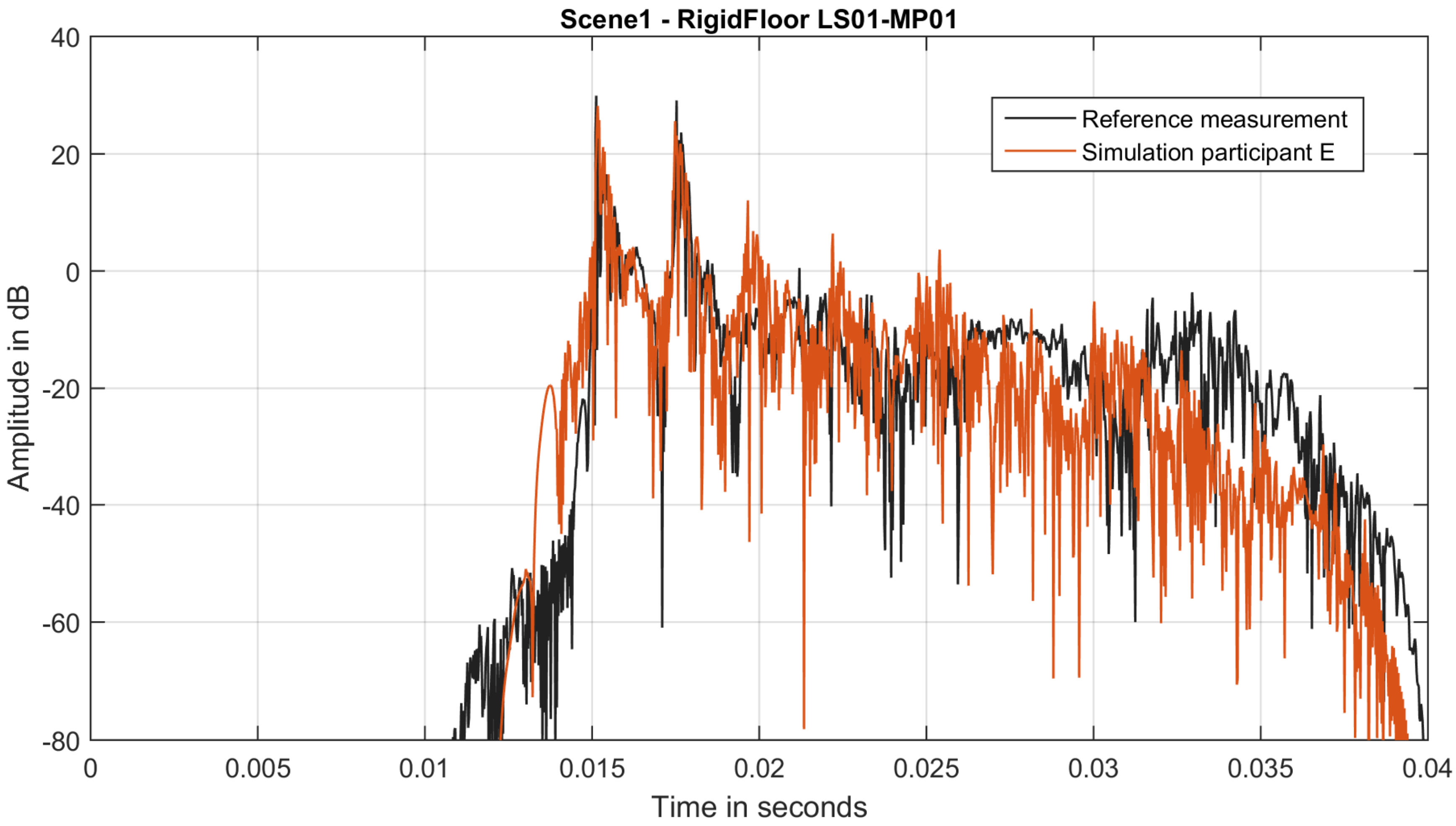
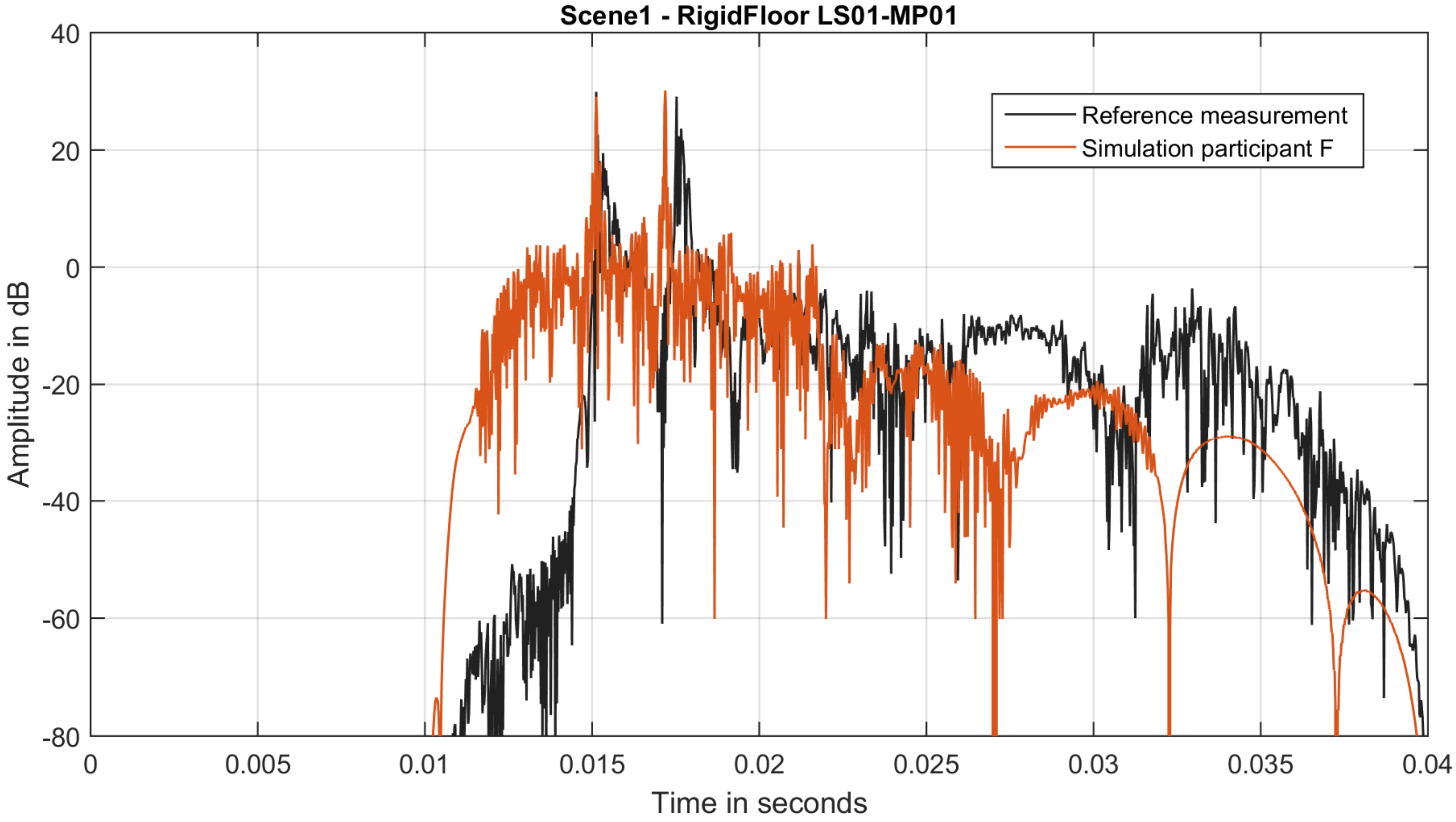
Scene1: Rigid floor reflection; time domain



F. Brinkmann, L. Aspöck, L, D. Ackermann, S. Lepa, M. Vorländer, S. Weinzierl (2019) A round robin on room acoustical simulation and auralization. J. Acoust. Soc. Am. 145 (4), 2746

Scene1: Rigid floor reflection ; frequency domain



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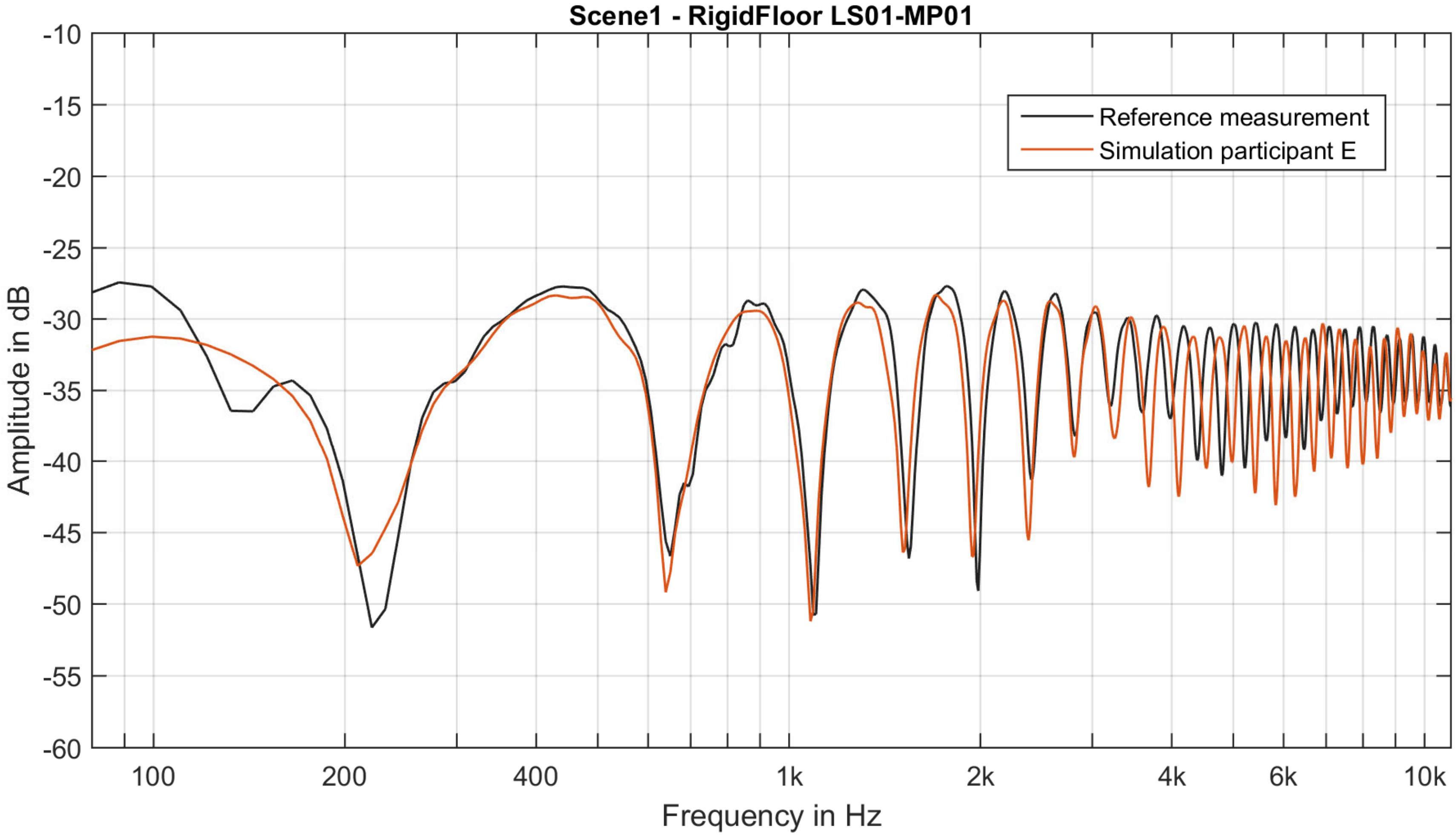

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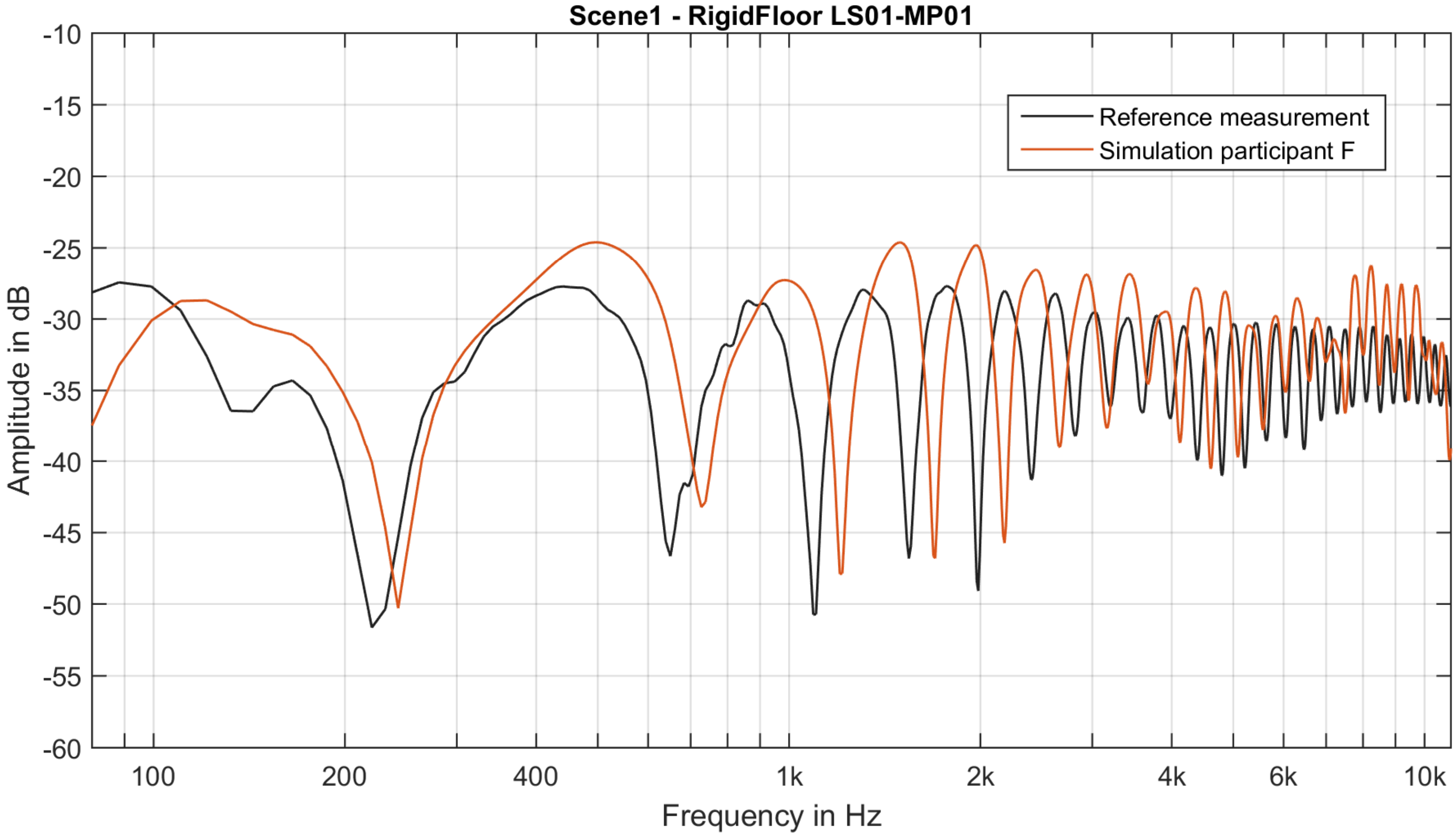

F. Brinkmann, L. Aspöck, L, D. Ackermann, S. Lepa, M. Vorländer, S. Weinzierl (2019) A round robin on room acoustical simulation and auralization. J. Acoust. Soc. Am. 145 (4), 2746

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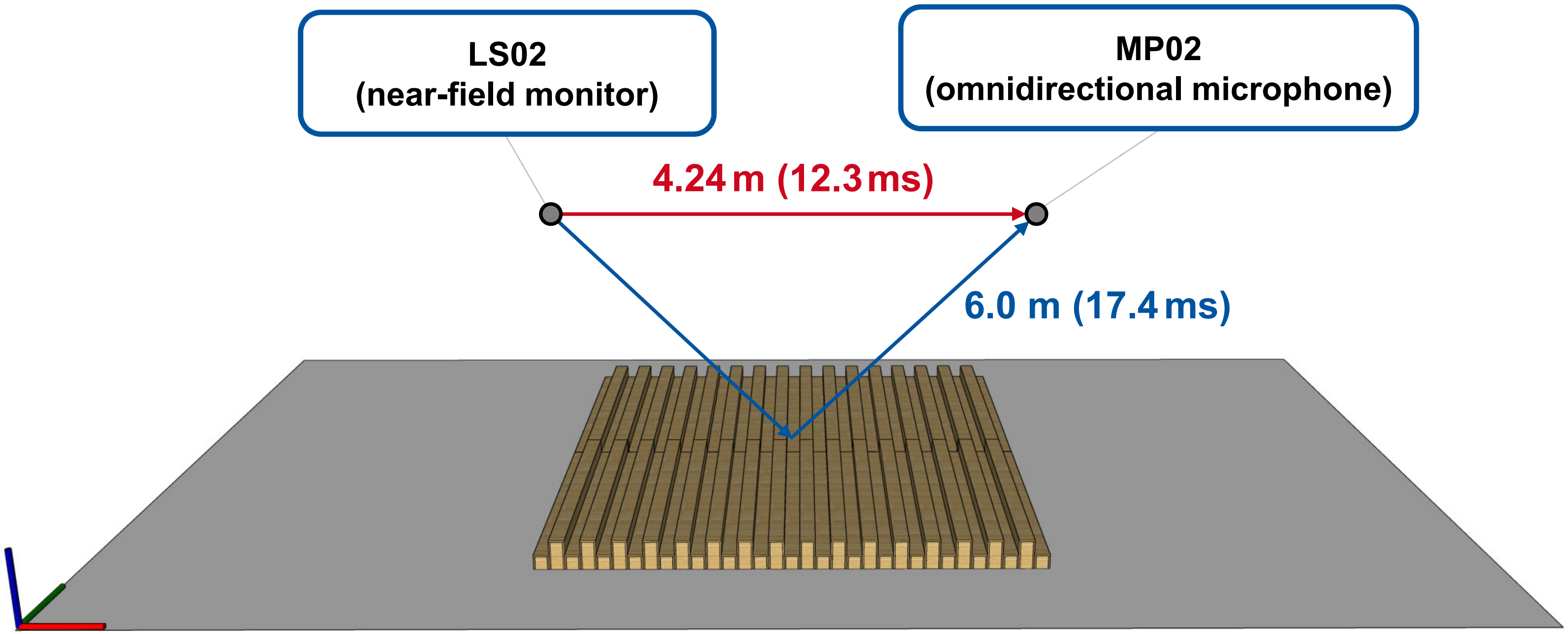
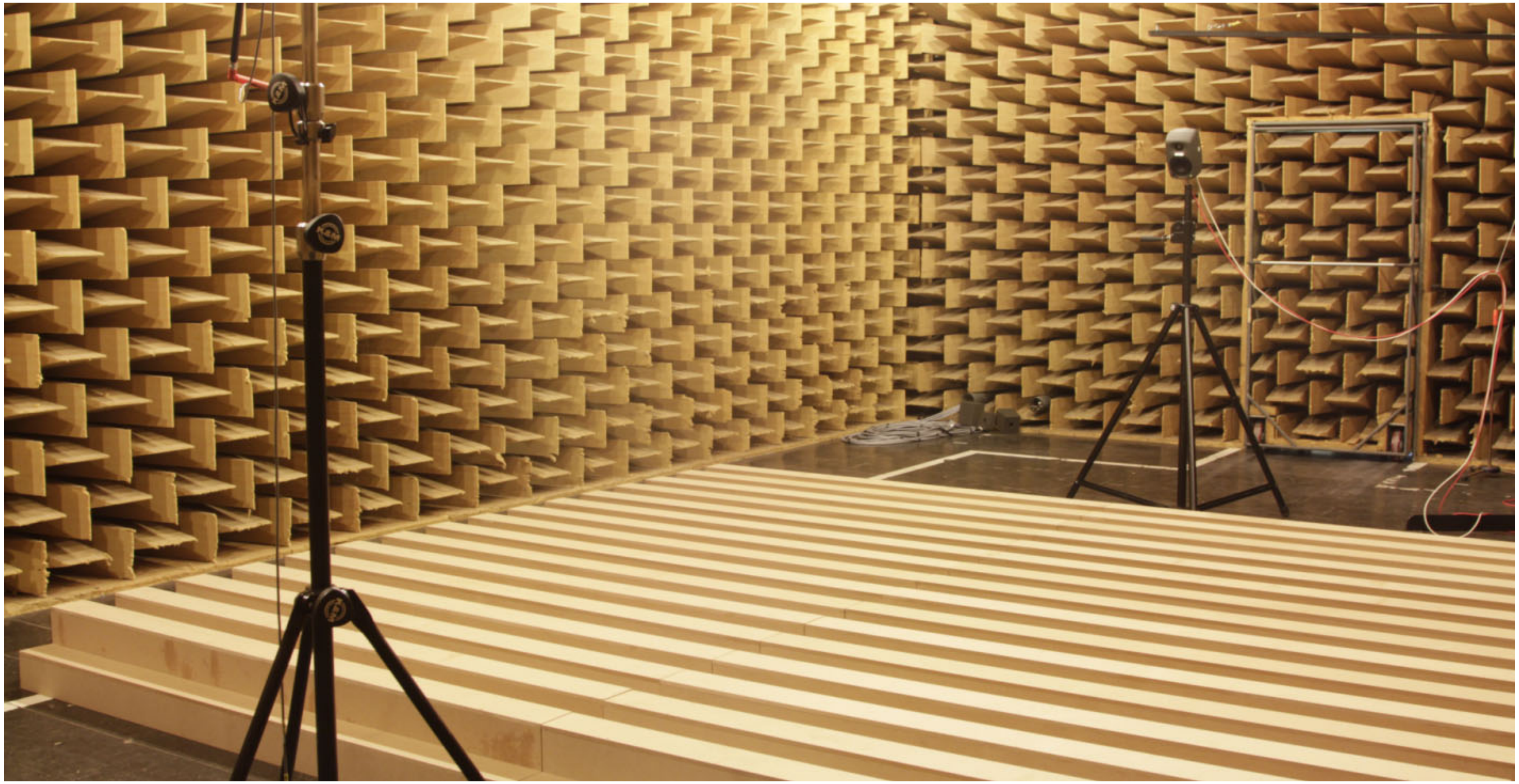
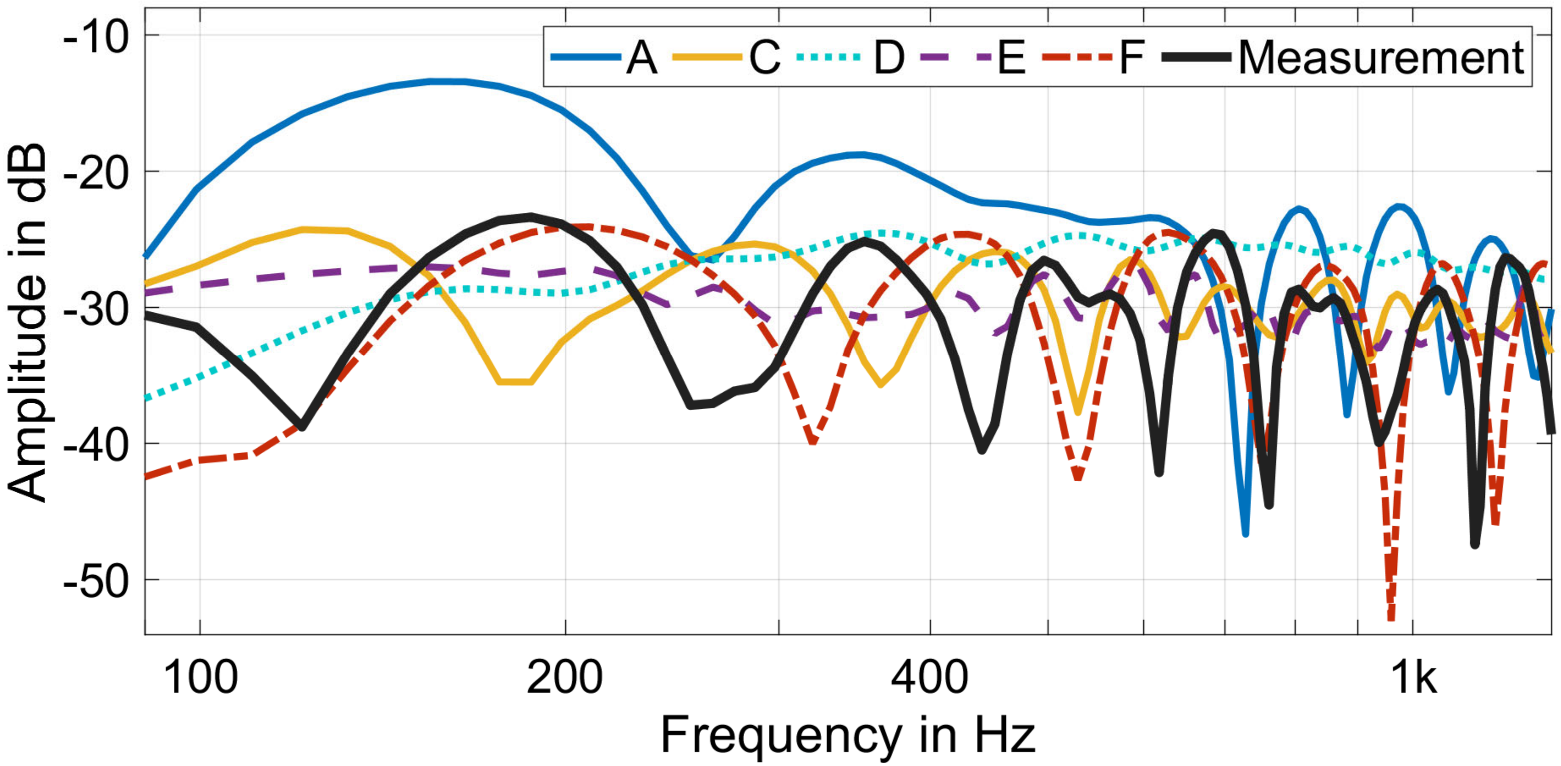
Scene 1: Single reflection, ϕ=45°, hemi anechoic chamber



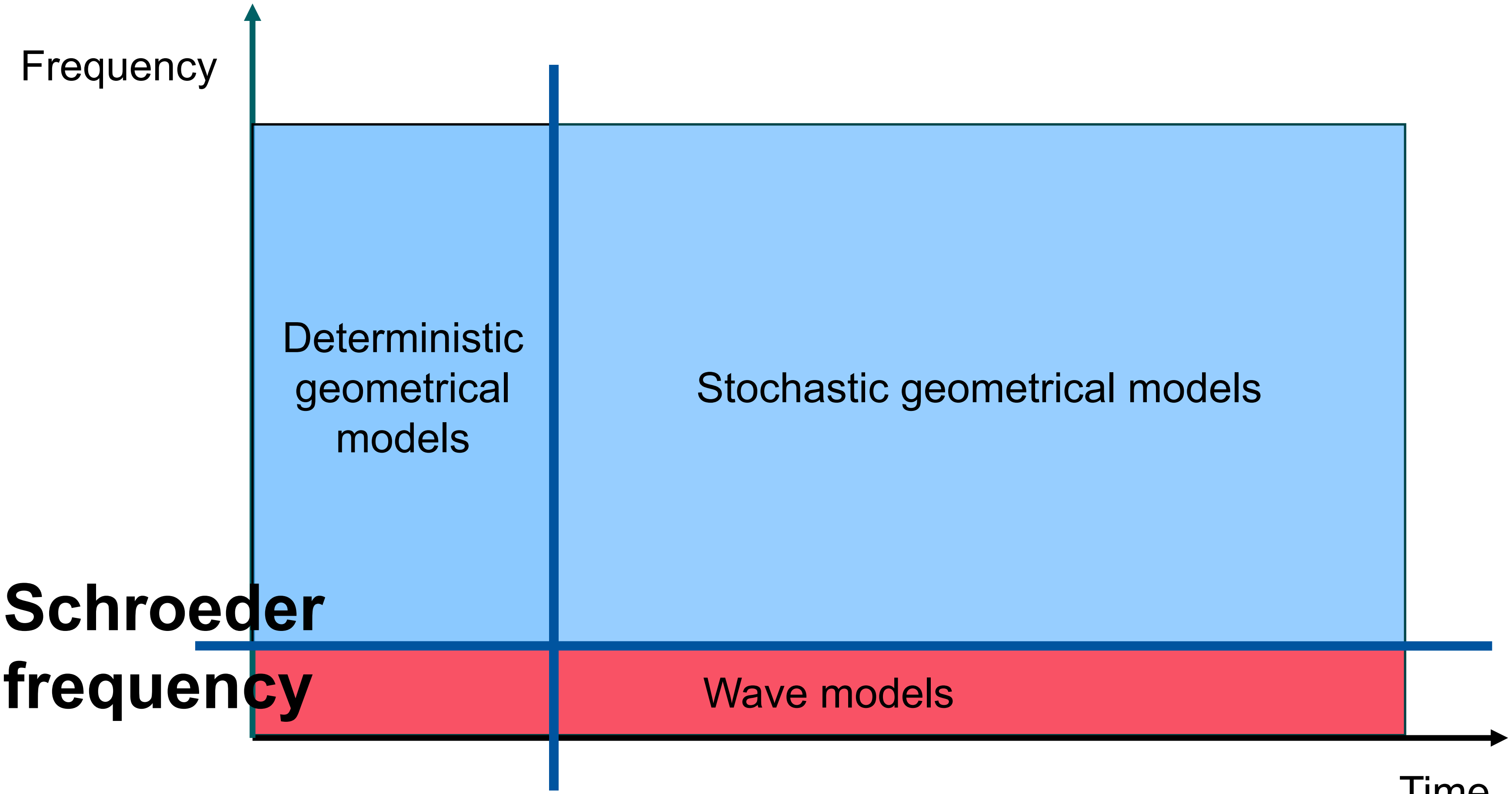
Scene 1: Single reflection on diffusor, ϕ=45°



Scene 1: Single reflection on diffusor, ϕ=45°



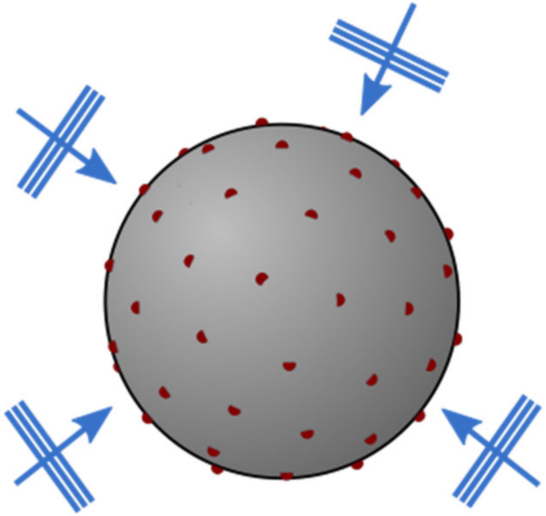
Hybrid methods



Transition time?

Directional sound field decomposition

- Diffuse sound field composed of infinitely many incoherent plane waves arriving uniformly at a receiver.



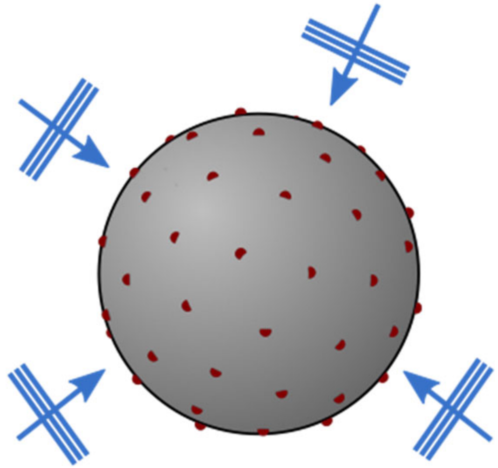
B. Rafaely (2004) Plane wave decomposition of the sound field on a sphere by spherical convolution. J. Acoust. Soc. Am. 116, 2149
B. Gover, J. Ryan, M. Stinson (2004), Measurements of directional properties of reverberant sound fields in rooms using a spherical microphone array. J. Acoust. Soc. Am. 116(4), 2138
M. Nolan, M., Berzborn, E. Fernandez-Grande (2020) Isotropy in decaying reverberant sound fields. J. Acoust. Soc. Am. 148(2), 1077
M Berzborn, M. Vorländer (2020) Directional Sound Field Decay Analysis in Performance Spaces. Building Acoustics (2020), January

The Directional Energy Decay Curve

- **Directional energy decay curve** using Schroeder integration

$$d(t,\theta_q,\phi_q) = \int_t^{\infty} \left|a(\tau,\theta_q,\phi_q)\right|^2 d\tau$$

$$= e(\theta_q,\phi_q) - \int_0^{t} \left|a(\tau,\theta_q,\phi_q)\right|^2 d\tau$$



- Directional variation of the directional energy decay curve

$$\sigma_d(t) = \frac{1}{\langle d(t)\rangle_\Omega} \sum_{q=1}^{Q} \left|d(t,\theta_q,\phi_q) - \langle d(t)\rangle_\Omega\right|$$

- Isotropy metric

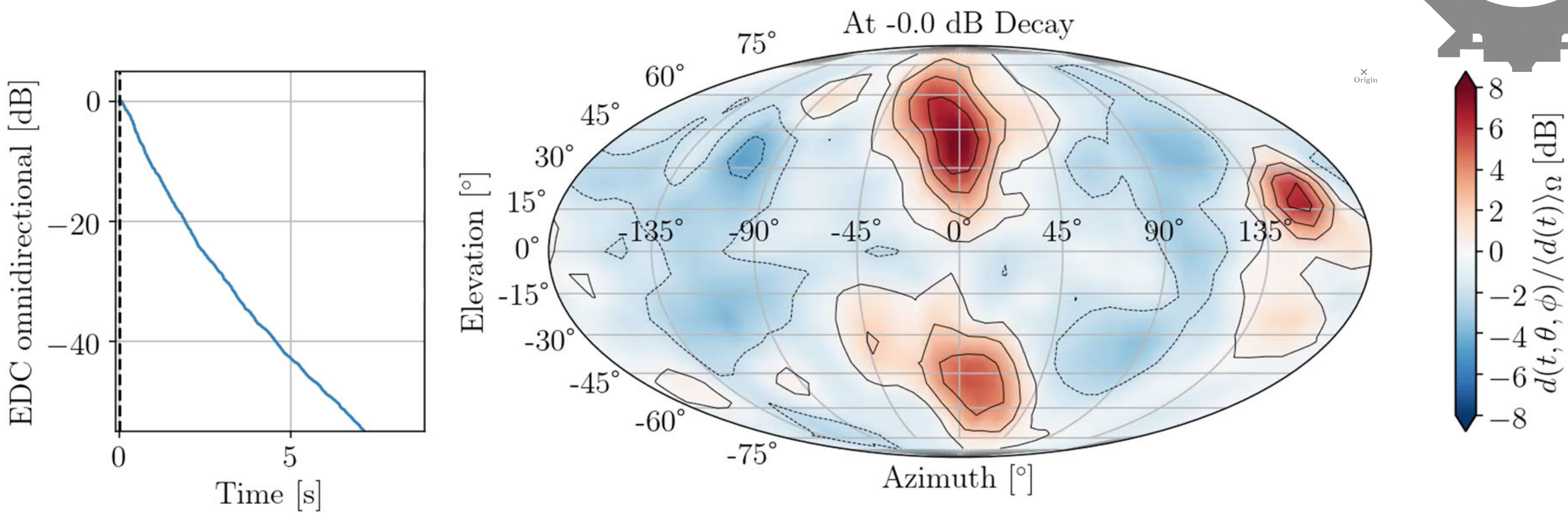
$$\mu_d(t) = 1 - \frac{\sigma_d(t)}{\sigma_{e,0}}$$

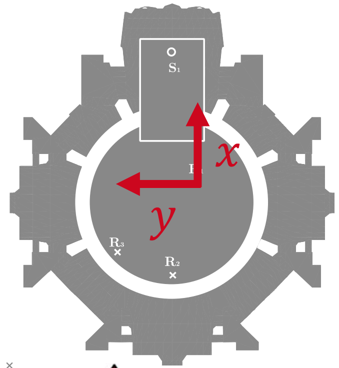
- <u>New insights:</u> Directional analysis of different energy states during the decay process

M Berzborn, M. Vorländer (2020) Directional Sound Field Decay Analysis in Performance Spaces. Building Acoustics (2020), January

Results

Position 1, 1 kHz octave





M Berzborn, M. Vorländer (2020) Directional Sound Field Decay Analysis in Performance Spaces. Building Acoustics (2020), January

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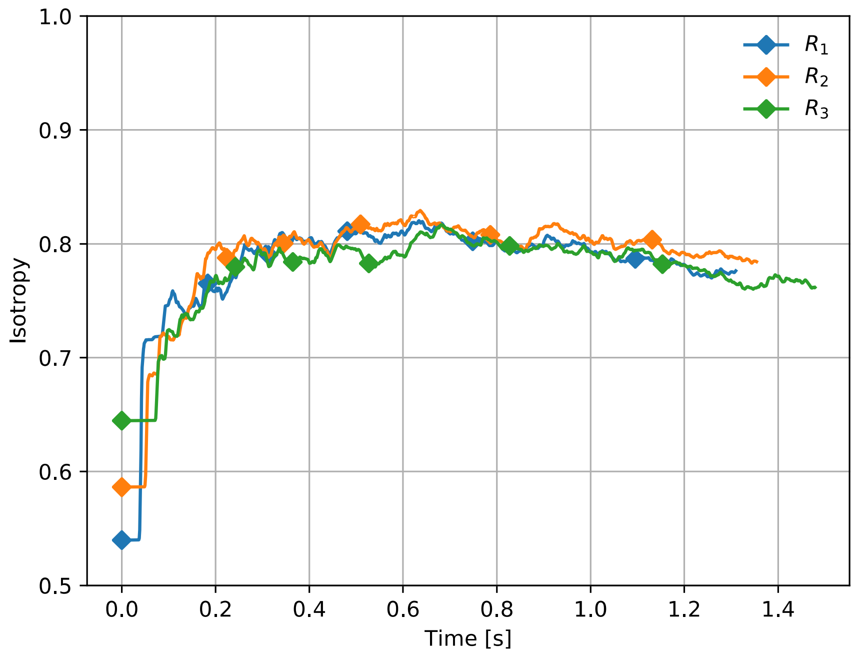
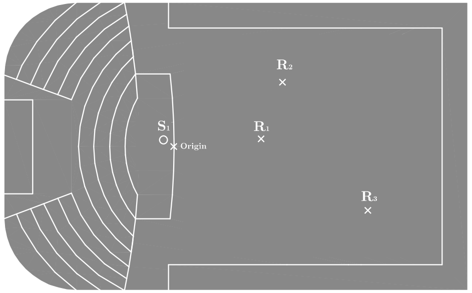
Results

Estimated isotropy, 1 kHz octave





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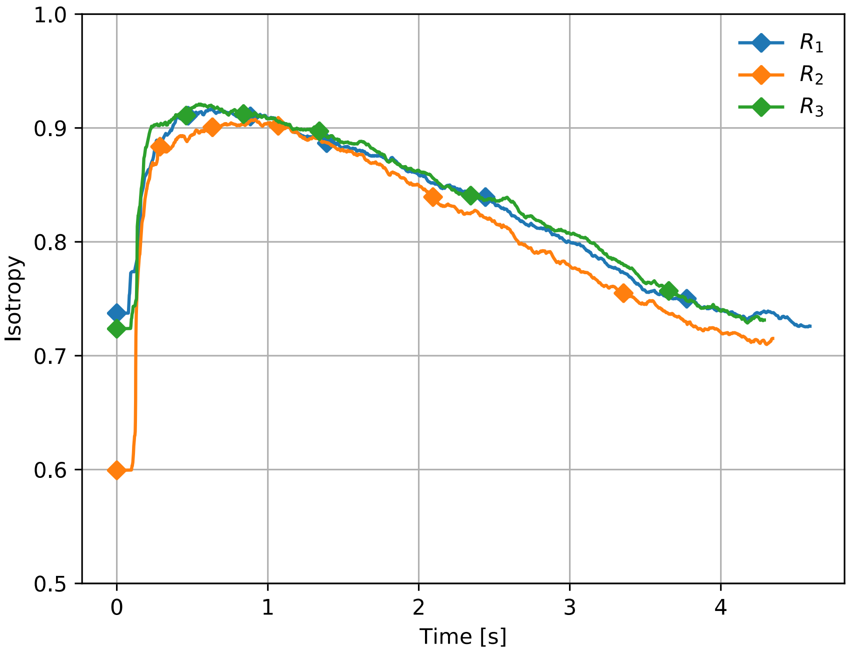

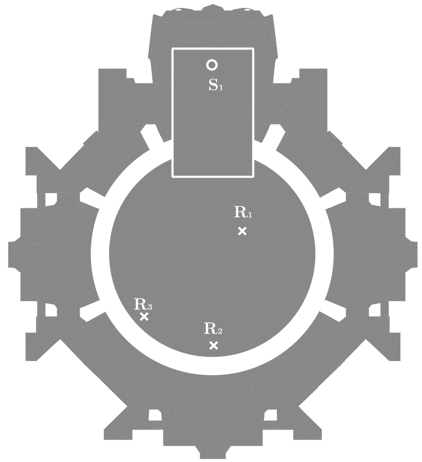

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Conclusion

- The uncertainty of auralizations can be as low as the uncertainty of measurements. With this, at least plausible (but not authentic) sound examples can be created and used for audio demonstrations.

- The signal processing parts (post processing) of impulse responses are as crucial as the acoustic simulation models.

- Wave models are required in the low (and mid) frequency range, in order to better predict diffraction and scattering (steering) effects.

- All simulation methods suffer from uncertain input data.

Conclusion

- Decay curves are curved (Kuttruff 1958).
- There is no simple approach to define a "mixing time". After this time, spatial segregation may occur, i.e. when the “long-surviving” modes determine the decay with specific directional features. Therefore it is not advisable to simulate just the early response and to add a “diffuse” decay.

Thank you for your attention!

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RWTH Aachen
mvo@akustik.rwth-aachen.de