ITA – Institute of Technical Acoustics

Prof. Dr. Michael Vorländer
mvo@akustik.rwth-aachen.de

Institute of Technical Acoustics

Personnel: 2 Professors, 1 Senior Researcher
19 Doctoral Assistants, 2 PostDocs
9 additional staff (workshops etc.)
about 20 students (Bachelor/Master)

Faculty Electrical Engineering and Information Technology

Who we are

Institute of Technical Acoustics – RWTH Aachen University

- Prof. Dr. rer. nat. Michael Vorländer
- Prof. Dr.-Ing. Janina Fels
- Staff:
  - → 19 Research Assistants
    2 Post Docs and
    1 academic senior councillor
  - → mechanical workshop und electronic laboratory
- Research
  - → Architectural Acoustics & Virtual Reality
  - → Electroacoustics & Measurement
  - → Binaural Technique & Spatial Audio
  - → Medical Acoustics

Institute of Technical Acoustics

Chair Technical Acoustics
Prof. Dr. Michael Vorländer

- Electroacoustics, Measurements — Dr.-Ing. G. Behler
  - Johannes Klein
  - Michael Kohnen
  - Samira Mohamady
  - Clemens Nau
  - Dr. Noam Shabtai
- Virtual Acoustics, Simulation, Auralization — Prof. Dr. M. Vorländer
  - Lukas Aspöck
  - Martin Guski
  - Fanyu Meng
  - Rob Opdam
  - Sönke Pelzer
  - Jonas Stienen
  - Frank Wefers
  - Ingo Witew

Chair Medical Acoustics
Prof. Dr.-Ing. Janina Fels

- Medical Acoustics, Psychoacoustics, Audiology — Prof. Dr.-Ing. J. Fels
  - Ramona Bomhardt
  - Margret Engel
  - Márcia Lins
  - Josefa Oberem
  - Florian Pausch
  - Dr. Zhao Ellen Peng
  - Jan-Gerrit Richter
  - Rhoddy Viveros Munoz

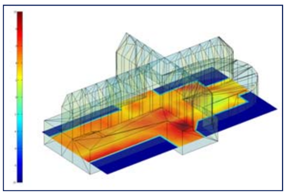
Secretariat Karin Charlier

Electr. Workshop, Rolf Kaldenbach

Mech. Workshop, Uwe Schlömer

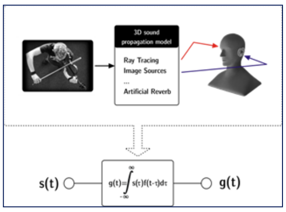
Acoustics & Signal processing

- Simulation and Auralization
  - Room and Building Acoustics, Noise Control
    Vehicle Acoustics
  - Numerical Methods: geometrical, FEM / BEM
  - Verification using measurement techniques and listening tests
- Hardware-near Programming
  - Digital Filters for Electro-acoustics
  - 3D-audio, Real-time systems: Virtual Reality



CAD-Model
Acoustic simulation

Auralisation
Virtual Acoustics



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Medical Acoustics, Communication Acoustics & Psychoacoustics

- Hearing Research and Neuroscience
  - Listening Experiments and Experiments on Cognitive Psychology (selective auditory attention) in complex acoustic scenarios
- Measurement Techniques / Reproduction Techniques for Spatial Audio, ENT, and Audiology
  - Binaural Technology, Surround Sound, Ear Couplers, Artificial Heads
- Noise Research und Psychoacoustics
  - Effects of Noise, Psychoacoustic Parameters

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Teaching

- Winter semester
  - V2 Ü1 Acoustic Virtual Reality (engl. MSc)
  - V2 Ü1 Akustische Messtechnik / Elektroakustik (elective MSc)
  - V2 Ü1 Medizinische Akustik 1 (MSc)
  - V2 Ü1 Psychoakustik (Prof. Genuit, MSc)
- Summer semester
  - V2 Ü1 Einführung in die Akustik (6. semester BSc)
  - V2 Ü1 Technische Akustik (MSc)
  - V2 Ü1 Medizinische Akustik 2 (MSc)
  - V2 Ü2 Intensivkurs Raumakustik und Beschallung (MSc)
  - V2 Ü1 Lärmschutz-Grundlagen (BSc)
- WS and SS
  - Ü3 / Ü4 Seminare Virtual Acoustics / Audio Engineering
  - Ü4 Akustisches Praktikum
  - Akustisches Kolloquium (Seminar Praxissemester)
  - Projekte, Bachelor / Master thesis

Filter design for room auralization

Michael Vorländer, RWTH Aachen University

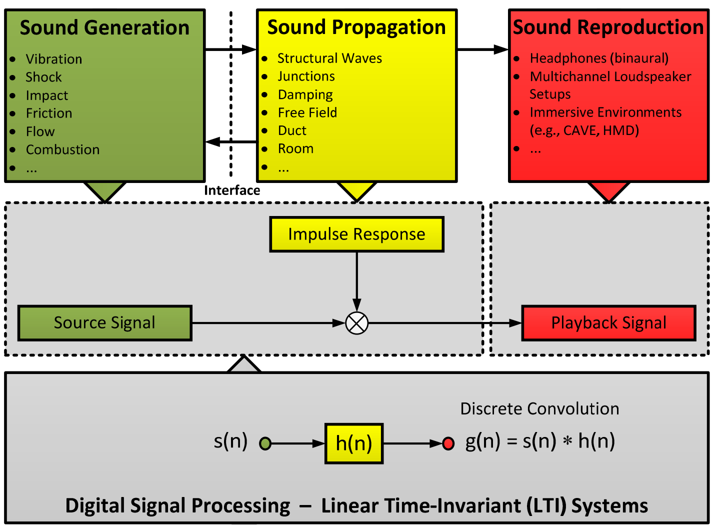
Outline

- Fundamentals of auralization

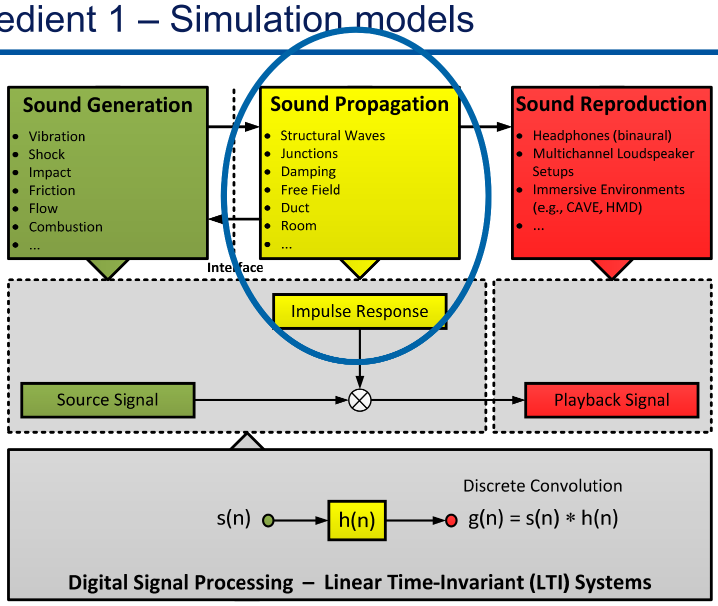
- Signal processing: real-time convolution filters
- Room impulse response filters
- Binaural filters

- Examples/Demos
- Conclusions

From data to sound



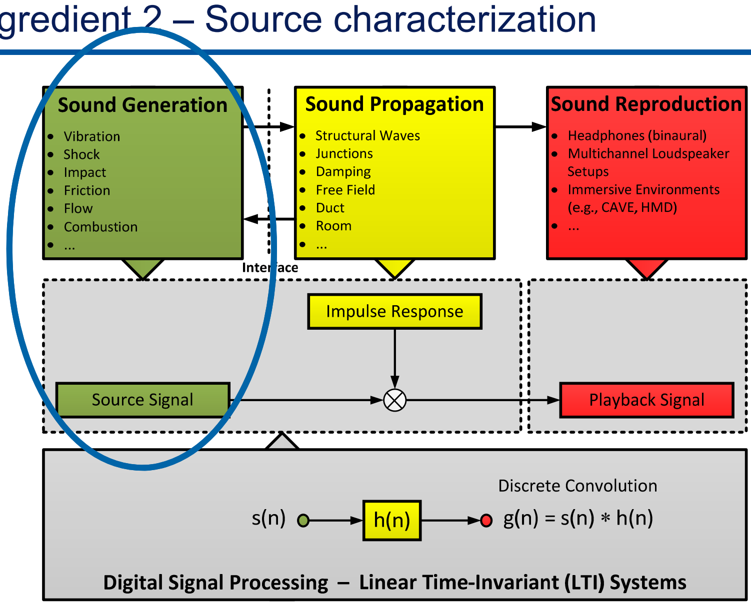
Ingredient 1 – Simulation models



Recent progress in acoustic simulation

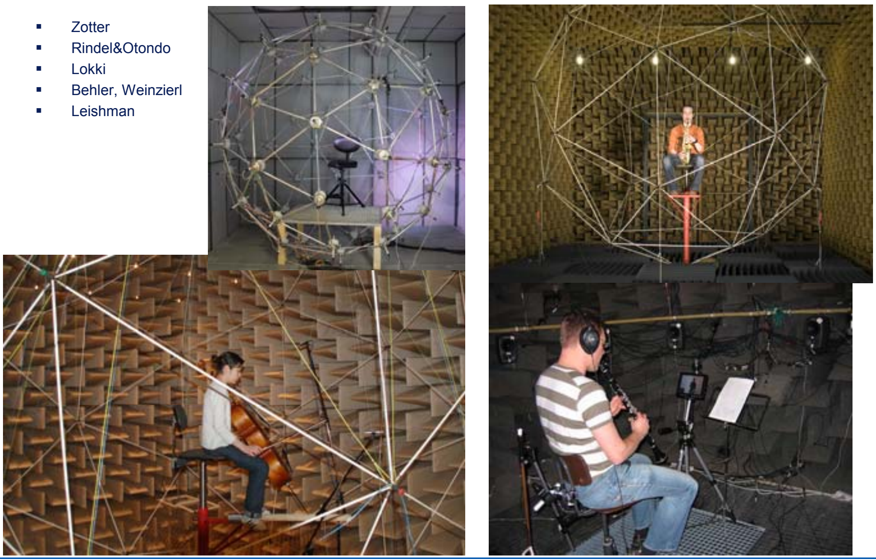
- Prediction models in standards (→ single-number metrics)
  - indoor: EN 12354
  - outdoor: ISO 9613-2
- „Exact" solution of wave acoustics
  - Helmholtz equation + boundary conditions
  - numerical methods
  - Frequency domain → IFFT → Time domain
  - or time domain BE/FE or FDTD
- Geometrical acoustics (approximations)
  - Image Sources
  - Ray Tracing
  - Hybrid Models

Ingredient 2 – Source characterization

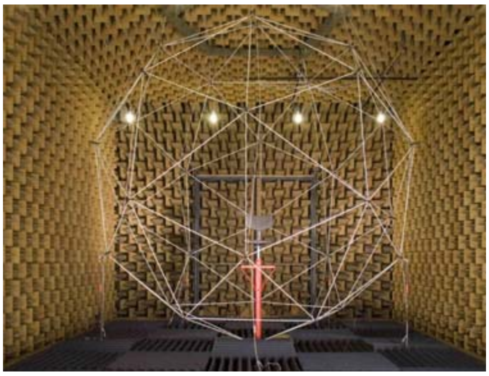


Source characterization

- Zotter
- Rindel&Otondo
- Lokki
- Behler, Weinzierl
- Leishman



Surrounding spherical microphone array



- regular placement of the microphones (32 x Sennheiser KE4-211-2)
- light and transportable microphone array of 4.4 m diameter
- adjustable chair to align the sound source to the center

Directivity measurements of musical instruments

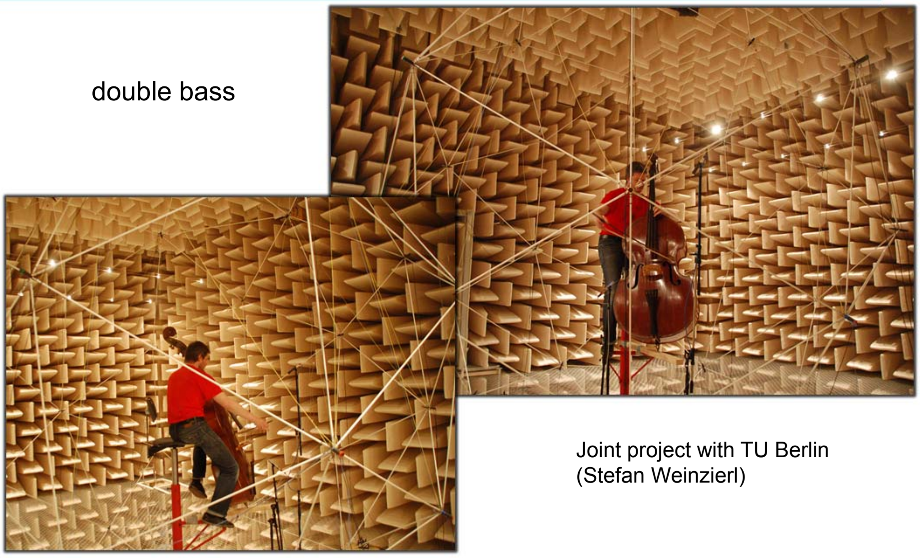
- Soprano
- Violin
- Violin (historic)
- Viola
- Classic Viola
- Violoncello
- Violoncello (historic)
- Contrabass
- Classic Contrabass
- Concert Guitar
- Pedal Harp
- Alto Saxophone (Eb)
- Tenor Saxophone (Bb)
- Wood Flute (finger hole)
- Wood Flute (key system)
- Concert Flute
- Oboe
- Classic Oboe (historical)
- Romantic Oboe (French, historical)
- English Horn
- Basset Horn (F)
- Dulcian (historic)
- Clarinet (Bb)
- Classic Clarinet (Bb)
- Bass Clarinet
- Bassoon
- Classical Bassoon
- Baroque Bassoon
- Contrabassoon
- Classical Natural Horn (Invention Horn)
- French Horn
- Natural Trumpet (D)
- Trumpet (C)
- Tenor Trombone (Bb/F)
- Classic Tenor Trombone
- Classic early-romantic Trombone
- Bass Trombone (Bb/F/G)
- Classic Bass Trombone (F)
- Tuba
- Timpani (historical)
- Timpani (plastic head)

- Modern and historical instruments measured, in total 41
- Center of musical instrument centered in array, if possible
- Single tones of a chromatic scale played (pianissimo & fortissimo)

J. Meyer 1970 , Behler et al. CFA/IoA 2012

Directivity measurements of musical instruments

double bass

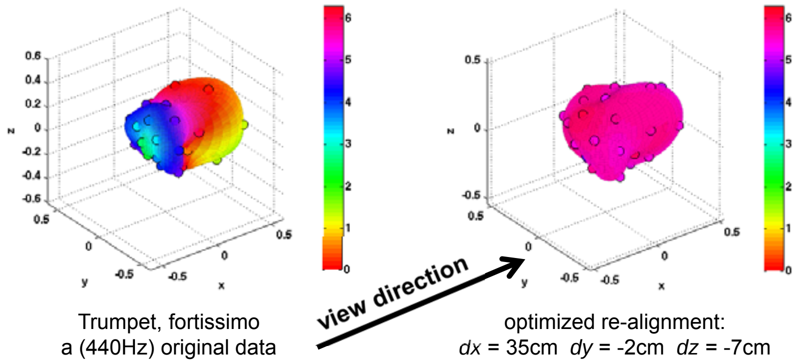


Joint project with TU Berlin
(Stefan Weinzierl)

Directivity balloons - OpenDAFF

- Alignment for low SH-orders using complex measurement data
  - Various approaches possible

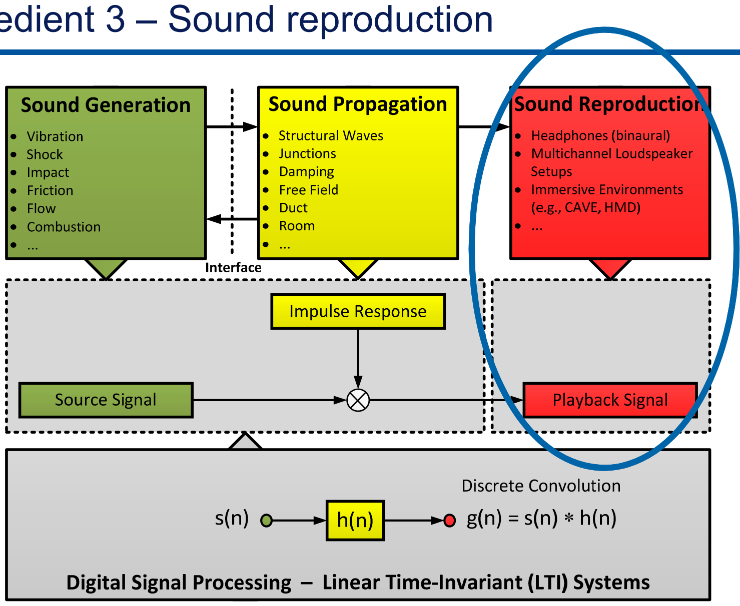
  Ben-Hagai et al: "Acoustic centering of sources measured by surrounding spherical microphone arrays", JASA 2011 and more recently Shabtai et al. (to be puplished)



Trumpet, fortissimo
a (440Hz) original data

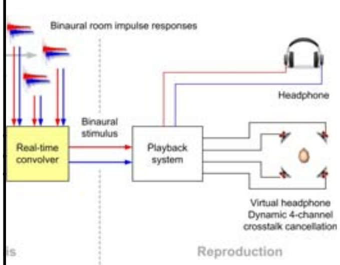
optimized re-alignment:
dx = 35cm *dy* = -2cm *dz* = -7cm

Ingredient 3 – Sound reproduction



Ingredient 3

- Binaural technology or surround sound system?



VA @ ITA RWTH

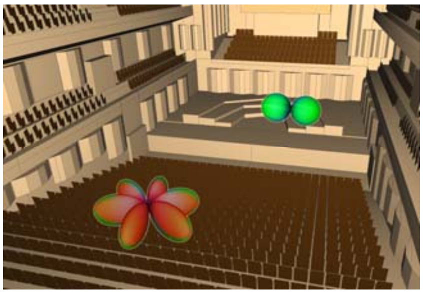
2 audio channels,
12 loudspeakers plus 9 subwoofers

Auditorium H104 TU Berlin

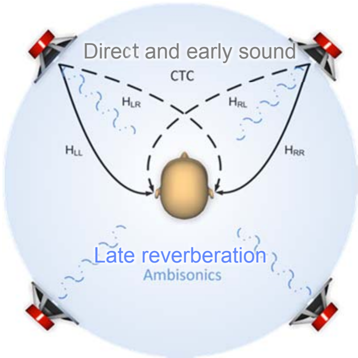
832 audio channels, >2000 loudspeakers

Ingredient 3

- or Ambisonics?



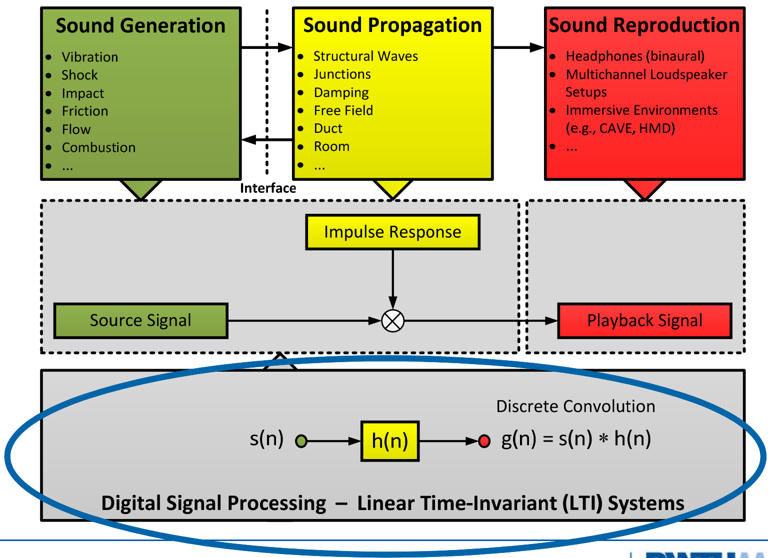
A. Farina, P. Martignon, A. Capra, S. Fontana, Measuring impulse responses containing complete spatial information. AES UK 2007



or hybrid?

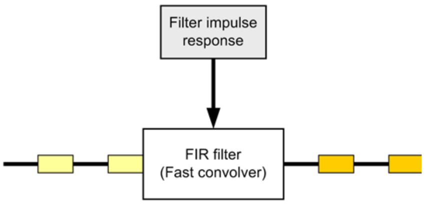
S. Pelzer, B. Masiero, M. Vorländer,
3D Reproduction of Room Auralizations by Combining Intensity Panning, Crosstalk Cancellation and Ambisonics. Proc. EAA Joint Symposium on Auralization and Ambisonics, Berlin, 2014

Ingredient 4 – Audio signal processing



Ingredient 4

- Audio streaming = Block-wise processing of samples



- Continuous input stream x(n) (block length B)
- Filter impulse response h(n) (length N filter coefficients)
- **Low input-to-output latency**

- W. G. Gardner, Efficient convolution without input-output delay. JAES 1995
- L. Savioja, J. Huopaniemi, T. Lokki, and R. Väänänen. Creating Interactive Virtual Acoustic Environments. JAES, 1999
- F. Wefers, M. Vorländer, Optimal filter partitions for real-time FIR filtering using partitioned FFT-based convolution in the frequency domain. DAFx 2011

Putting that all together - and run it very very quickly

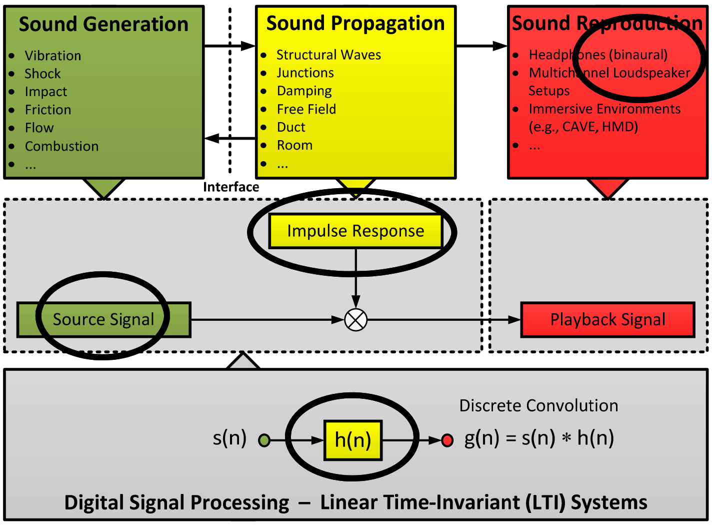
Sources
Acoustic simulation
Signal processing
Spatial Audio

Virtual Acoustics

Acoustic Virtual Reality
- AVR -

real-time
multimodal
interaction

Where are filters?



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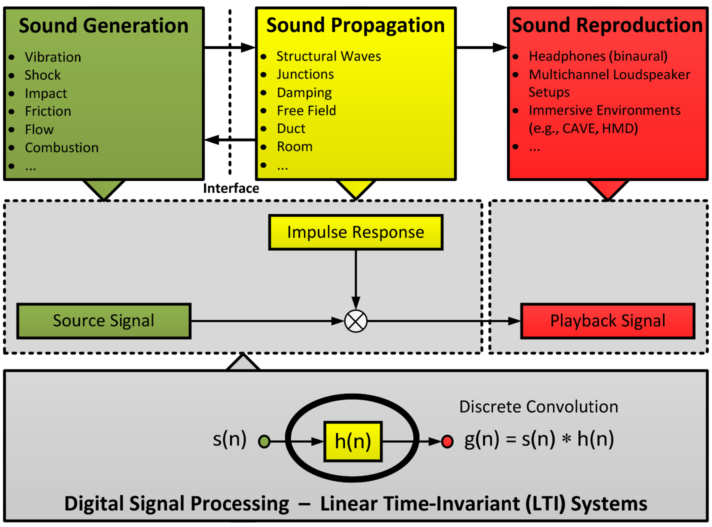
Where are filters?



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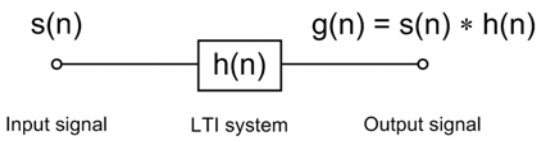
Basic principles

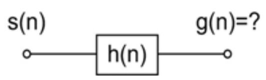
- System theory: Linear time-invariant (LTI) system



- Impulse response h(n) fully describes the LTI system (like an „acoustic *fingerprint*")
- Attention!! VR ≠ LTI
- possible: slices of LTI, and appropriate filter updates

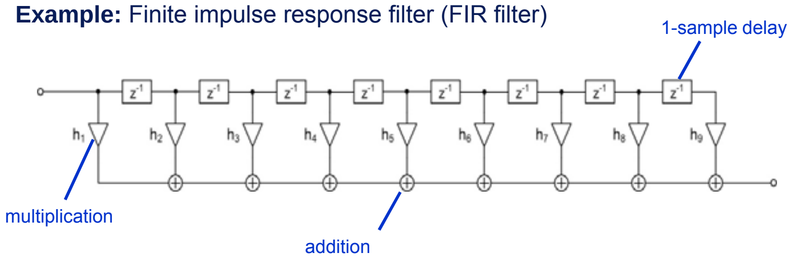
Digital filters and convolution

- **Discrete convolution** → Calculate the system response for arbitrary inputs



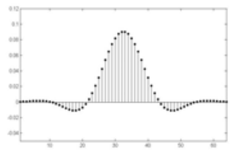
$$\boxed{g(n) = s(n) * h(n) = \sum_{m=-\infty}^{\infty} s(m)h(n-m)}$$

- **Example:** Finite impulse response filter (FIR filter)

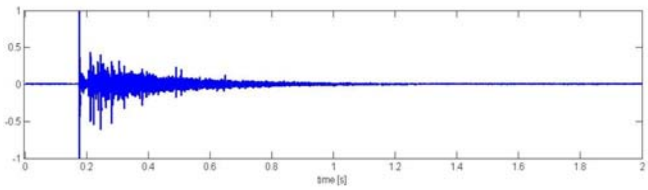


Sound examples

- Original (dry) sound sample
- 4 kHz lowpass filter
  (64 filter coefficients)



- Room impulse response „Eurogress Aachen“
  (2s @ 44.1 kHz = 88200 filter coefficients)



Discrete Fourier transform

Discrete Fourier transform (DFT)

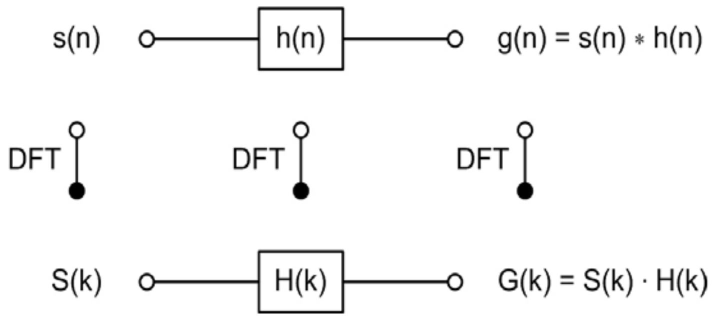
$$\mathrm{DFT}\{s(n)\} = \sum_{i=0}^{N-1} s(i) e^{-2\pi j \frac{ik}{N}}$$

Inverse Discrete Fourier transform (IDFT)

$$\mathrm{DFT}^{-1}\{S(k)\} = \frac{1}{N} \sum_{i=0}^{N-1} S(i) e^{2\pi j \frac{ik}{N}}$$

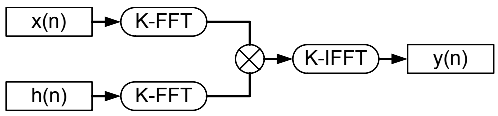
- **Idea:** Decompose a time signal into a superposition of sinusoidals
- **Other interpretation**: Which „frequencies“ are contained in a signal?
- Efficient computation in $\mathcal{O}(n \log n)$ (*Fast Fourier Transform*, *FFT*)

Time domain vs. Frequency domain



Fast convolution using FFT

- Signal $x(n)=x_0..x_{M-1}$ and filter $h(n)=h_0..h_{N-1}$ (length M, N)

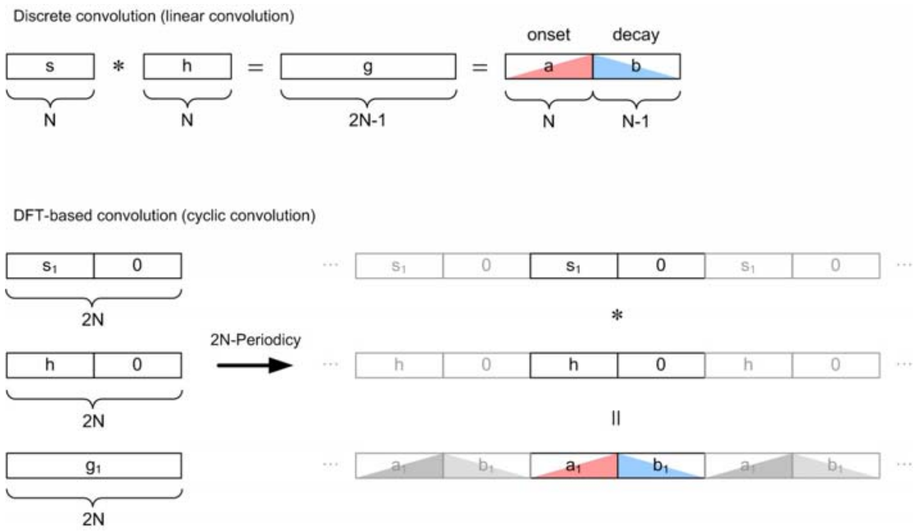


$$y(n) = \sum_{k=-\infty}^{\infty} x(k) \cdot h(n-k)$$

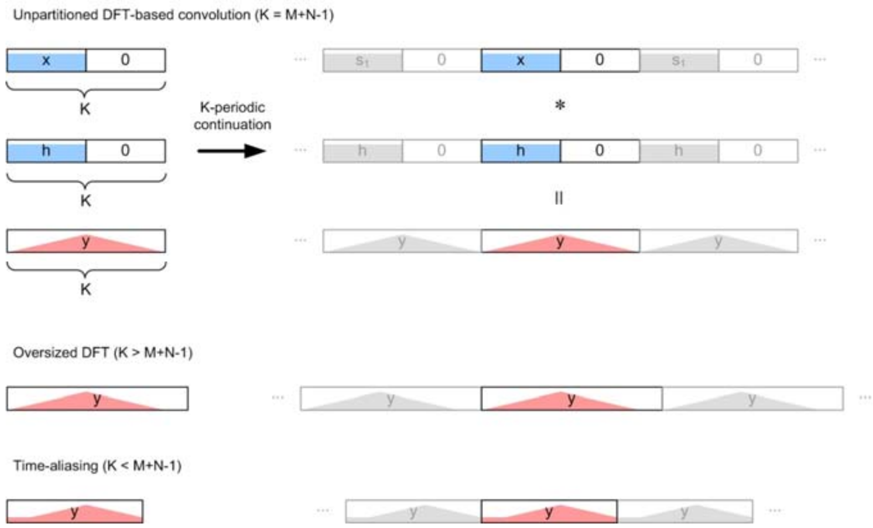
$$y(n) = DFT^{-1}_{(k)}\{DFT_{(k)}\{x(n)\} \cdot DFT_{(k)}\{h(n)\}\}$$

- Condition:
- ***Fast*** **convol** $K \geq M + N - 1$ (thanks to FFT) $\mathcal{O}(n \log n)$

Cyclic convolution in DFT domain

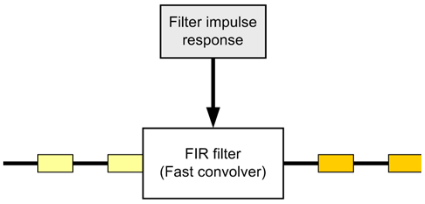


Choice of DFT transform size



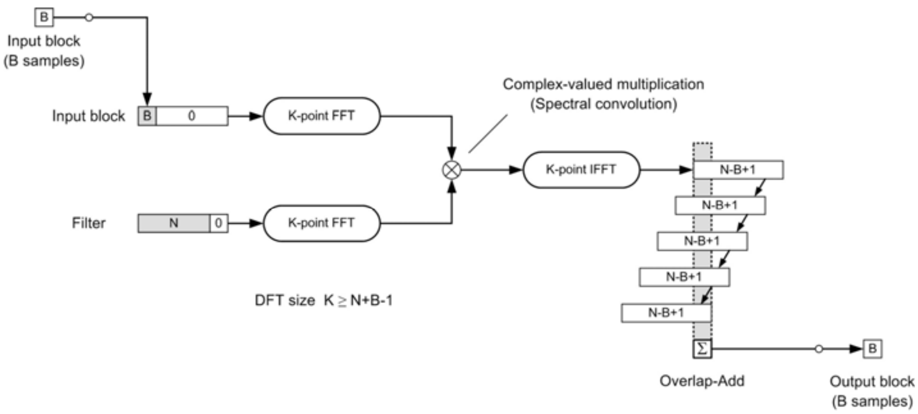
Real-time filtering

- Audio streaming = Block-wise processing of samples

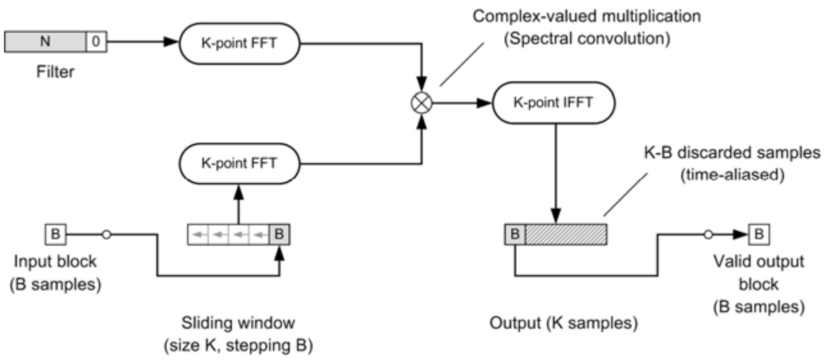


- Continuous input stream x(n) (block length B)
- Filter impulse response h(n) (length N filter coefficients)
- Low input-to-output latency

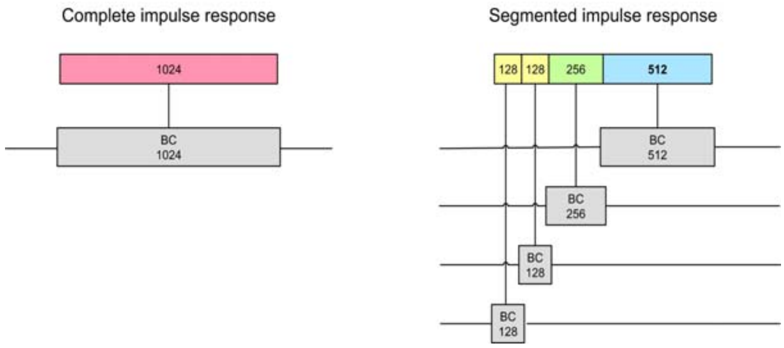
Overlap-add (OLA) scheme



Overlap-save (OLS) scheme

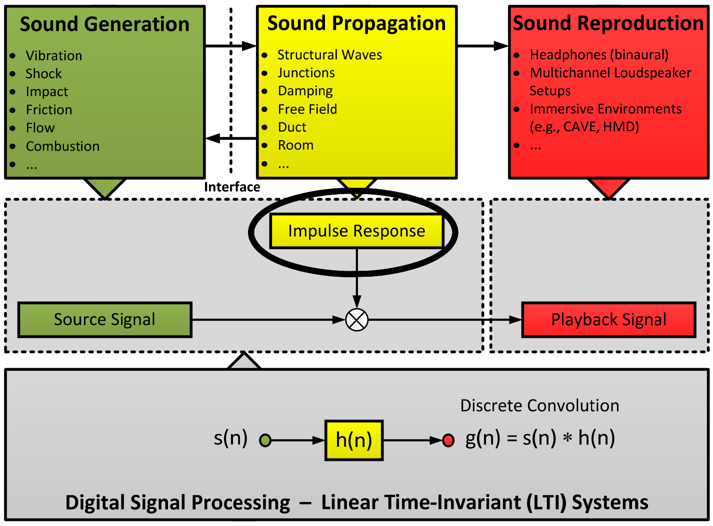


Segmented convolution



- short blocks -> small I/O latency
- long blocks -> high efficiency

Where are filters?



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Today‘s Room Acoustic Simulations

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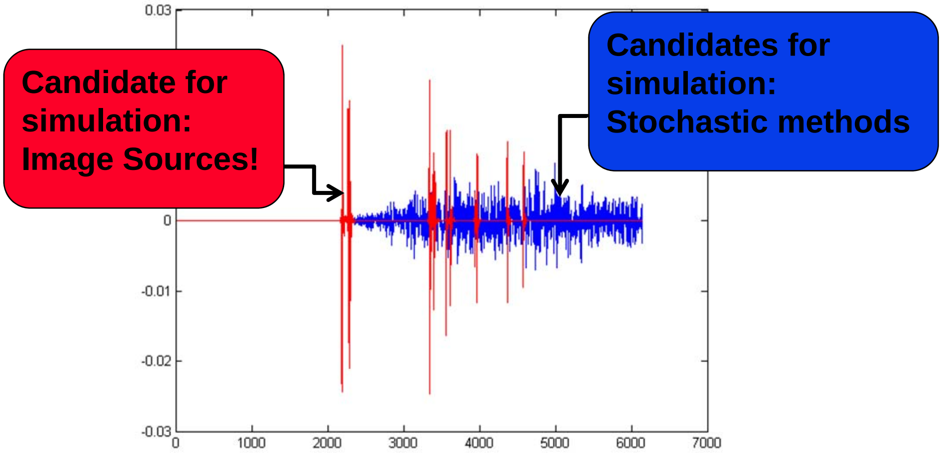
Final (binaural) filter impulse response



Example: Eurogress Aachen

Image sources + Ray Tracing

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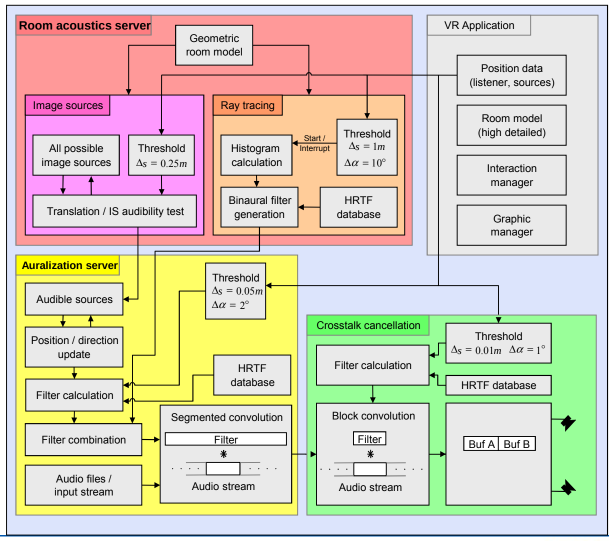
The VRCA system / details



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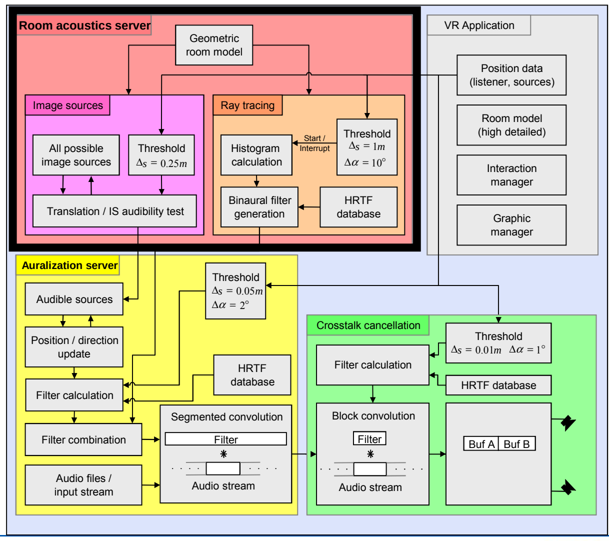
The VRCA system / details



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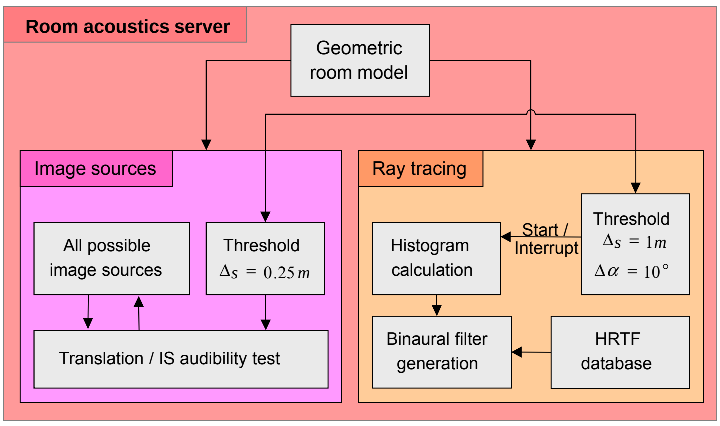
The VRCA system / Room acoustics: **RAVEN**



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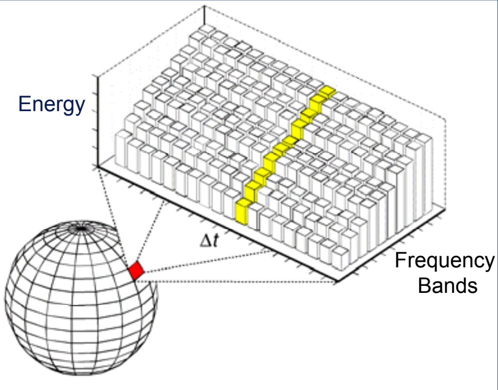
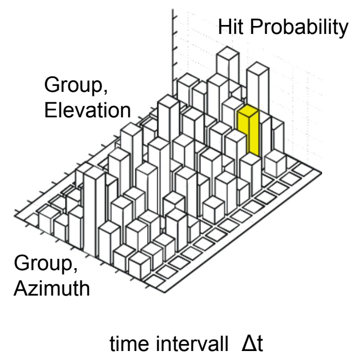
From envelopes to BRIR

The ITA method (1993 - 2015):
Vorländer, Heinz, Schröder, Pelzer

- Detection sphere is divided into directivity groups
- Energy histogram for any group and any frequency band
- Determine hit probability of each group for any time intervall





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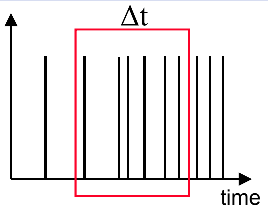
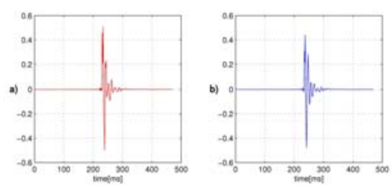
Filter construction – temporal structure

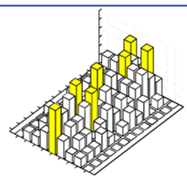


Poisson impulses

*



Head Related Impulse Responses



HRIRs with highest probability
during time interval Δt

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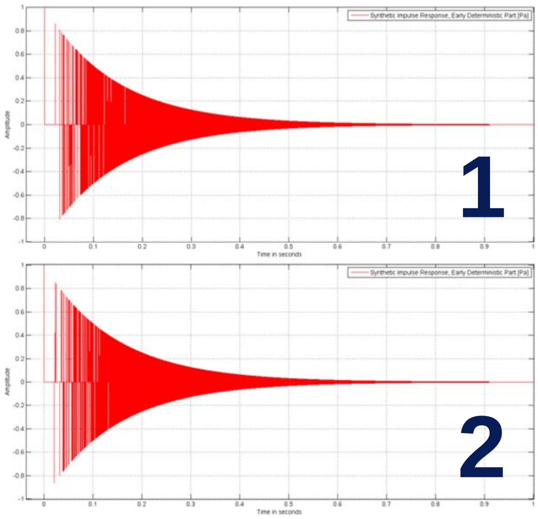
Room Impulse Reponses



RT1 = RT2
G1 = G2
C1 = C2
…

Do they sound different?
→ Yes!

Only difference:
fine structure of pulses/reflections

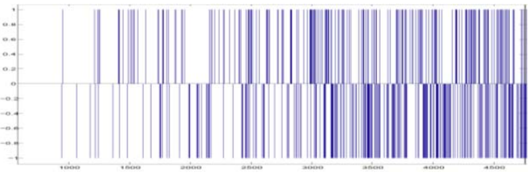
Monte Carlo Simulations

- Artificial impulse responses
  - Independent of room acoustical simulation implementation details
- Dirac Impulse distribution follows exponential growing reflection density
- Early part held constant up to a certain transition time
- Varying late reverberation
- Transition times chosen as multiples of the mean free path travel time
  - Relation from transition times to reflection orders in simulations
- Room Volumes ($5m^3$-$15000m^3$), Reverberation Times (0.2s-2s)
- 1000 simulations each
- Standard deviation of one-third octave band levels
  - As a first approach to the human auditory system

Building IRs - Stochastic Reverberation

- Reflection density

$$\mu(t(n)) = \sqrt[3]{\frac{4\pi c^3 t^2}{V}}$$



- Poisson process, with
- Exponential Decay Curve

$$p(t) = \left(\sum_{n=0}^{n_{Max}} \delta(t - t(n)) \cdot s(n)\right) \exp\left(-\frac{3\ln 10}{T} t\right)$$

$$t(n) = \begin{cases} 0 & \text{for} \quad n = 0 \\ \sqrt[3]{\frac{3V}{4\pi c^3}} & \text{for} \quad n = 1 \\ t(n-1) = \frac{1}{\mu(t(n-1))}\ln(\frac{1}{z}) & \text{for} \quad n > 2 \end{cases}$$

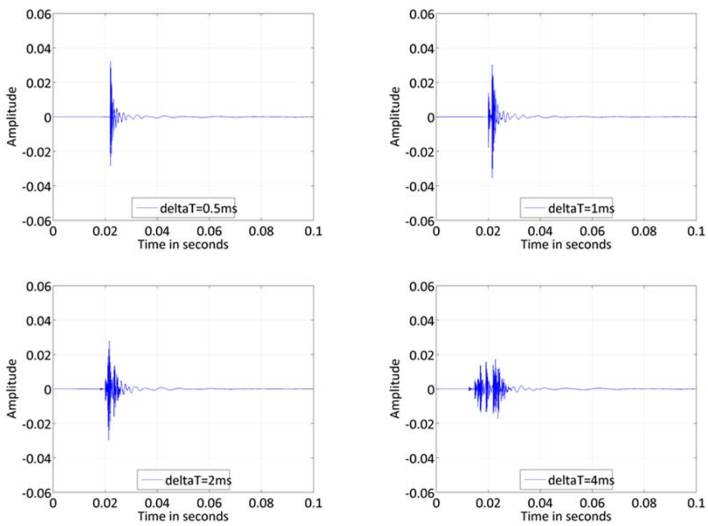
Cremer, Müller H. L.: "Principles and Applications of Room Acoustics (translated by T.J. Schultz)". Vol. I. Applied Science, London, 1982

Vorländer, M.: "Revised Relation between the Sound Power and the Average Sound Pressure Level in Rooms and Consequences for Acoustic Measurements". In: ACUSTICA 81 (1995), S. 332–343

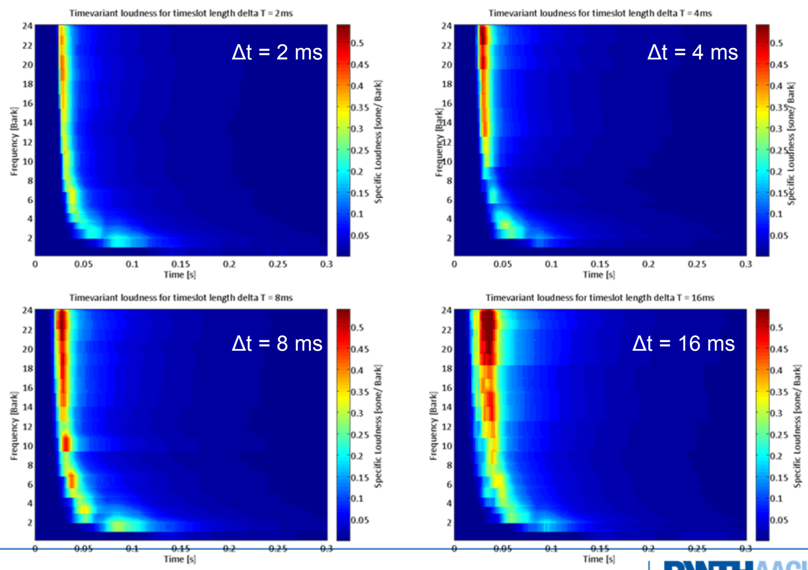
Feller, W.: "An introduction to probability theory and its applications". Vol. I. 2. John Wiley & Sons, 1966

Schroeder, M.R.: "Natural Sounding Artificial Reverberation". In: 13th AES Convention, 1961

Time signal: single reflection (Δt)



Time variant loudness: single reflection



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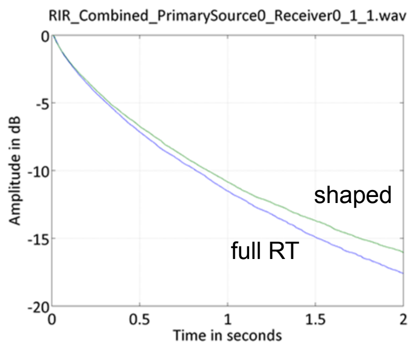
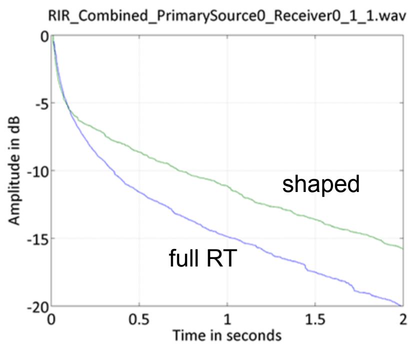
Overall decay: full Ray Tracing vs. Shaped Noise



Homogeneously distributed absorption



Inhomogeneously distributed absorption

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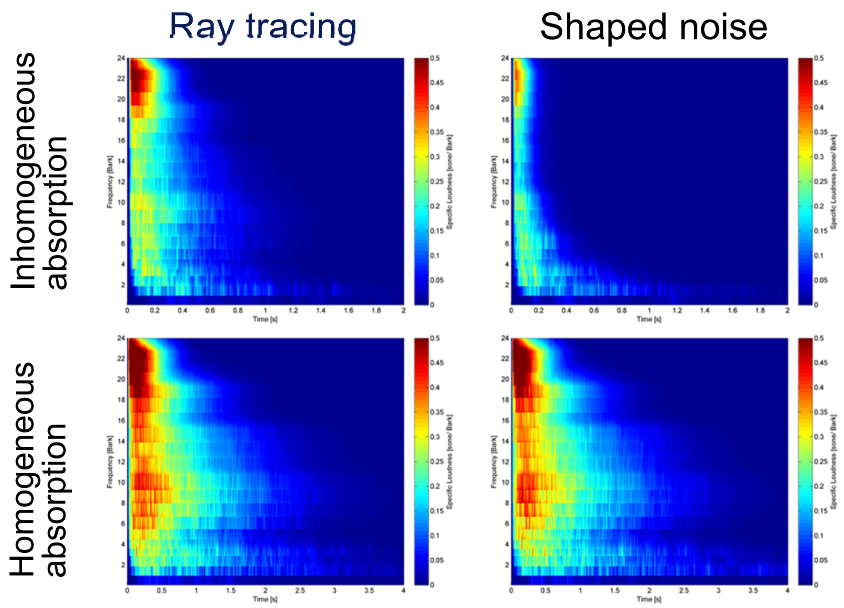
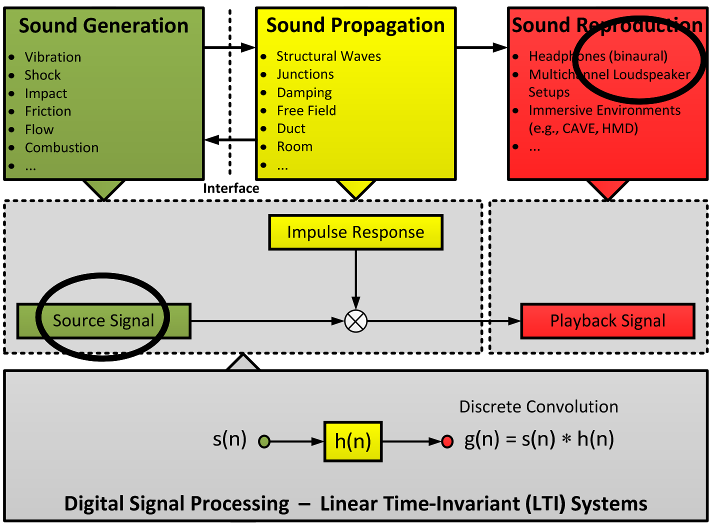
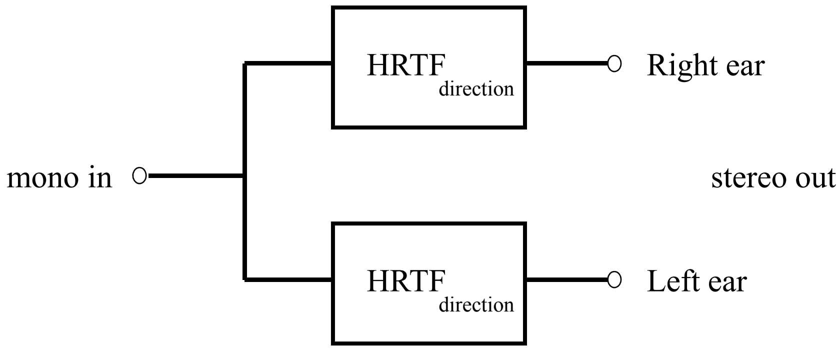
Time variant loudness



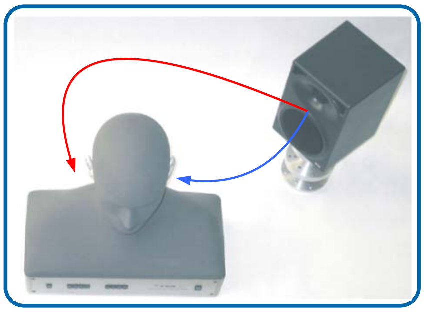
Where are filters?

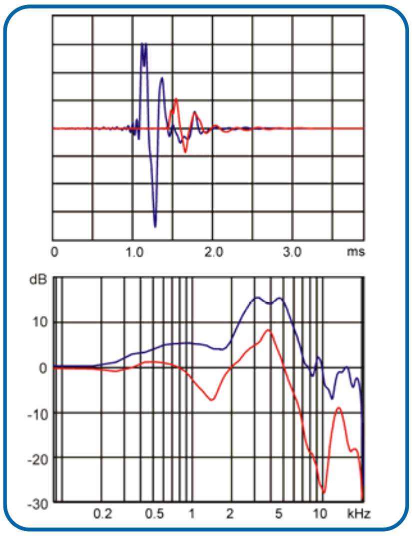


„Directional mixing console“



Basics: Binaural Technique

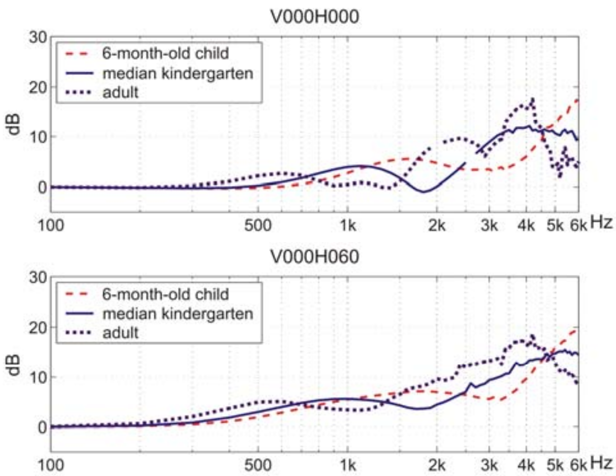




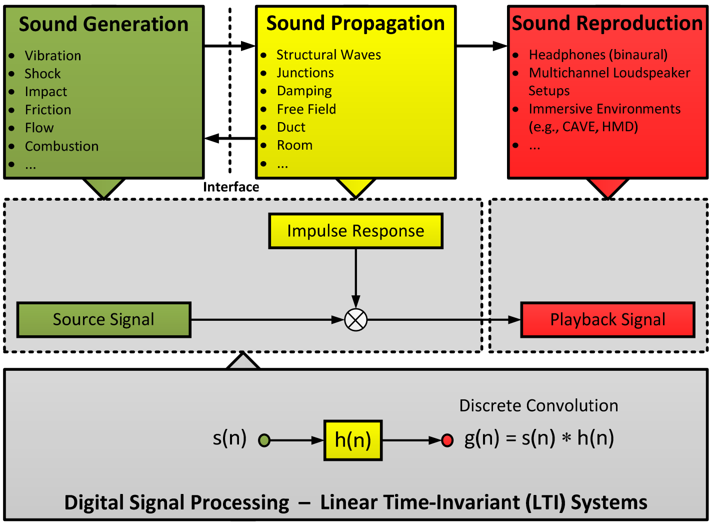
- Interaural Cues
  - ITD, ILD
  - Temporal structure
  - Spectral differences
- Monaural Cues
  - Only spectral patterns

Rapid measurement of individual HRTF

Comparison: 6-month-old, median kindergarten, adult



Examples



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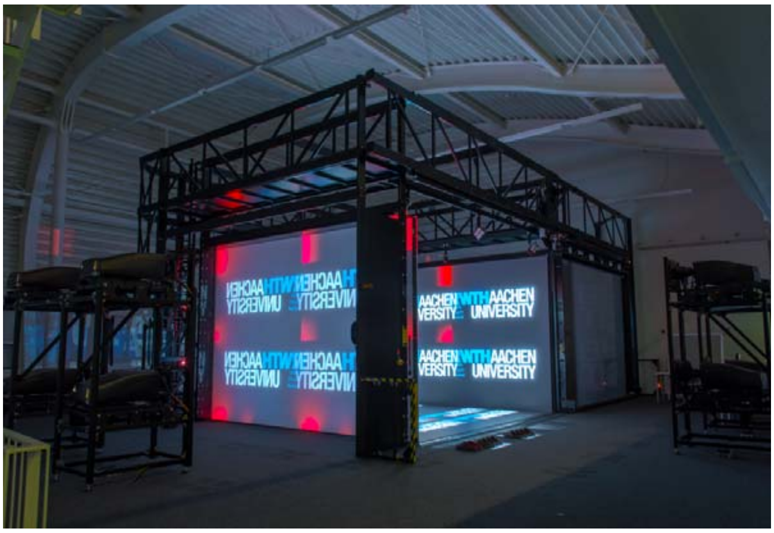
aixCAVE environment @ RWTH Aachen University



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VR Hardware

aixCAVE visualization system

- 5-sided immersive display (no ceiling)
- Dimensions: 5.25m x 5.25m x 3.2m
- 24 Full HD+ active stereo projectors (Barco NW12, three-chip DLP, 1920x1200)
- Optical infrared tracking cameras
- Active stereoscopy (shutter glasses)

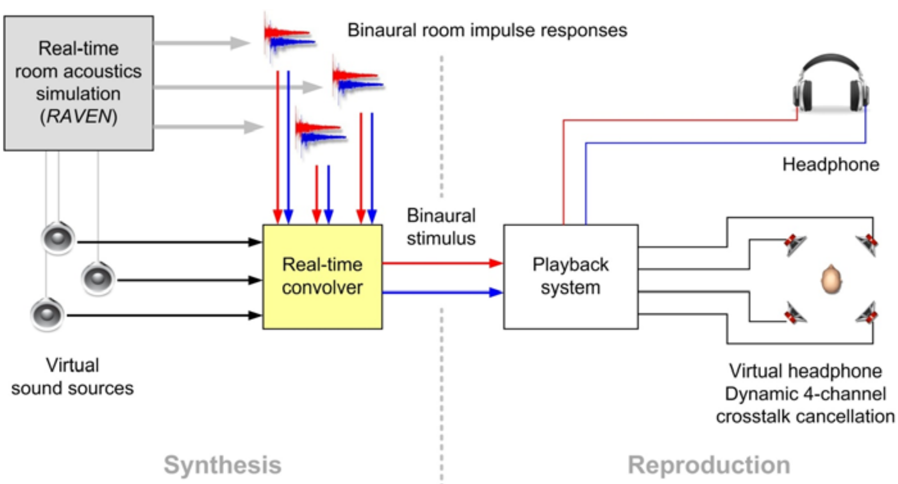
aixCAVE audio system

- 12 near-field monitor speakers (KH120A)
- 9 sub woofers (ProDipe 10S)
- Wireless headphone
- Array of 21 electret microphones (ceiling)

aixCAVE immersive display

Infrared tracking cameras & glasses

System overview | Audio rendering



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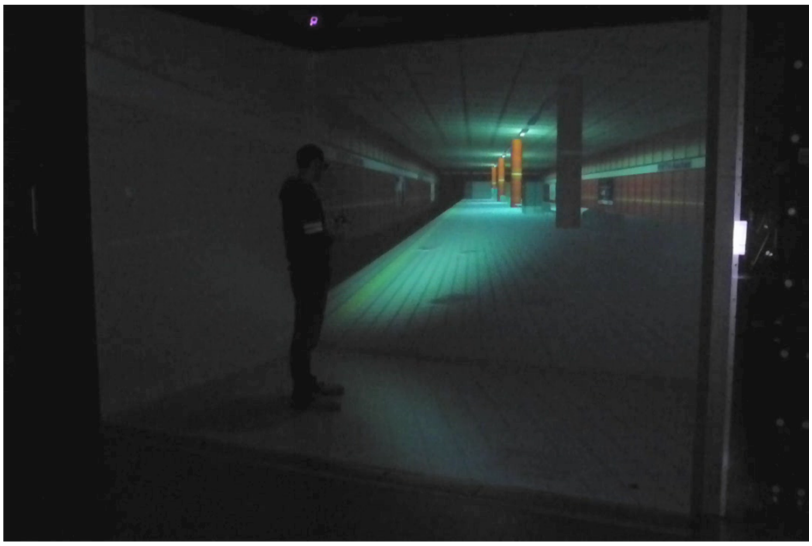
Metro station



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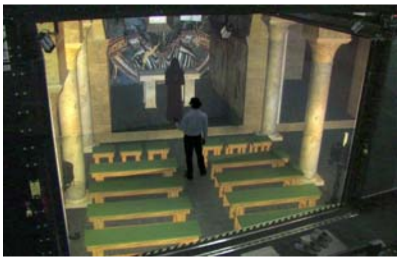
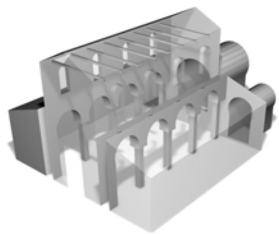
aixCAVE Demo | Medieval spanish church *San Juan de Baños*





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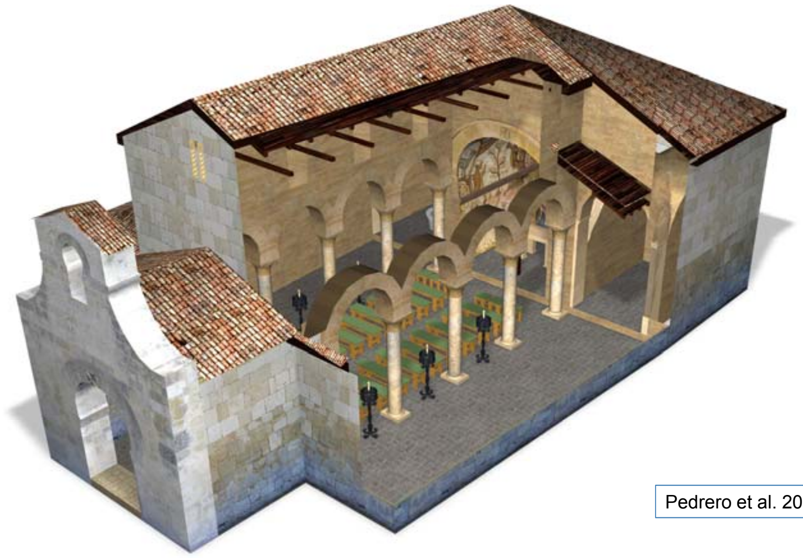
Mozarabic chant in an 11th century church



Pedrero et al. 2013

Comparsion of two simulators

- „RAVEN“ (ITA RWTH) and „BRASS“ (UFRJ, Brasil)

Motivation

- Acoustical simulation is widely used for evaluating the sound quality in rooms and sound pressure level in urban areas. Nowadays, the auralization is one of the most important tools for evaluating how the sound is heard in a given room.
- The acoustic evaluation of a room is based on acoustic quality parameters, extracted from the simulated of impulse responses.
- Each software developer implements different methods and techniques to obtain the Monoaural or Binaural Impulse Responses (BIRs).
- Depending on such methods and signal processing, simulated impulse responses may present similar parameter values, but different binaural characteristics.

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Software Description

	RAVEN	BRASS
Development	Institute of Technical Acoustics RWTH Aachen University. Germany.	Polytechnic School Federal University of Rio de Janeiro. Brazil.
Early Reflections	Image Method	Raytracing + Clustering
Diffuse reflections	Stochastic Raytracing	Traditional Raytracing
Sound Sources	Sound sources are modeled by inclusion of their directivity and free field sensitivity. (DAFF files)	
Receivers	Spherical Energy detectors – HRIR measurements from ITA with 1 degree resolution (256 samples)	
BIRs	rays are processed according to their incidence angle distribution.	Rays are individually processed according to its incidence angle.

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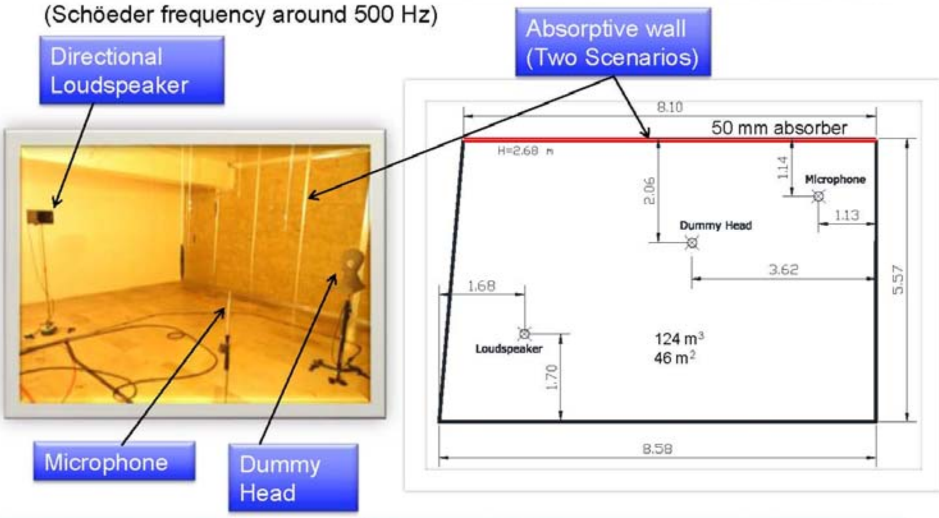
Controlled Scenario Description

The enviroment selected for this evaluation was the reverberant chamber at ITA.
(Schöeder frequency around 500 Hz)



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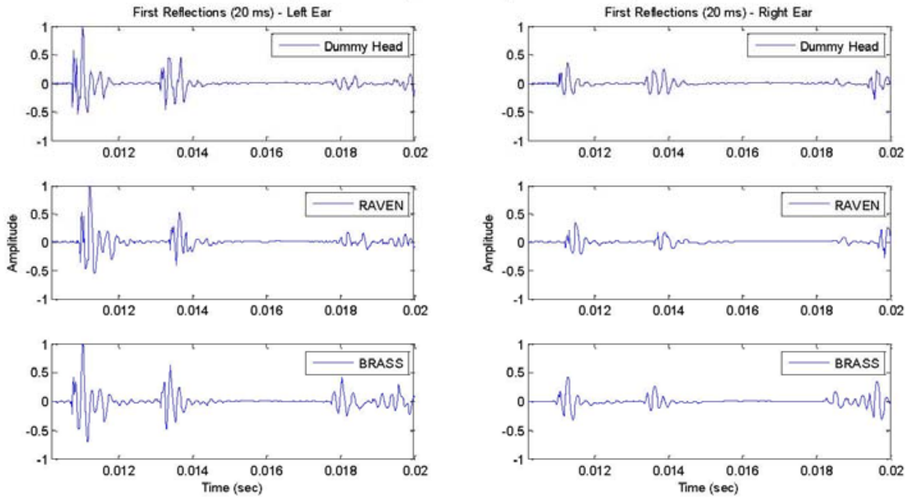
Binaural Comparison
Reverberant Scenario

Impulse Responses (first 20 ms)



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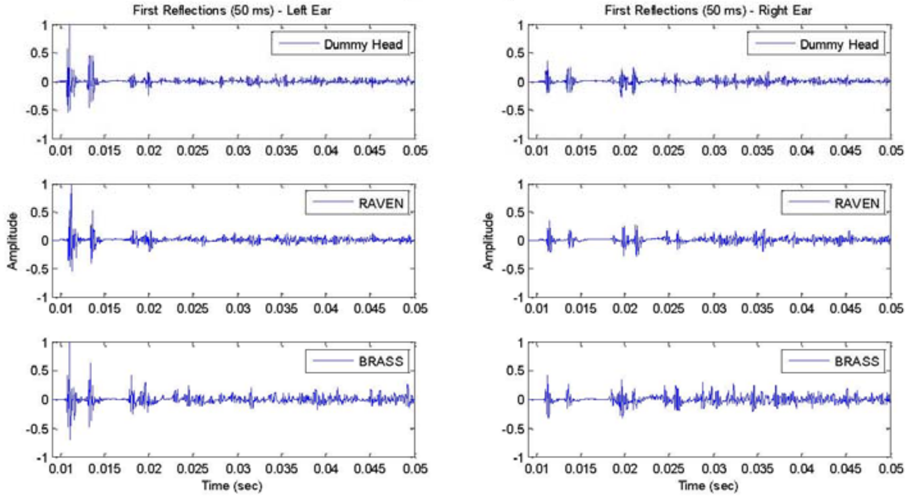
Binaural Comparison
Reverberant Scenario

Impulse Responses (first 50 ms)



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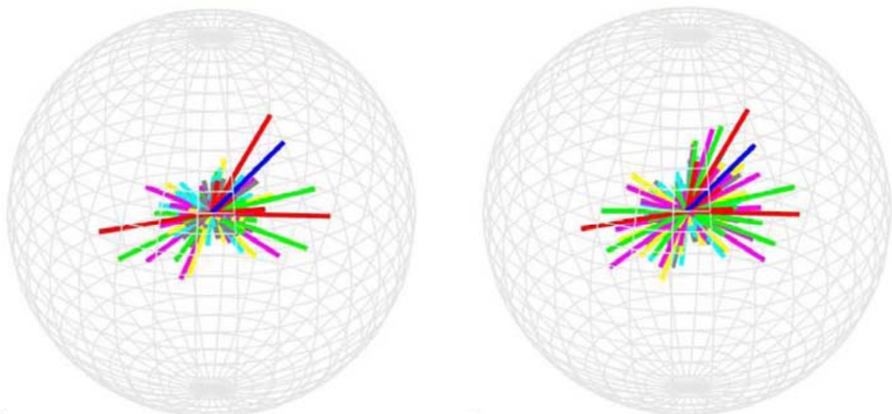
Binaural Comparison
Rays Direction and Presure

Ray Visualization

RAVEN BRASS



Specular reflections up 6th order:
RAVEN – Image Method
BRASS – Raytracing Clustering

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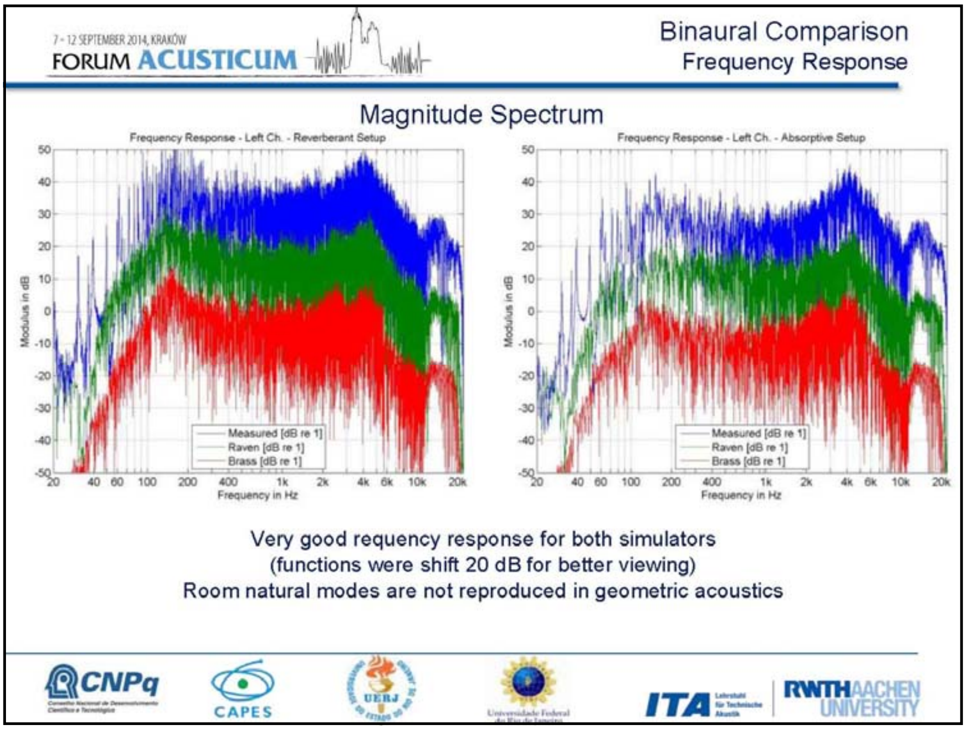
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Binaural Comparison
Frequency Response
Magnitude Spectrum
Frequency Response - Left Ch. - Reverberant Setup
Frequency Response - Left Ch. - Absorptive Setup
Modulus in dB
Frequency in Hz
Measured [dB re 1]
Raven [dB re 1]
Brass [dB re 1]
Very good requency response for both simulators
(functions were shift 20 dB for better viewing)
Room natural modes are not reproduced in geometric acoustics
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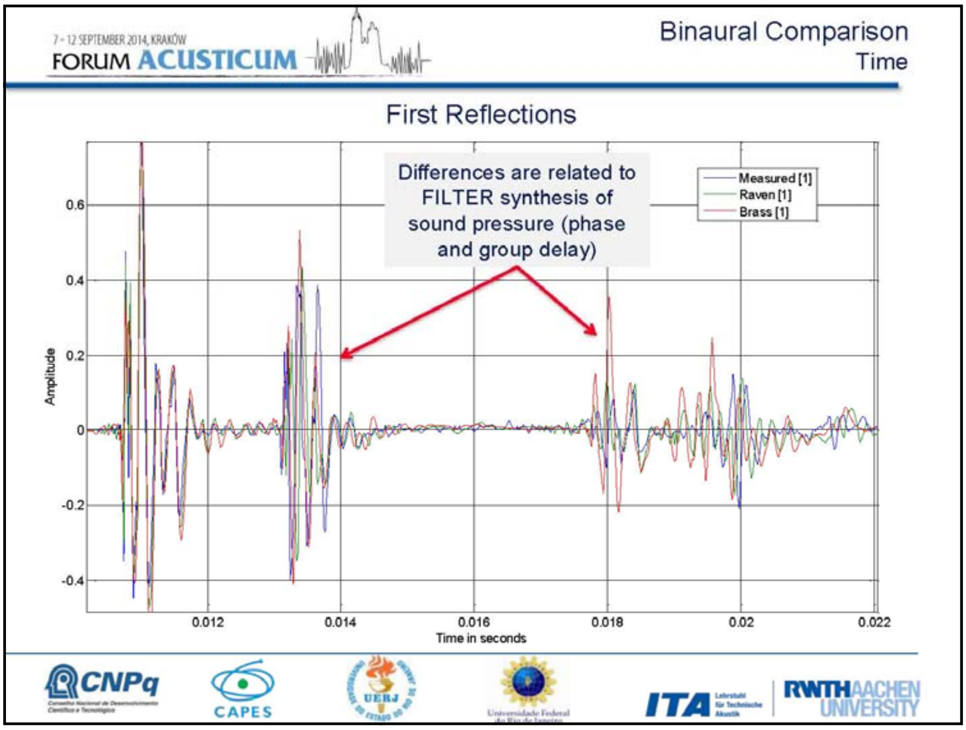
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Binaural Comparison
Time
First Reflections
Differences are related to FILTER synthesis of sound pressure (phase and group delay)
Measured [1]
Raven [1]
Brass [1]
Amplitude
Time in seconds
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What causes such small differences?

- Filters Design for time pressure synthesis
- Octave sub-band filtering;

Are these differences noticeable?

- Subjective listening tests will be performed to compare measurements with simulations

- How to quantify the impact of such differences in the auralization? Plausibility?

Outline

- Fundamentals of auralization

- Signal processing: real-time convolution filters
- Room impulse response filters
- Binaural filters

- Examples/Demos
- Conclusions