Aalto University

Parametric Time-Frequency-Domain Spatial Audio – Delivering Sound According to Human Spatial Resolution

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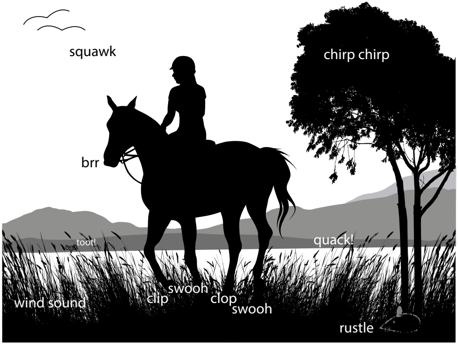
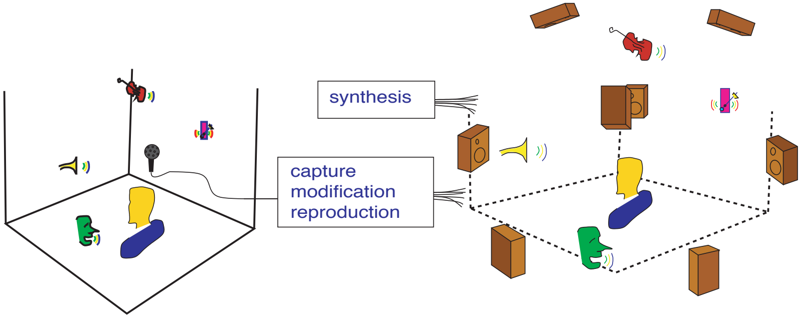
16-Oct-2017

Spatial sound



- Spatial: Where is it? / How far is it?
- Spectral: What is it?

Reproduction of spatial sound



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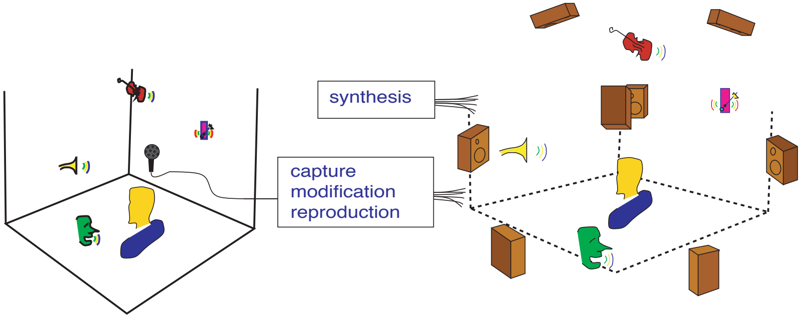
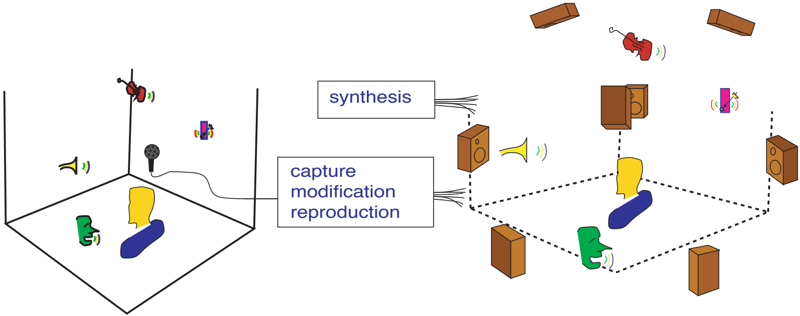


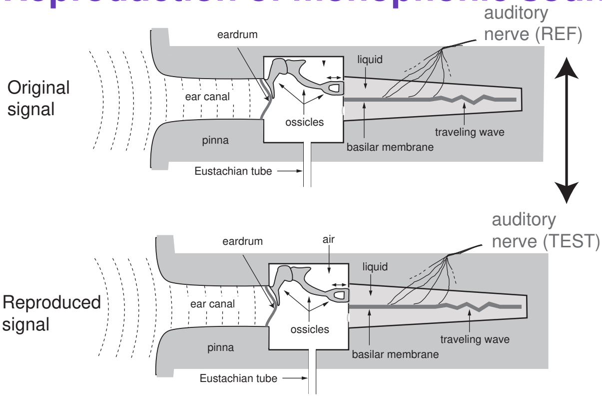
- Relay the perception

Reproduction of spatial sound



- Relay the perception
- Synthesize a desired perception

Reproduction of monophonic sound



- Auditory nerve outputs should match btw original and reproduced sound

Perceptual audio coding

- Reproduced signal does not have to be PCM samples of $x(t)$

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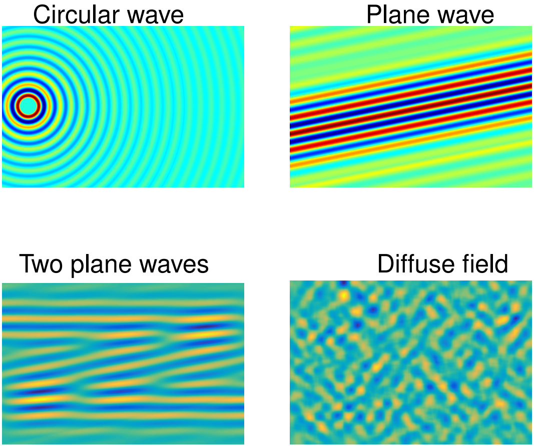
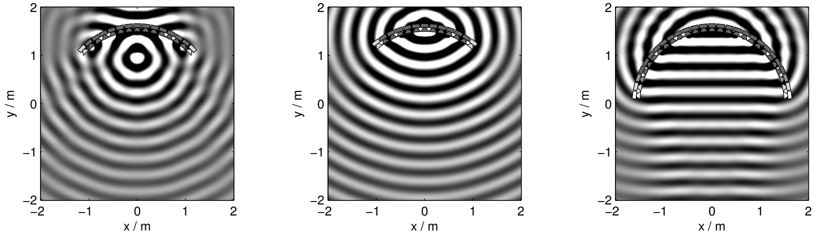
Perceptual audio coding

- Reproduced signal does not have to be PCM samples of $x(t)$
- In perceptual approaches the signal is a frequency-band representation with various masking effects taken into account
- What is the "signal" in spatial audio?

Examples of sound fields



Physical approach: Wave field synthesis



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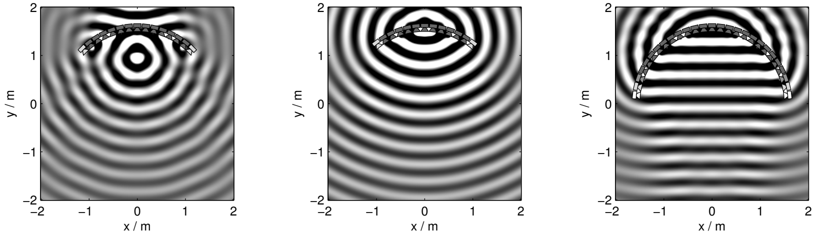

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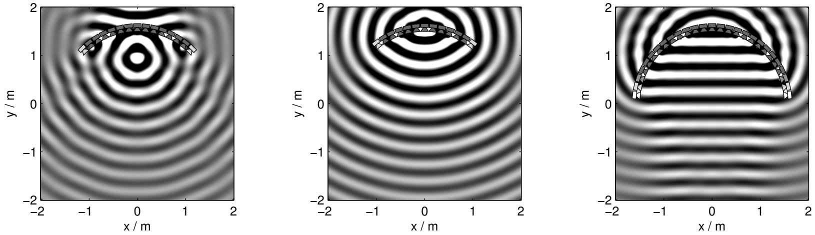

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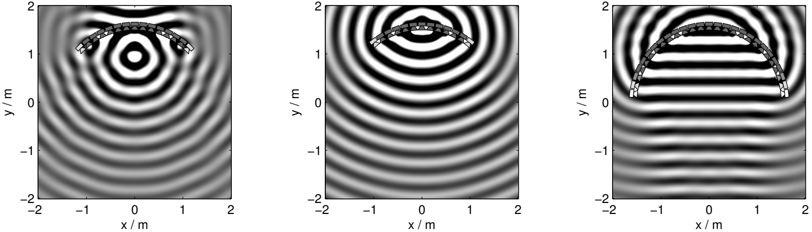

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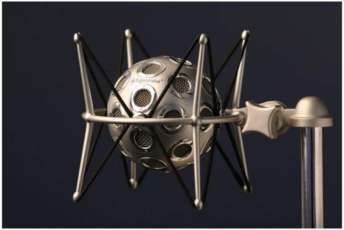
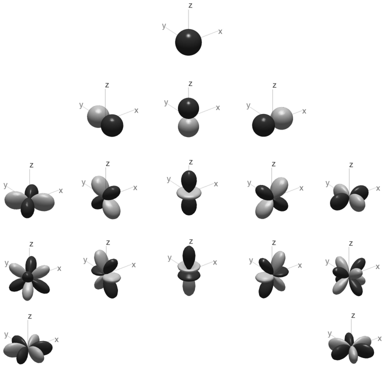
- 2D: Need of hundreds of loudspeakers, 3D: hundreds of thousands of loudspeakers
- Quality issues: spatial aliasing causes colorations, low frequency effects
- Only synthesized content, no microphone techniques available

Physical approach: B-format recording





- Signals with directional patterns following to spherical harmonics

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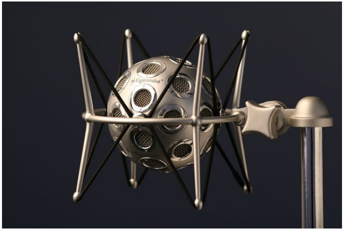
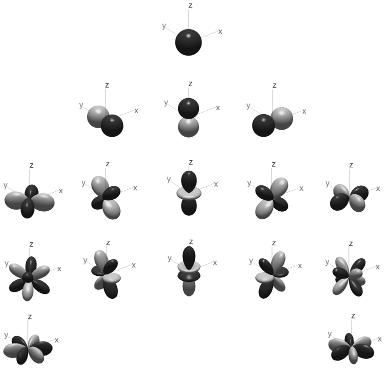
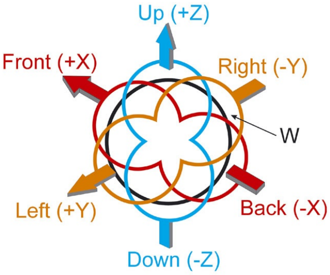




- Signals with directional patterns following to spherical harmonics
- Reproduce plane-wave expansion over loudspeakers

First-order B-format recording



www.soundfield.com

- Captures signals with zeroth-order and first-order spherical harmonics

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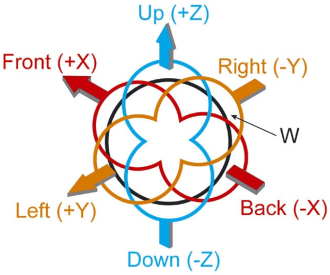

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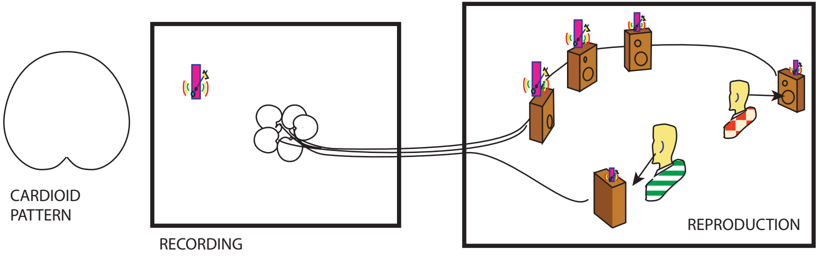
- Captures signals with zeroth-order and first-order spherical harmonics
- Pressure signal W. 3D velocity signals XYZ.

First-order Ambisonics



- Weighted sum of WXYZ signals (mixing, matrixing)

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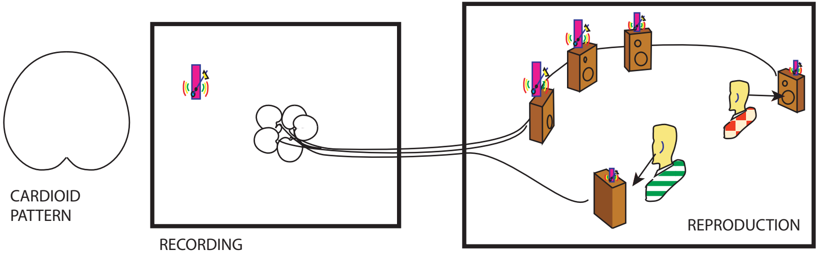

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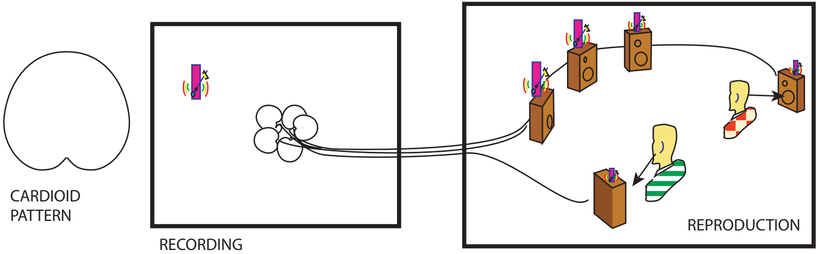

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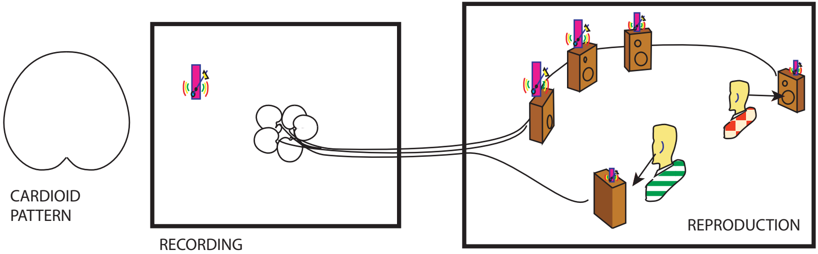
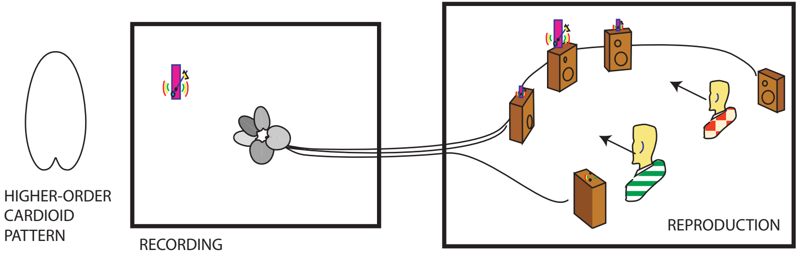


- Weighted sum of WXYZ signals (mixing, matrixing)
- High coherence between loudspeaker signals
- Spectral and spatial issues, very small listening area
- Moderate issues with low-frequency noise and spatial aliasing

Higher-order Ambisonics



- More spherical harmonics captured

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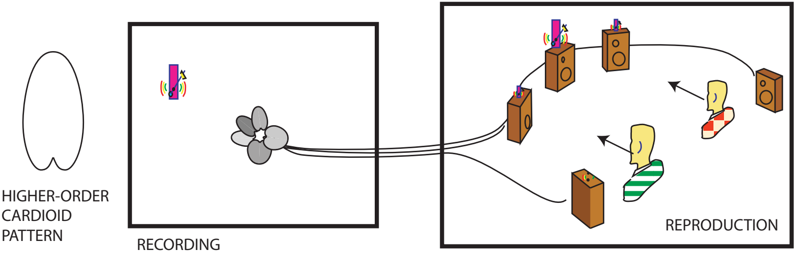

- More spherical harmonics captured
- Better resolution, more expensive devices

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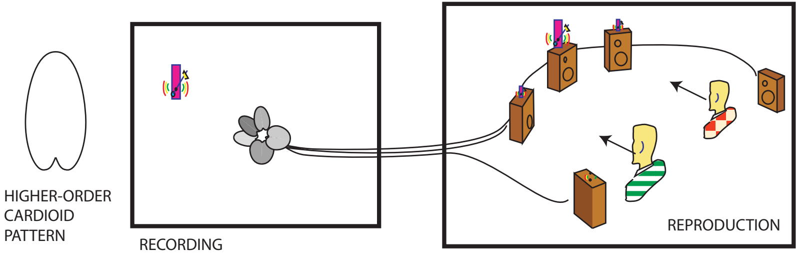

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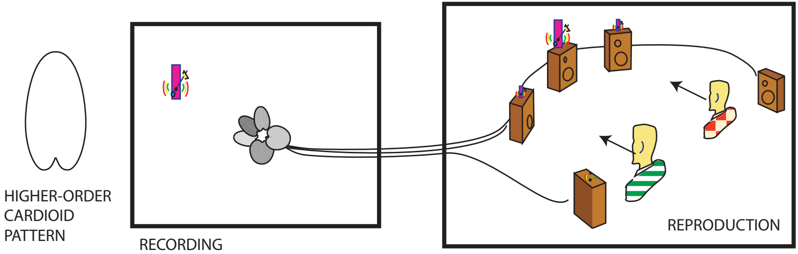

- More spherical harmonics captured
- Better resolution, more expensive devices
- Good quality in limited frequency window
- Emphasized problems with low-frequency noise and high-frequency aliasing

Spatial sound perception

- Physical methods for spatial sound have shortcomings

Spatial sound perception

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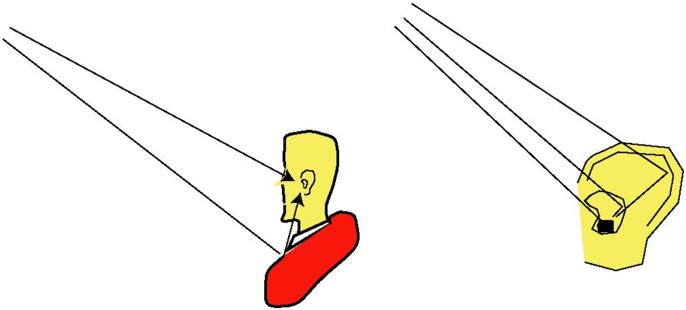
- Lets have a look on human spatial hearing

Spatial sound perception

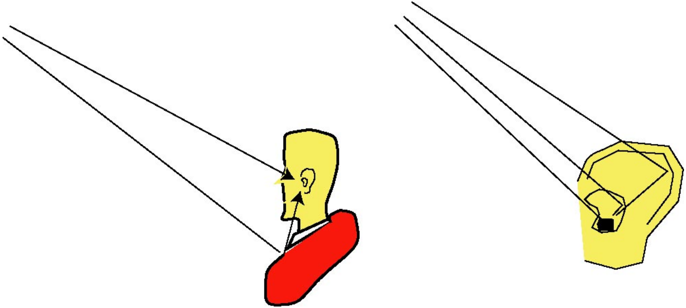
- Physical methods for spatial sound have shortcomings
- Lets have a look on human spatial hearing
- Could we bypass the problems somehow

Human spatial hearing



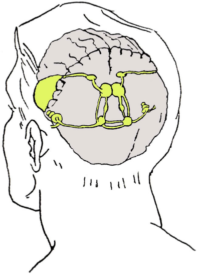
- One ear alone knows quite little of direction

Human spatial hearing



- One ear alone knows quite little of direction
- Response to very large range of wavelengths (2cm–30m)

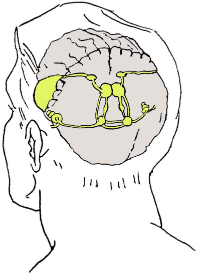
Human spatial hearing



ⓒJ. Blauert

- The perception of space is formed in signal analysis by the brains

Human spatial hearing



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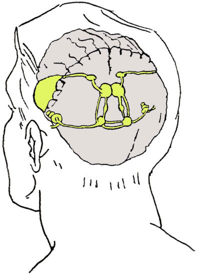

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- The perception of space is formed in signal analysis by the brains
- Signal characteristics in one ear / Signal differences between two ears
- Hearing mechanisms estimate the location of the source(s) and also the properties of the room

Monaural and binaural cues that carry spatial information

- Binaural differences depending on frequency and time
  - Interaural time difference (ITD)
  - Interaural level difference (ILD)

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Could we reproduce these cues somehow?

Reproducing spatial cues?

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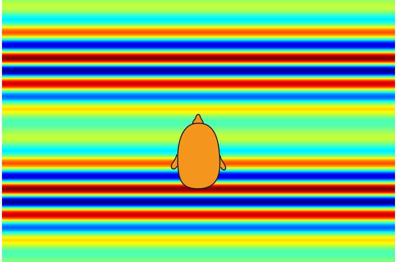
- Lets have a look at characteristic cases of sound fields

Plane wave



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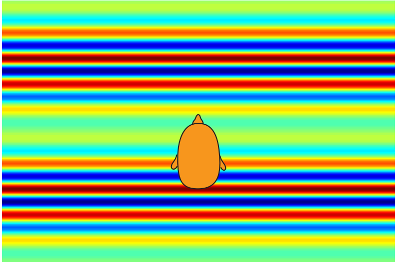

- Real field:
  - Consistent ITD, ILD and spectral cues
  - Accurate localization in most cases

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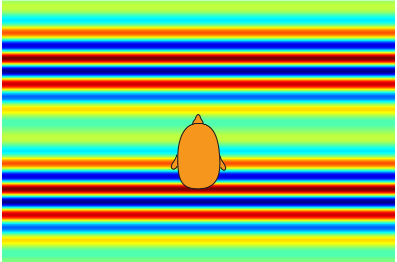

- Real field:
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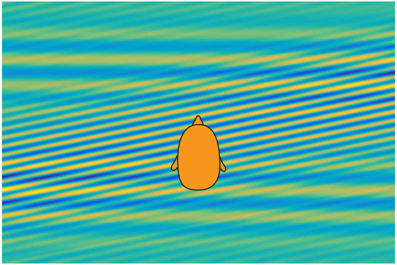
- Reproduced field:
  - Should be reproduced as a plane wave preserving the spectral content

Several plane waves separated in frequency



- Real field
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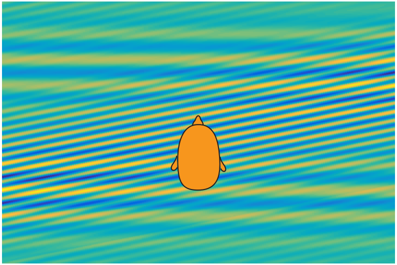
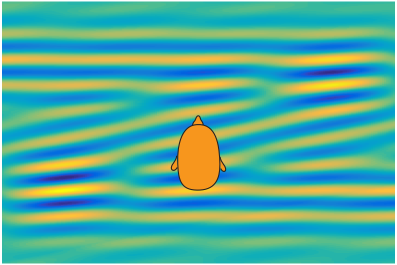


- Real field
  - Perceived as individual auditory objects
- Reproduced field
  - Spatial characteristics should be preserved

Several plane waves overlapping in frequency



- Real field:
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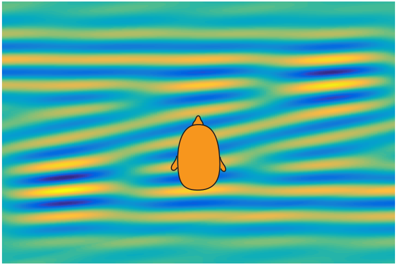

- Real field:
  - Localization may be erronious
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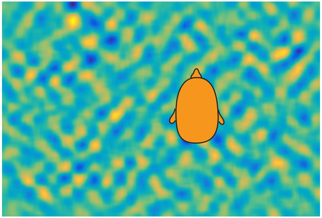
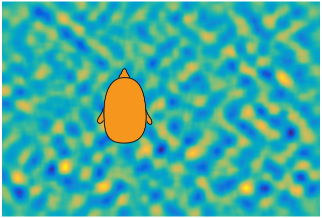
- Reproduced field
  - Reproduce spectral content right
  - *Spatial reconstruction does not have to be accurate!*

Diffuse field





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  - Not sensitive to the instantaneous spatial fine structure of wave field

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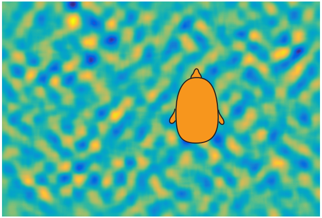

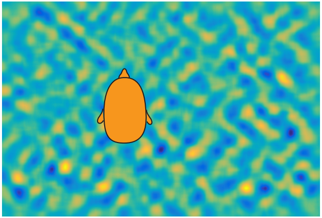

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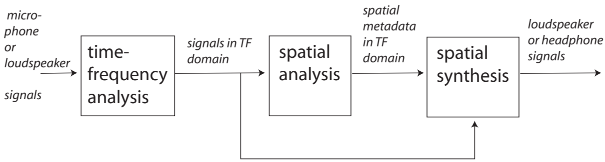

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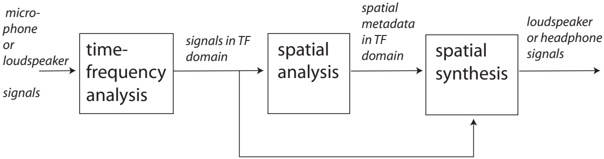

- Separation of wave field to plane waves and residual

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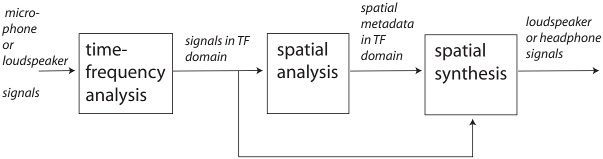

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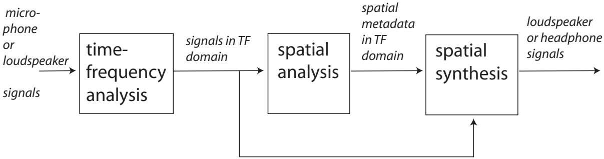
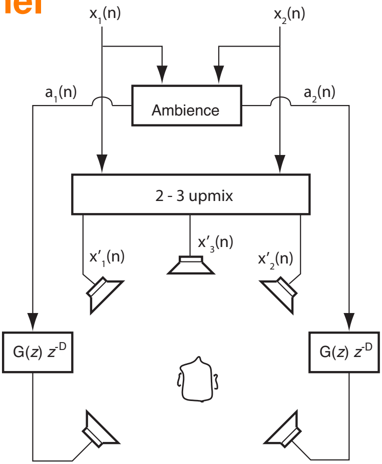
- Reproduce plane waves with point-like virtual sources

Parametric time-frequency-domain spatial audio



- Separation of wave field to plane waves and residual
- Reproduce plane waves with point-like virtual sources
- Reproduce the residual with surrounding method

First approach: upmixing of stereo to multichannel



- Avendano & Jot [JAES, 2004] (Demo 2002 in AES 22nd Conf).

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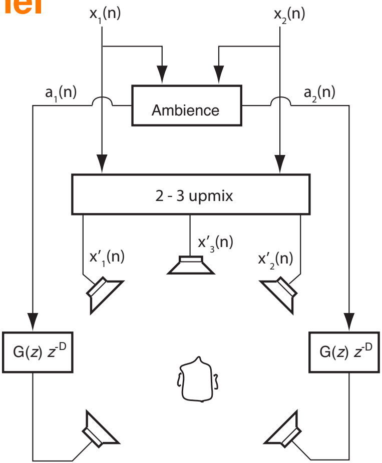

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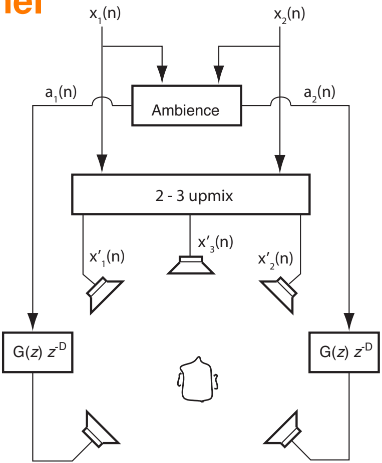

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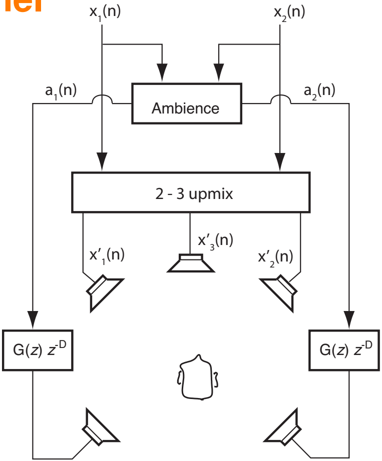
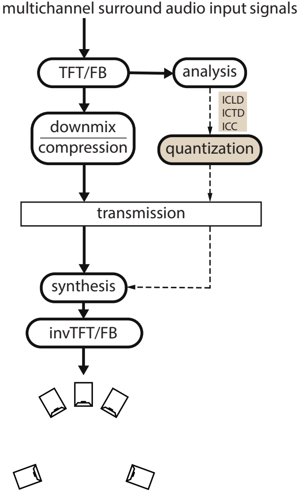


- Avendano & Jot [JAES, 2004] (Demo 2002 in AES 22nd Conf).
- Extract panned and ambient components from two-channel stereophonic input
- Use amplitude panning to reproduce "panned" components
- Reproduce ambient component with surround loudspeakers

Coding of multichannel audio



- Faller & Baumgarte [IEEE Trans. on Speech and Audio Processing, 2003]

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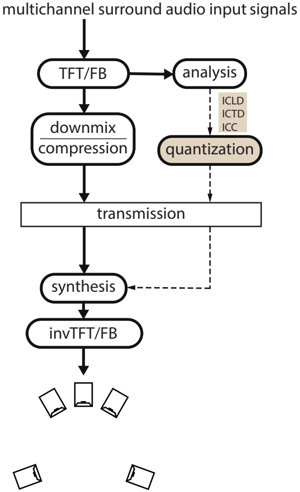

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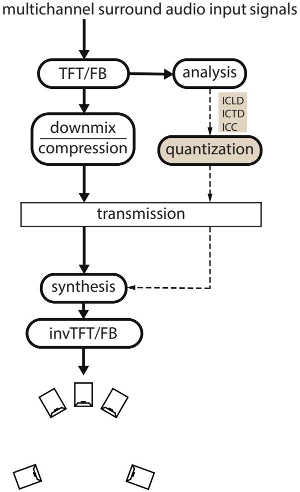
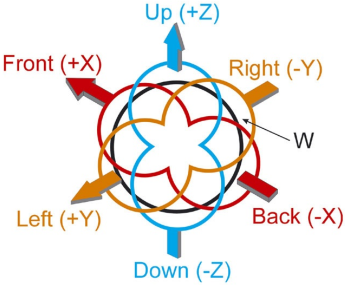


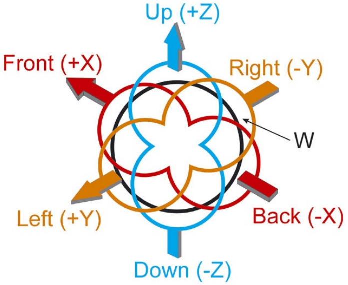
- Faller & Baumgarte [IEEE Trans. on Speech and Audio Processing, 2003]
- Inter-channel differences are used as metadata
- Huge savings in data rate

Reproduction of recorded spatial sound



- 1999-2000: First-order B-format has some kind of Cartesian coordinate system, why does it not work?

Reproduction of recorded spatial sound



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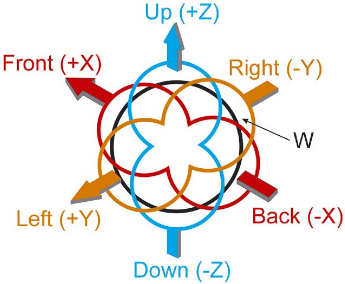

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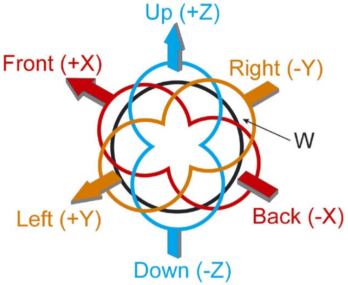

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- Spatial impulse response rendering (SIRR), Merimaa & Pulkki [WASPAA 2013]
- Directional audio coding (DirAC), Pulkki [JAES 2007]

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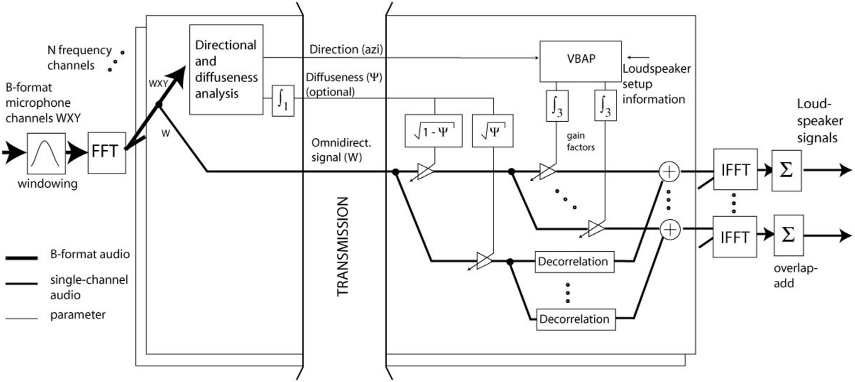
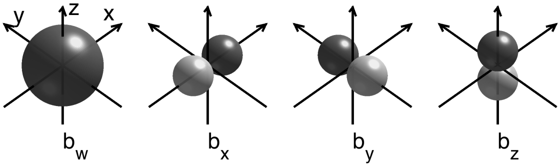
We thus indirectly assume thus that the sound field consists of single plane wave and diffuse component independently at each frequency band

"Teleconference" implementation



[Pulkki, AES Conv 2006]

Acoustical quantities measured with first-order B-format microphone



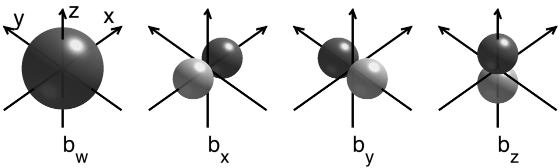
Pressure: $p(n) = (1/s)b_w(n)$

3D velocity vector: $\mathbf{u}(n) = -1/(s\rho_0 c\sqrt{2}) \begin{bmatrix} b_x(n) \\ b_y(n) \\ b_z(n) \end{bmatrix}$

3D intensity vector: $\mathbf{i}(n) = p(n)\mathbf{u}(n)$

Instantaneous energy: $e = \frac{\rho_0}{2}||\mathbf{u}||^2 + |p|^2/2\rho_0 c^2$

Analysis of spatial parameters



Direction:	intensity vector	$\mathrm{DOA} = \angle \mathrm{E}[-\mathbf{i}]$
Diffuseness	net flow / total energy	$\psi = 1 - \frac{\|\|\mathrm{E}[\mathbf{i}]\|\|}{c\mathrm{E}[e]}$
	temporal fluctuation of **i**	$\psi = \sqrt{1 - \frac{\|\|\mathrm{E}[\mathbf{i}]\|\|}{\mathrm{E}[\|\|\mathbf{i}\|\|]}}$

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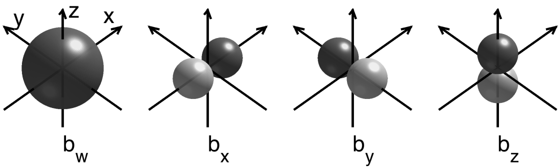

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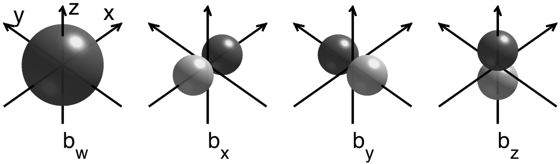

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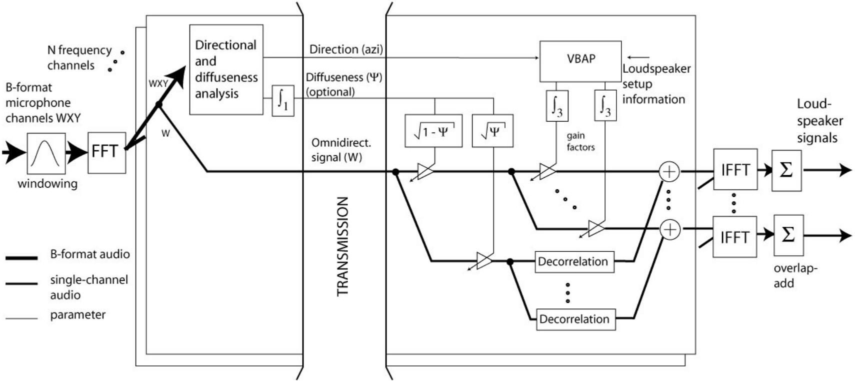
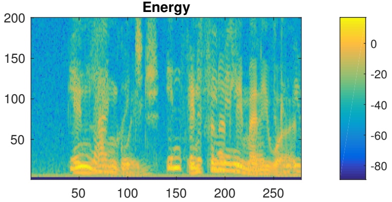
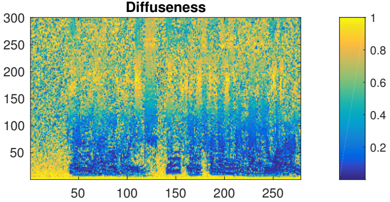
- Robust to small deviations from ideal microphone characteristics
- Measures energetic properties of sound field within given frequency band, useful?

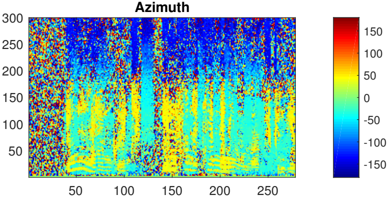
"Teleconference" implementation

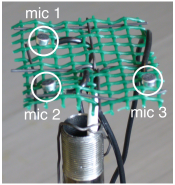


Example with low-end 3-microphone 2D array





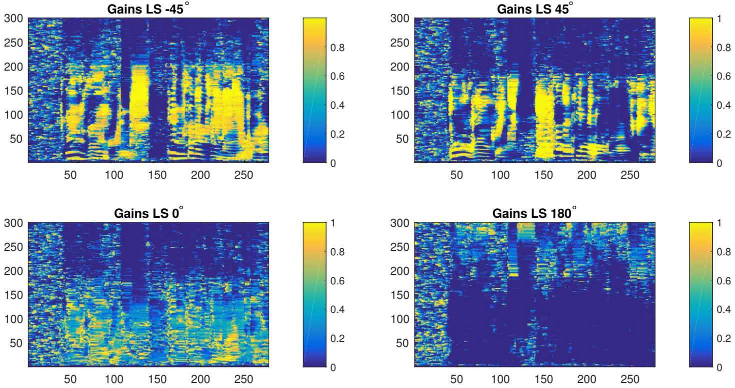




Two speech sources in $\pm 45^{\circ}$, anechoic chamber

▷ Sound captured with one of the microphones

Examples of soft masks for non-diffuse stream



Rendering to 8-channel octagonal loudspeaker setup

▷ Mono ▷ ND2ch ▷ D2ch ▷ ND+D2ch ▷ ALL CHAN

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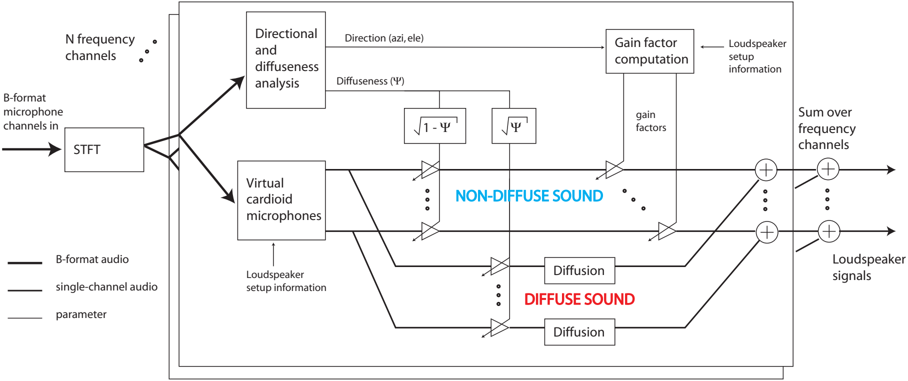
  - Sources near noise masking threshold: impossible to localize

Why these artifacts?

"HQ" implementation



This works better, but dont exactly know why (2007).

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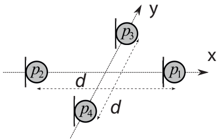
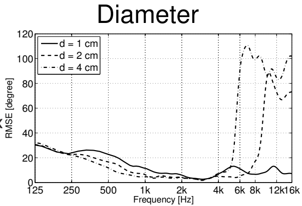
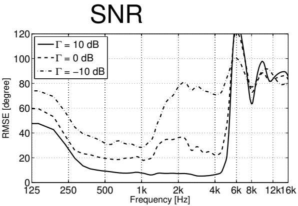
- Spatial aliasing
  - Highly biased directional values
  - In some cases can be mitigated

Square array

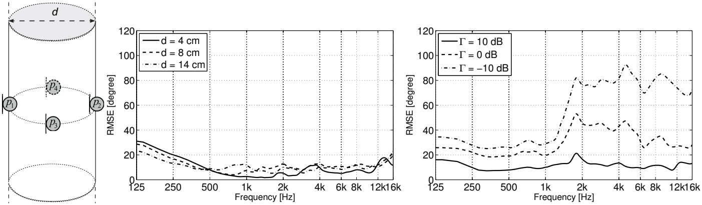






- Pressure gradient
- Square arrays of omni microphones, B-format microphones
- LF noise, HF aliasing
- Ahonen, del Galdo et al [JAES 2012]

Arrays with shadowing



$$
\begin{aligned}
\widetilde{i}_x(n,k) &= |p_1(n,k)|^2 - |p_2(n,k)|^2, \\
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\end{aligned}
$$

- When capsule signals are available, and some shadowing takes place

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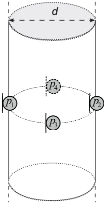

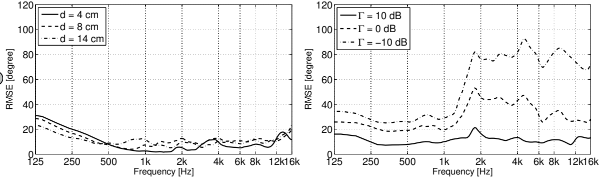

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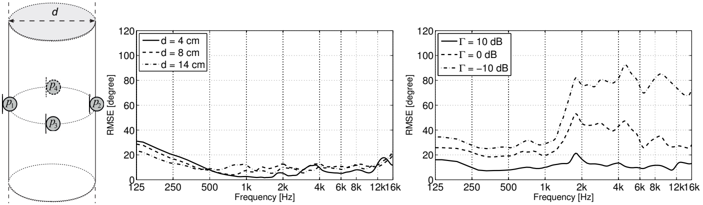

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- When capsule signals are available, and some shadowing takes place
- LF+MF: pressure gradient
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- A-format microphones, cylinder arrays and spherical arrays

Other microphone arrays with DirAC

- Multiple microphones in array: ESPRIT by Thiergart, Kratschmer et al, [AES Conv 2011]

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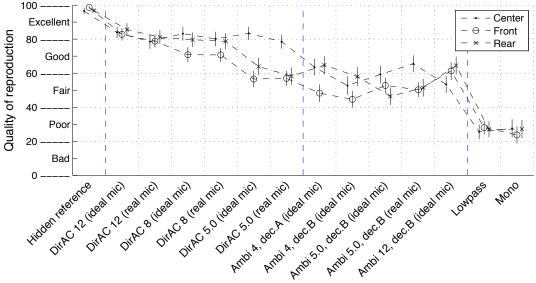
- Basically any DOA analysis method can be applied

HQ-DirAC subjective tests



- HQ-DirAC, comparison to reference scenario with 24 loudspeakers
- Largest issues with spatially complex scenarios audible as small timbral artifacts
- Vilkamo [JAES 2009]

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- Target for development: minimize decorrelated energy!

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- Perform more elaborate analysis to sound field (e.g., multiple DOA values), Thiergart [IEEE TASLP, 2014]

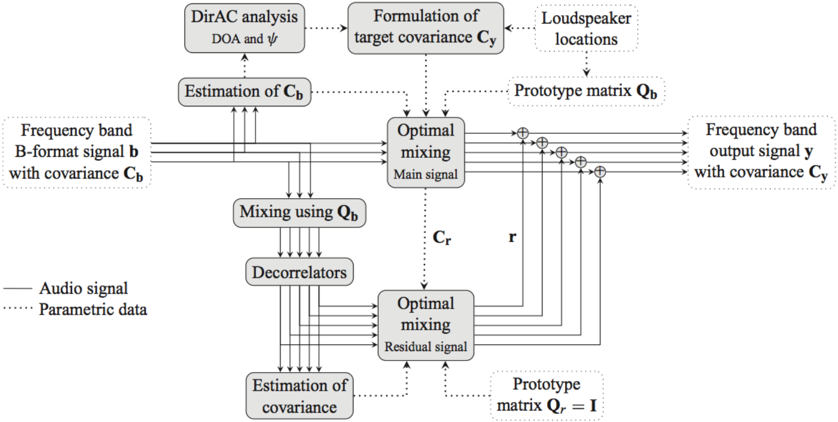
Covariance-domain processing

Least-squares optimized solution for synthesis

- the covariance matrix of output is dictated by directional parameters
- optimized mixing solution leads to minimization of decorrelated energy

[Vilkamo, Bäckström, Kuntz: JAES 2013]

Covariance-domain processing



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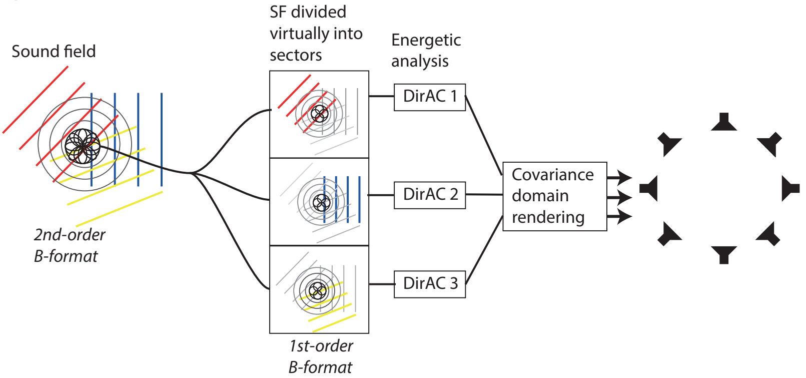
- How to use that information in sound reproduction?
- Divide sound field into sectors (Pulkki, Politis), perform lower-order reproduction for each
- Analyze multiple DOAs, and then reproduce (Thiergart & Habets, Mouchtaris group, Berge)

Sector-based parametric spatial sound reproduction



[Politis et al: IEEE J. Selected Topics Sig Proc 9.5 (2015)]

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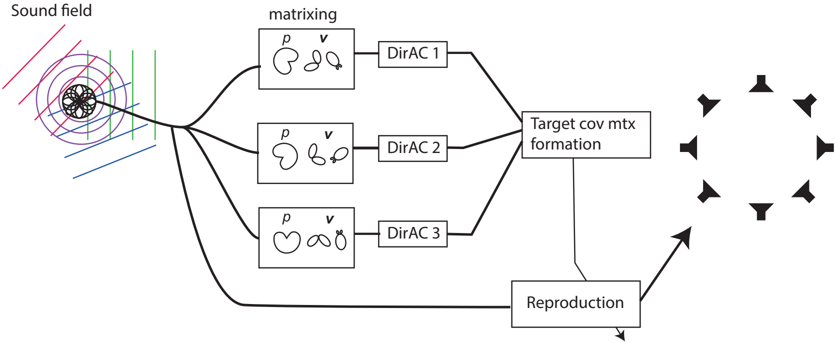

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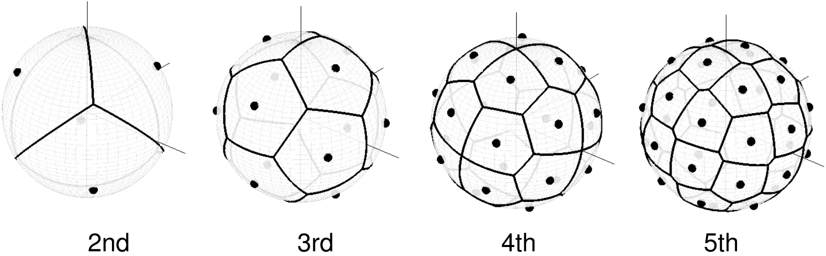
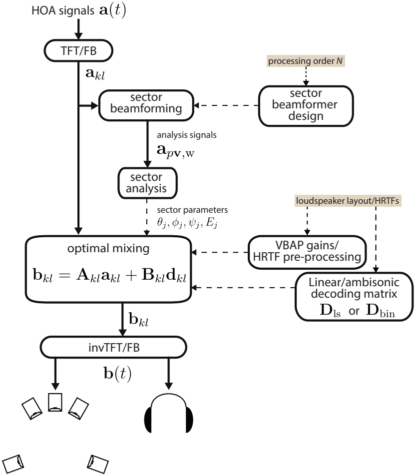
- System does not lose acoustic energy in any case

Sectors for HO-microphones

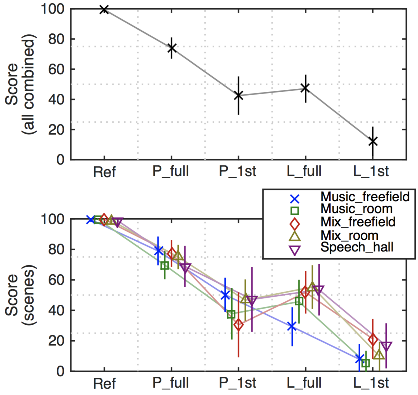


Different frequency bands utilize different number of sectors

Processing


HOA signals $\mathbf{a}(t)$
TFT/FB
$\mathbf{a}_{kl}$
processing order N
sector beamforming
sector beamformer design
analysis signals
$\mathbf{a}_{p\mathbf{v},\mathrm{w}}$
sector analysis
sector parameters
$\theta_j, \phi_j, \psi_j, E_j$
loudspeaker layout/HRTFs
optimal mixing
$\mathbf{b}_{kl} = \mathbf{A}_{kl}\mathbf{a}_{kl} + \mathbf{B}_{kl}\mathbf{d}_{kl}$
VBAP gains/
HRTF pre-processing
Linear/ambisonic decoding matrix
$\mathbf{D}_{\mathrm{ls}}$ or $\mathbf{D}_{\mathrm{bin}}$
$\mathbf{b}_{kl}$
invTFT/FB
$\mathbf{b}(t)$

Subjective evaluation



- [Politis & Vilkamo & Pulkki IEEE J. Selected Topics Sig Proc 9.5 (2015)]
- Reference: 28 loudspeakers in anechoic chamber, very challenging 3D sound environments
- Test: Eigenmic recording, playback over HO-DirAC, 1st-order DirAC, 4th-order Ambisonics, 1st-order Ambisonics

Why does HO-DirAC provide better results?

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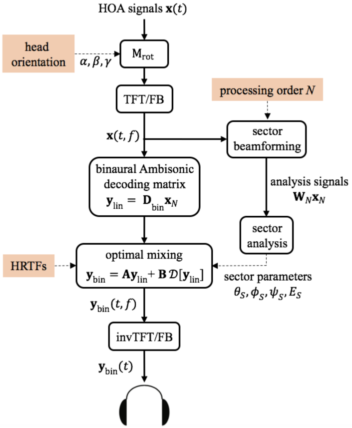
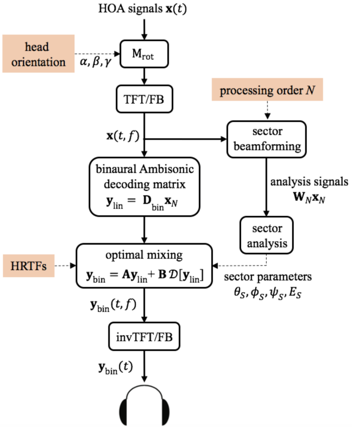
- Avoidance of decorrelation!

HO-DirAC for head-tracked headphones



- Processing optimized for dynamic rendering

HO-DirAC for head-tracked headphones



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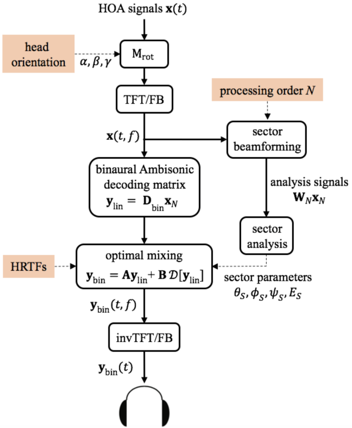
- Sector-based computation is used to derive covariance matrices

HO-DirAC for head-tracked headphones



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- WASPAA 2017: Wed 10:30–12:30 *Enhancement of ambisonic binaural reproduction...* Politis, McCormack, Pulkki

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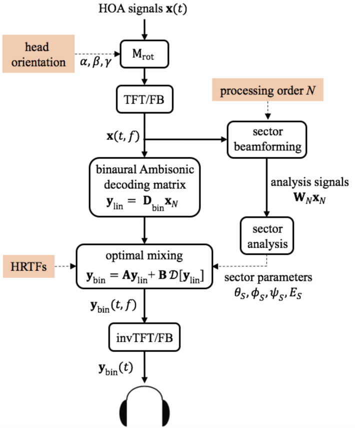

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- **DEMOS AVAILABLE**

Time-frequency spatial audio in general

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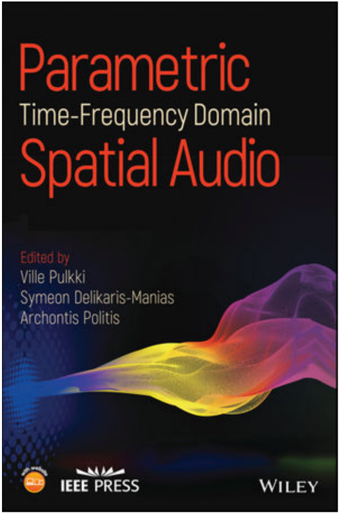
- ... and we have edited a book about that. :-)

Book

- 15 chapters, 416 pages
- Matlab code
- Available in Dec 2017



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- Sound Field Analysis using Sparse Recovery
  C. T. Jin, N. Epain and T. Noohi

Reproduction of spatial sound

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  J. Nikunen and T. Virtanen

Signal-dependent spatial filtering

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- Parametric spatial audio techniques in teleconferencing and remote presence
  A. Alexandridis, D. Pavlidi, N. Stefanakis, and A. Mouchtaris

Conclusions

- Parametric time-frequency-domain spatial audio – treating also spatial auditory cues as signal in reproduction

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- Task-specific signal-dependent and spatial-condition-dependent non-linear DSP

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- Parametric time-frequency-domain spatial audio – treating also spatial auditory cues as signal in reproduction
- Task-specific signal-dependent and spatial-condition-dependent non-linear DSP
- Enhancement of quality of spatial sound when compared with linear methods