Universität Rostock

Traditio et Innovatio

Time-Domain Realisation of Model-Based Rendering for 2.5D Local Wave Field Synthesis Using Spatial Bandwidth-Limitation

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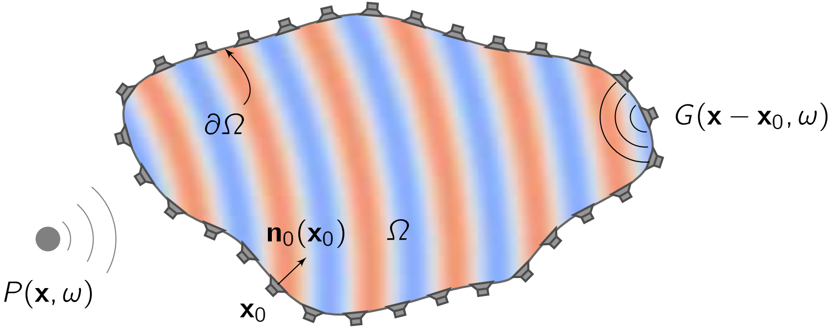
Sound Field Synthesis



$$\underbrace{P(\mathbf{x},\omega)}_{\substack{\text{desired}\\ \text{sound field}}} \stackrel{!}{=} \oint_{\partial\Omega} \underbrace{D(\mathbf{x}_0,\omega)}_{\text{driving signal}} \underbrace{G(\mathbf{x}-\mathbf{x}_0,\omega)}_{\substack{\text{sound field of}\\ \text{loudspeaker at } \mathrm{x}_0}} \, \mathrm{d}A_0(\mathbf{x}_0) \quad \forall \mathbf{x} \in \Omega$$

Sound Field Synthesis

Fundamental Principles of Rendering

Model-Based

- uses mathematical models for virtual sources which are fed by (dry) source signals
- acoustic scene is typically composed of multiple virtual sources
- frequently used models are point sources and plane waves

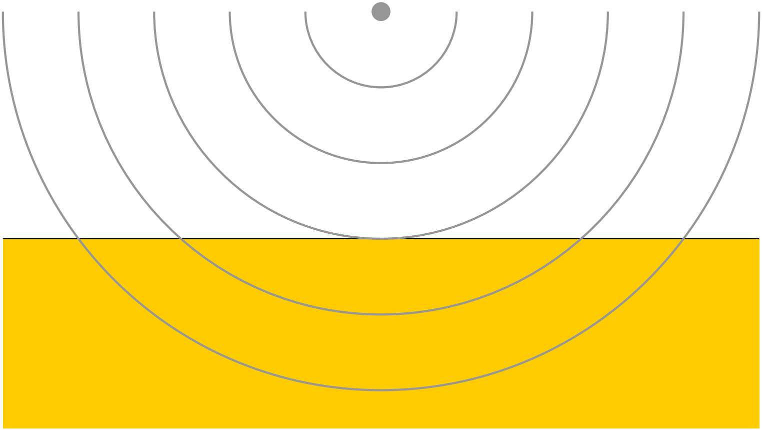
$$P_{\mathrm{ps}}(\mathbf{x},\omega) = S(\omega)\frac{\mathrm{e}^{-\mathrm{j}\frac{\omega}{c}|\mathbf{x}-\mathbf{x}_{\mathrm{ps}}|}}{4\pi|\mathbf{x}-\mathbf{x}_{\mathrm{ps}}|} \qquad P_{\mathrm{pw}}(\mathbf{x},\omega) = S(\omega)\mathrm{e}^{-\mathrm{j}\frac{\omega}{c}\mathbf{n}_{\mathrm{pw}}^{\mathrm{T}}\mathbf{x}}$$

Data-Based

- reproduces a scene acquired via Sound Field Analysis techniques

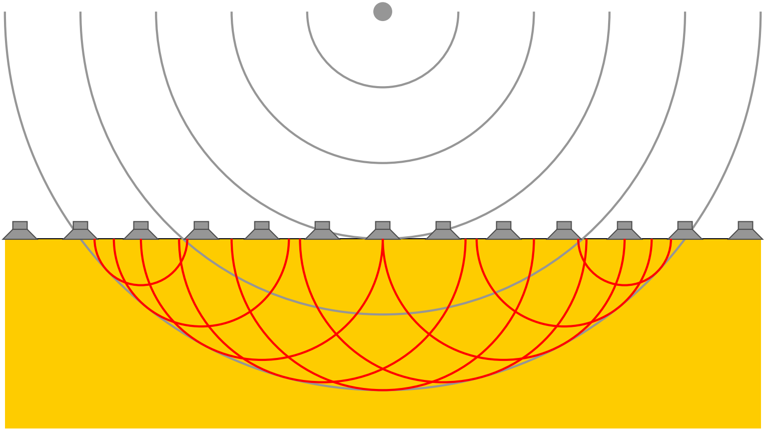
Wave Field Synthesis

Huygens–Fresnel principle



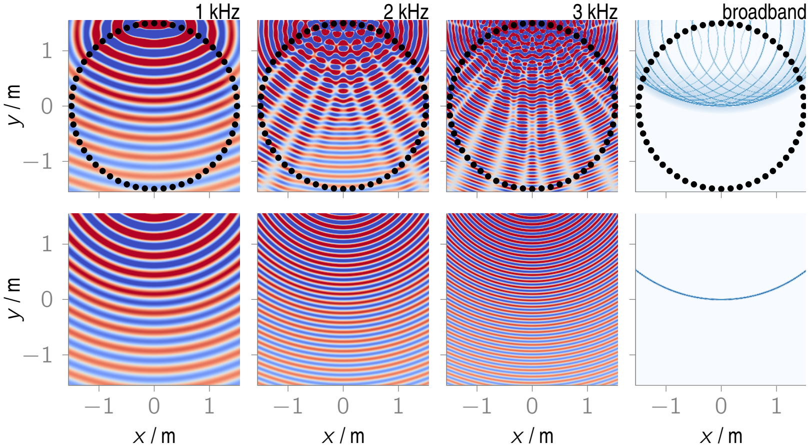
Wave Field Synthesis

Huygens–Fresnel principle

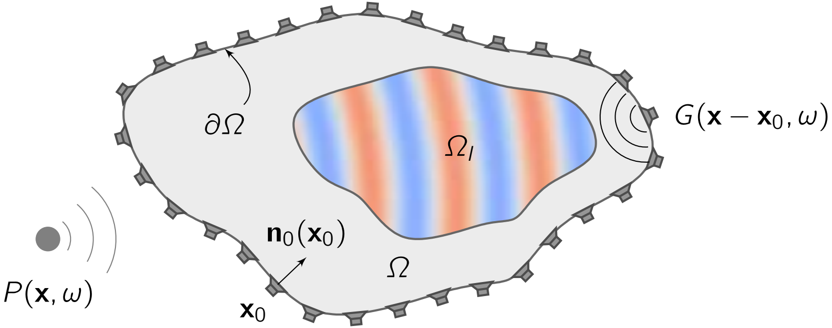


Wave Field Synthesis

Spatial Aliasing



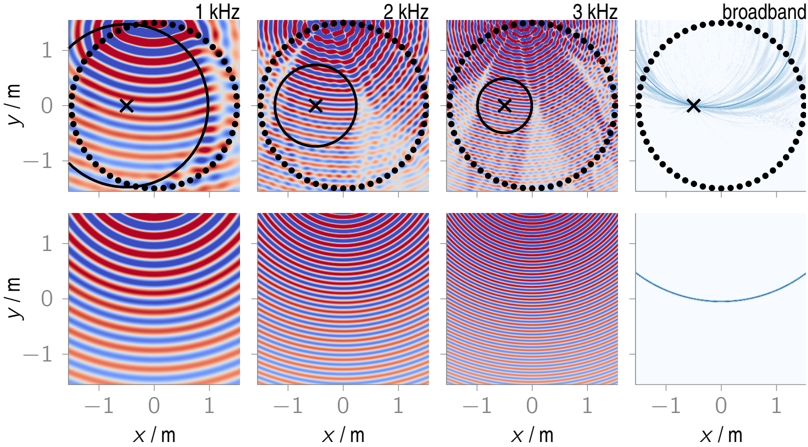
Local Sound Field Synthesis



$$\underbrace{P(\mathbf{x},\omega)}_{\substack{\text{desired}\\ \text{sound field}}} \stackrel{!}{=} \oint_{\partial\Omega} \underbrace{D(\mathbf{x}_0,\omega)}_{\text{driving signal}} \underbrace{G(\mathbf{x}-\mathbf{x}_0,\omega)}_{\substack{\text{sound field of}\\ \text{loudspeaker at } \mathbf{x}_0}} \, \mathrm{d}A_0(\mathbf{x}_0) \quad \forall \mathbf{x} \in \Omega_l$$

Local Wave Field Synthesis (LWFS) using Spatial Bandwidth Limitation (SBL)

Spatial Aliasing



LWFS-SBL

Driving Signal I

Truncated Circular Harmonics Expansion around $\mathbf{x}_\mathrm{c}$

$$P(\mathbf{x},\omega) \approx S(\omega) \sum_{\mu=-M}^{M} \check{P}_\mu(\mathbf{x}_\mathrm{c},\omega) J_\mu(k\rho') \mathrm{e}^{+\mathrm{j}\mu\phi'}$$

Conversion between Representations $\downarrow$ $\bar{P}(\phi_\mathrm{pw},\mathbf{x}_\mathrm{c},\omega) = \sum_{\mu=-M}^{M} \mathrm{j}^\mu \check{P}_\mu(\mathbf{x}_\mathrm{c},\omega) \mathrm{e}^{+\mathrm{j}\mu\phi_\mathrm{pw}}$

2D Plane Wave Decomposition around $\mathbf{x}_\mathrm{c}$

$$P(\mathbf{x},\omega) \approx S(\omega) \frac{1}{2\pi} \int_{-\pi}^{\pi} \bar{P}(\phi_\mathrm{pw},\mathbf{x}_\mathrm{c},\omega) \mathrm{e}^{-\mathrm{j}k\langle \mathrm{x}' | \mathrm{n}_\mathrm{pw}\rangle} \, \mathrm{d}\phi_\mathrm{pw}$$

Apply conventional WFS driving $\downarrow$ function to each plane wave

LWFS Driving Signal in Time-Frequency Domain

$$D^\mathrm{LWFS}(\mathbf{x}_0,\omega) = S(\omega) \frac{1}{2\pi} \int_{-\pi}^{\pi} \bar{P}(\phi_\mathrm{pw},\mathbf{x}_\mathrm{c},\omega) D_\mathrm{pw}^\mathrm{WFS}(\mathbf{x}_0',\phi_\mathrm{pw},\omega) \, \mathrm{d}\phi_\mathrm{pw}$$

$\downarrow \mathcal{F}_t^{-1}$

LWFS-SBL

Driving Signal II

LWFS Driving Signal in Continuous Time Domain

$$d^{\mathrm{LWFS}}(\mathbf{x}_0, t) = s(t) *_t \frac{1}{2\pi} \int_{-\pi}^{\pi} \bar{p}(\phi_{\mathrm{pw}}, \mathbf{x}_{\mathrm{c}}, t) *_t d^{\mathrm{WFS}}_{\mathrm{pw}}(\mathbf{x}'_0, \phi_{\mathrm{pw}}, t)\, \mathrm{d}\phi_{\mathrm{pw}}$$

Temporal Sampling $f(t) \to f(nT_s) \to f[n]$

LWFS Driving Signal in Discrete Time Domain

$$d^{\mathrm{LWFS}}[\mathbf{x}_0, n] = s[n] *_n \frac{1}{2\pi} \int_{-\pi}^{\pi} \bar{p}[\phi_{\mathrm{pw}}, \mathbf{x}_{\mathrm{c}}, n] *_n d^{\mathrm{WFS}}_{\mathrm{pw}}[\mathbf{x}'_0, \phi_{\mathrm{pw}}, n]\, \mathrm{d}\phi_{\mathrm{pw}}$$

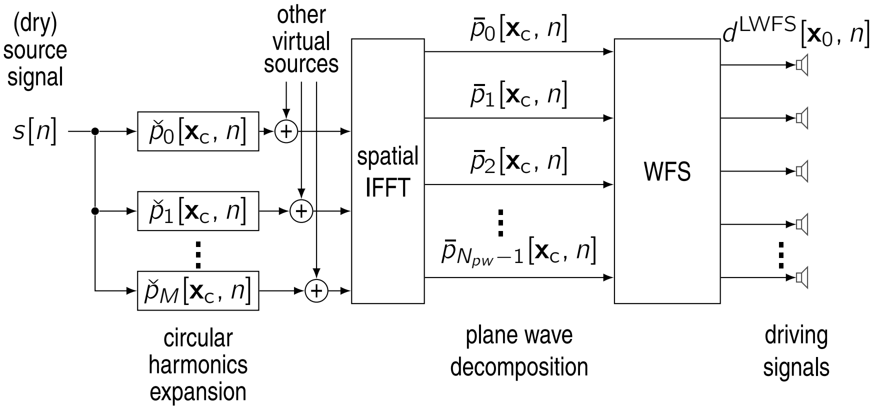
Rectangle Method with equi-angular Sampling $f(\phi_{\mathrm{pw}}) \to f\left(\frac{2\pi m}{N_{\mathrm{pw}}}\right) \to f_m$

$$d^{\mathrm{LWFS}}[\mathbf{x}_0, n] \approx s[n] *_n \frac{1}{N_{\mathrm{pw}}} \sum_{m=0}^{N_{\mathrm{pw}}-1} \bar{p}_m[\mathbf{x}_{\mathrm{c}}, n] *_n d^{\mathrm{WFS}}_{\mathrm{pw},m}[\mathbf{x}'_0, n]$$

with $\bar{p}_m[\mathbf{x}_{\mathrm{c}}, n] = \sum_{\mu=-M}^{M} \mathrm{j}^{\mu} \breve{p}_{\mu}[\mathbf{x}_{\mathrm{c}}, n]\, \mathrm{e}^{+\mathrm{j}\frac{2\pi}{N_{\mathrm{pw}}}\mu m}$

LWFS-SBL

System Layout



! Open Task: Time-Realisation of Circular Harmonics Coefficients

Circular Harmonics Expansions

Plane Wave

$$\breve{P}_\mu(\mathbf{x}_\mathrm{c}, \omega) = \mathrm{j}^{-\mu} \mathrm{e}^{-\mathrm{j}\mu\phi_\mathrm{pw}}$$

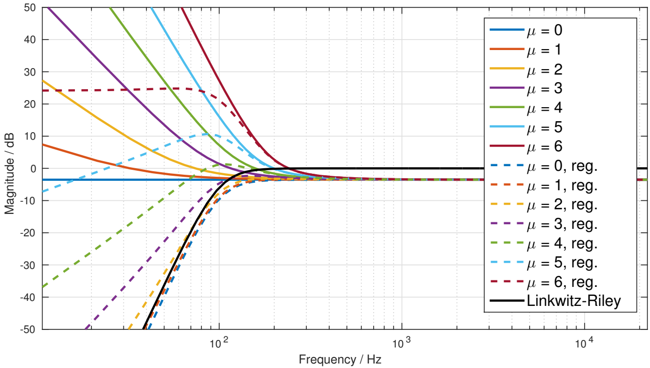
+ straightforward implementation possible

Point Source

$$\breve{P}_\mu(\mathbf{x}_\mathrm{c}, \omega) \approx \frac{\mathrm{j}^{|\mu|-\mu}}{4\pi} \left(-\mathrm{j}\frac{\omega}{c}\right) h^{(2)}_{|\mu|}\left(\frac{\omega}{c}\rho'_\mathrm{ps}\right) \mathrm{e}^{-\mathrm{j}\mu\phi'_\mathrm{ps}}$$

+ analytical expression in Laplace-Domain available $\rightarrow$ IIR implementation
– pole of order $|\mu|$ at $\omega = 0 \rightarrow$ unstable
! regularisation/pole compensation needed

Regularisation for Point Source



- apply Linkwitz-Riley highpass filter of order $2\eta \geq M$ to all modes μ
- ! explicit combination of highpass filter and spherical Hankel functions necessary
- discrete-time realisation via bilinear transform
- – results in strongly highpass filtered source signal

Dual-Band Approach for Point Source

- conventional WFS is aliasing-free and stable at low frequency
- combine conventional WFS and LWFS-SBL via Linkwitz-Riley frequency crossover

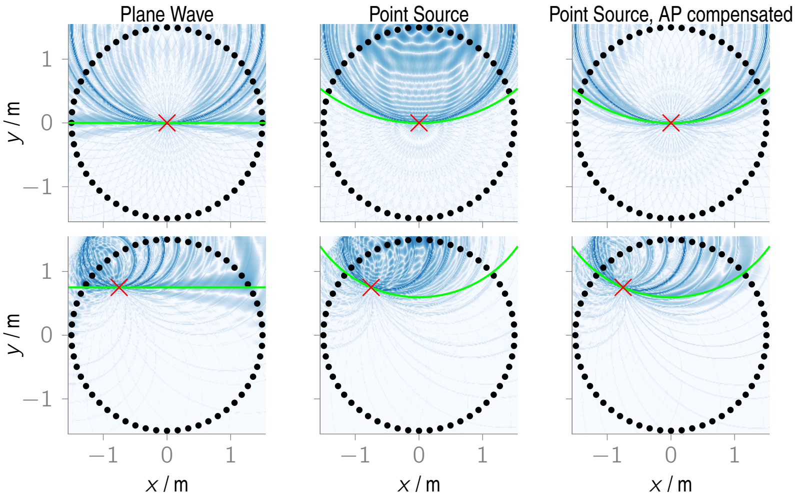
$$D_{\mathrm{ps}}^{\mathrm{Dual}}(\mathbf{x}_0, \omega) = D_{\mathrm{ps}}^{\mathrm{WFS}}(\mathbf{x}_0, \omega) LP^{2\eta}(\omega) + D_{\mathrm{ps}}^{\mathrm{LWFS}}(\mathbf{x}_0, \omega) HP^{2\eta}(\omega)$$

  with

  - $LP^{2\eta}(\omega)$ - Linkwitz-Riley lowpass filter of order 2η
  - $HP^{2\eta}(\omega)$ - Linkwitz-Riley highpass filter of order 2η
  - $AP^{2\eta}(\omega) = LP^{2\eta}(\omega) + HP^{2\eta}(\omega)$ - joined allpass characteristic
- allpass characteristic may be compensated using Backward-Filtering $\rightarrow$ non-causal

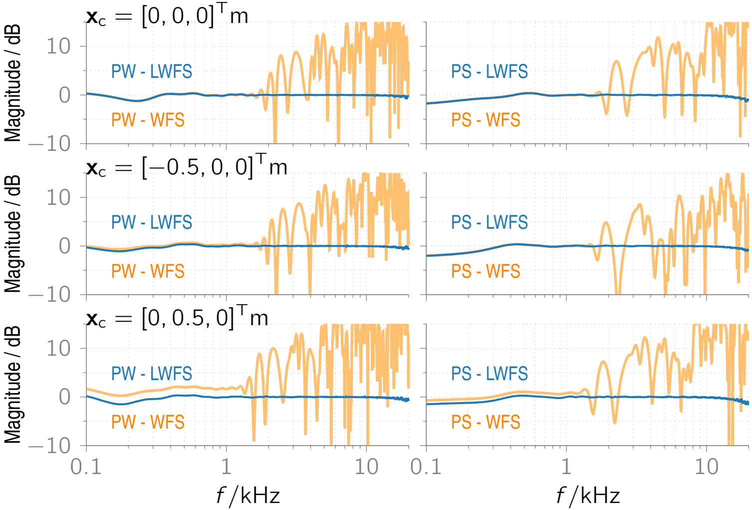
Simulations

Reproduced Sound Field, 56 Loudspeaker, $M = 27$



Simulations

Magnitude Spectrum, 56 Loudspeaker, $M = 27$



Conclusion & Future Work

Conclusion

- system layout for the time-domain realisation of LWFS-SBL
- existing WFS software (e.g. SoundScape Renderer) may be used to synthesise plane wave decomposition
- realisation of point source requires additional regularisation and crossover between conventional WFS and LWFS-SBL
- implementation available as part of the Sound Field Synthesis Toolbox

Future Work

- **fair** evaluation and comparison to other approaches w.r.t to run time[a]
- perceptual evaluation[b]

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[a] Hahn et al., *Synthesis of a Spatially Band-Limited Plane Wave in the Time-Domain Using Wave Field Synthesis*, EUSIPCO 2017

[b] Winter et al., *Colouration in 2.5D Local Wave Field Synthesis Using Spatial Bandwidth-Limitation*, WASPAA 2017

Thank you for your attention!

http://sfstoolbox.org