Universität Rostock

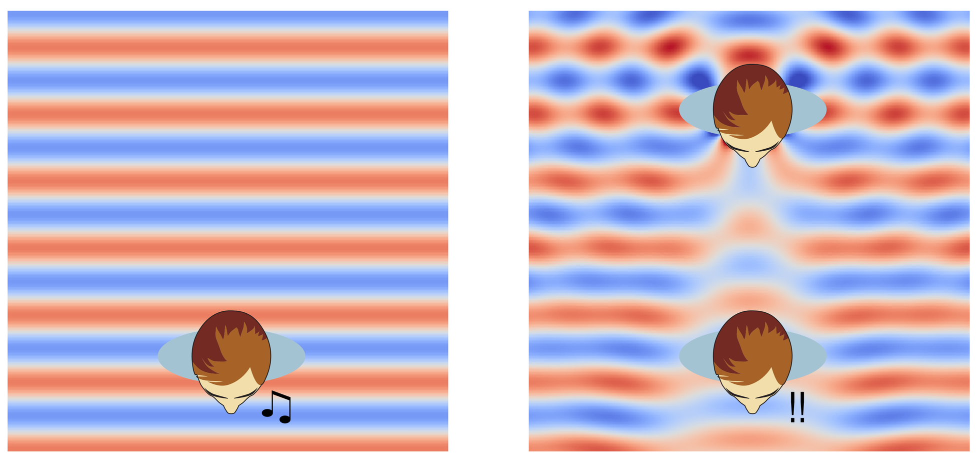
Traditio et Innovatio

Nara Hahn, Sascha Spors
Institute of Communications Engineering
{nara.hahn,sascha.spors}@uni-rostock.de

Synthesis of a Sound Field Scattered by a Virtual Object Using Near-field Compensated Higher-order Ambisonics (NFC-HOA)

Motivation

- synthesis of virtual sound fields with scattering objects [1, 2, 3, 4]

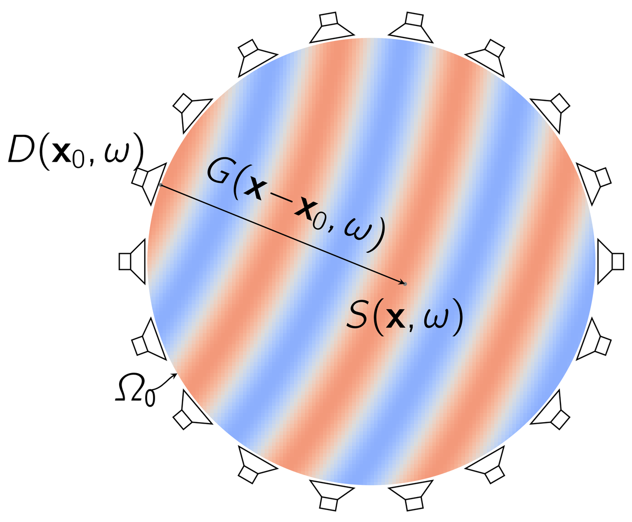


Sound Field Synthesis

- goal: reconstruction of the desired sound field within a target region by using a loudspeaker array
- solve the synthesis equation with respect to the driving function $D(\mathbf{x}_0, \omega)$

$$S(\mathbf{x}, \omega) = \int_{\Omega_0} D(\mathbf{x}_0, \omega) G(\mathbf{x}-\mathbf{x}_0, \omega) \mathrm{d}\Omega_0$$

- $S(\mathbf{x}, \omega)$ desired sound field
- $G(\mathbf{x}-\mathbf{x}_0, \omega)$ acoustic transfer function
- $D(\mathbf{x}_0, \omega)$ driving function



- e.g. wave field synthesis (WFS) and near-field compensated higher-order Ambisonics (NFC-HOA)

NFC-HOA

- based on spherical/circular harmonics representation of the sound field

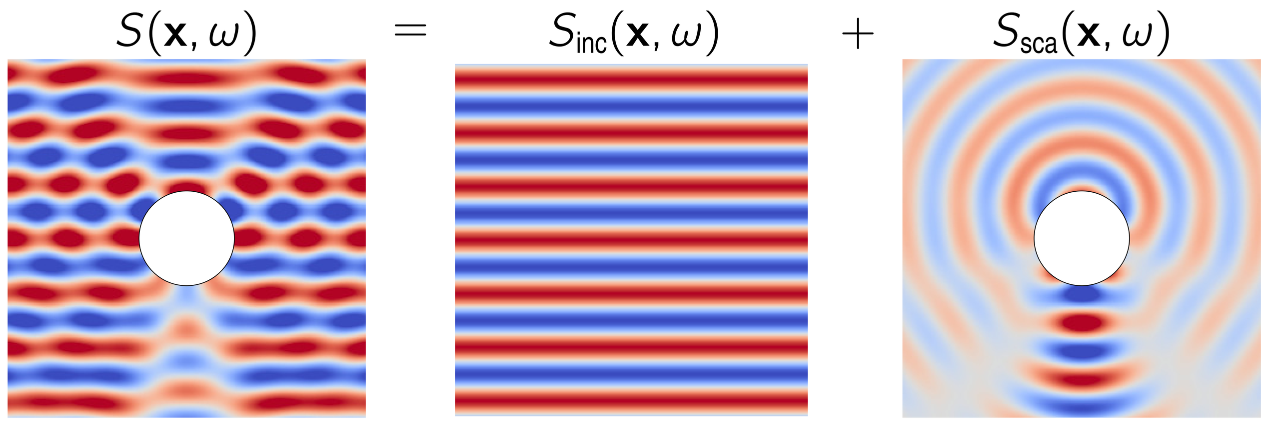
$$S(\mathbf{x}, \omega) = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \breve{S}_n^m(\omega) j_n(\tfrac{\omega}{c} r) Y_n^m(\theta, \phi), \quad S(\mathbf{x}, \omega) = \sum_{m=-\infty}^{\infty} \mathring{S}_m(\omega) J_m(\tfrac{\omega}{c} r \sin\theta) e^{im\phi}$$

- 2.5D NFC-HOA (circular distribution of secondary sources) [5, 6]

$$D_{2.5\mathrm{D}}(\phi, \omega) = \sum_{m=-\infty}^{\infty} \mathring{D}_m(\omega) e^{im\phi}, \quad \mathring{D}_m(\omega) = \frac{1}{2\pi r_0} \frac{\breve{S}_{|m|}^m(\omega)}{\breve{G}_{|m|}^m(\omega)}$$

Sound Field Scattered by a Cylinder

- superposition of the incident field and the scattered field



- incident plane wave $e^{-i\langle \mathbf{k}, \mathbf{x} \rangle}$ scattered by a cylindrical scatterer at $\mathbf{x}_c$ with radius a

$$\breve{S}_n^m(\omega) = \breve{S}_{\mathrm{inc},n}^m(\omega) + \underbrace{\breve{S}_{\mathrm{inc},n}^m(\omega) F_m(\mathbf{x}_c, a, \omega)}_{\breve{S}_{\mathrm{sca},n}^m(\omega)}$$

- $F_m(\mathbf{x}_c, a, \omega) = e^{-i\langle \mathbf{k}, \mathbf{x}_c \rangle} \sum_{\mu=-\infty}^{\infty} i^{-(\mu-m)} e^{-i(\mu-m)\phi_{\mathrm{PW}}} B_\mu(\tfrac{\omega}{c} a) H_{m-\mu}^{(2)}(\tfrac{\omega}{c} r_c) e^{-i(m-\mu)\phi_c}$
- $B_\mu(\tfrac{\omega}{c} a) = \begin{cases} -\dfrac{J'_\mu(\frac{\omega}{c} a)}{H_\mu^{(2)\prime}(\frac{\omega}{c} a)} & \text{sound-hard} \\ -\dfrac{J_\mu(\frac{\omega}{c} a)}{H_\mu^{(2)}(\frac{\omega}{c} a)} & \text{sound-soft} \end{cases}$

- 2.5D NFC-HOA driving function

$$\mathring{D}_m(\omega) = \frac{1}{2\pi r_0} \frac{\breve{S}_{\mathrm{inc},|m|}^m(\omega) \big(1 + F_m(\mathbf{x}_c, a, \omega)\big)}{\breve{G}_{|m|}^m(\omega)}$$

- incident plane wave $\breve{S}_{\mathrm{inc},n}^m(\omega) = 4\pi i^{-n} Y_n^m(\tfrac{\pi}{2}, \phi_{\mathrm{PW}})^*$
- secondary point sources $\breve{G}_{\mathrm{ps},n}^m(\omega) = -i\tfrac{\omega}{c} h_n^{(2)}(\tfrac{\omega}{c} r_0) Y_n^m(\theta_0, \phi_0)^*$

Evaluation

- numerical simulation using the Sound Field Synthesis (SFS) Toolbox (MATLAB)
- incident plane wave ($\phi_{\mathrm{pw}} = -\frac{\pi}{2}$)
- cylindrical scatterer ($\mathbf{x}_c = (0, 2)$, $a = 0.4$ m)
- 2.5D NFC-HOA ($r_0 = 1.5$ m, $N_{\mathrm{loudspeaker}} = 60$, $f_{\mathrm{alias.}} \approx 1$ kHz, order: 29)
- ○ : scatterer, • : secondary sources

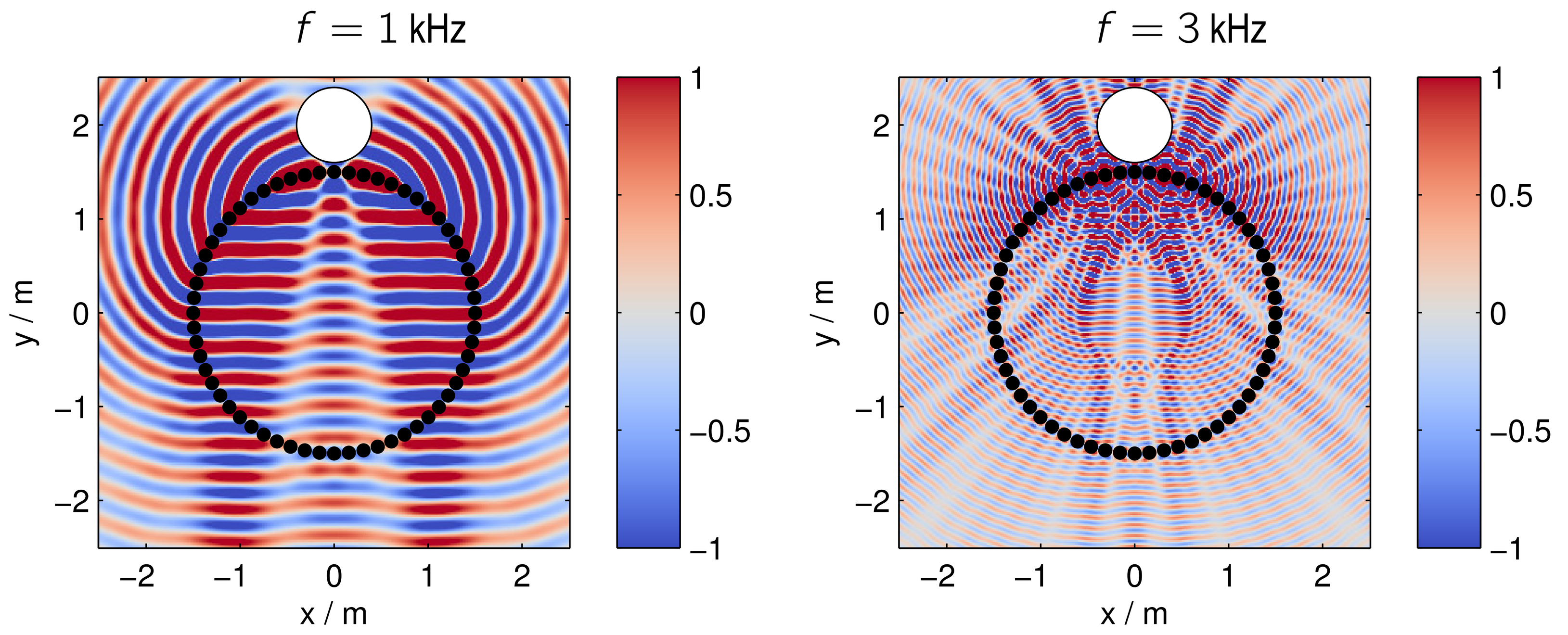


Figure: Monochromatic sound fields. Sound-hard scatterer.

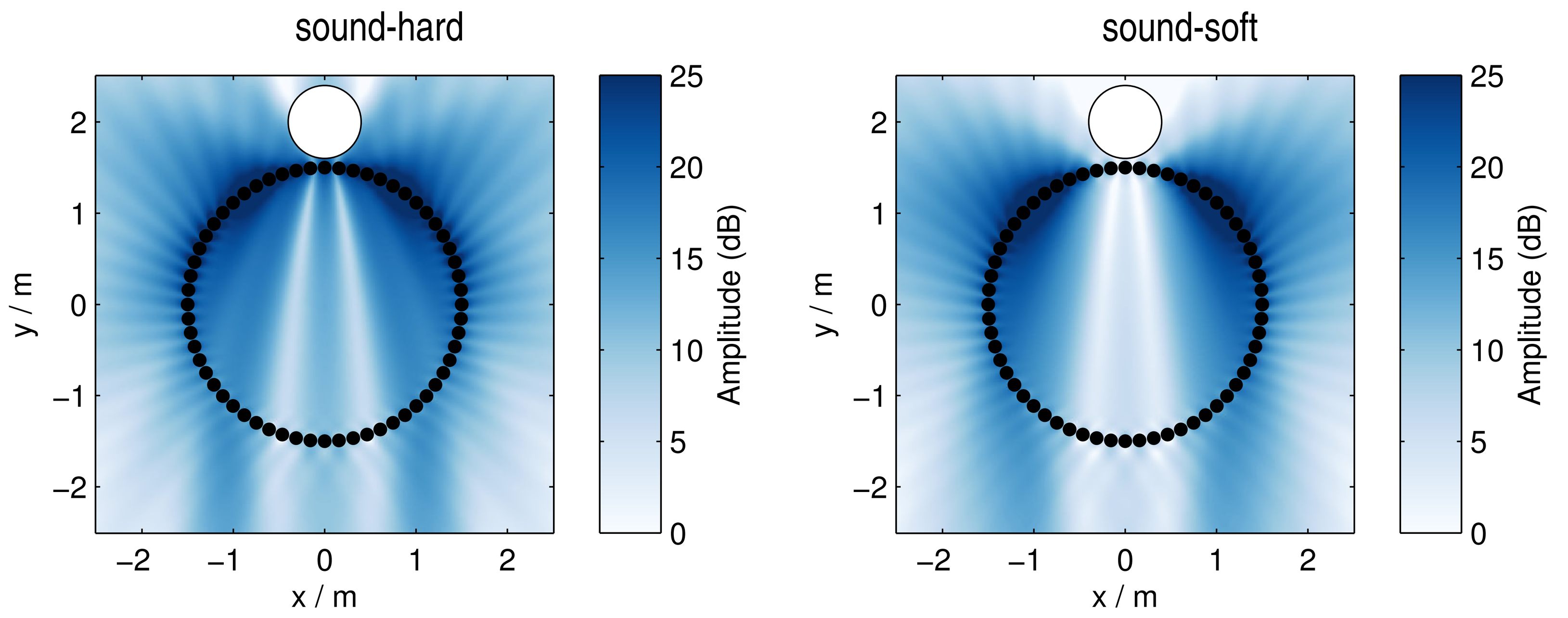


Figure: Monochromatic sound fields (dB). $f = 1$ kHz.

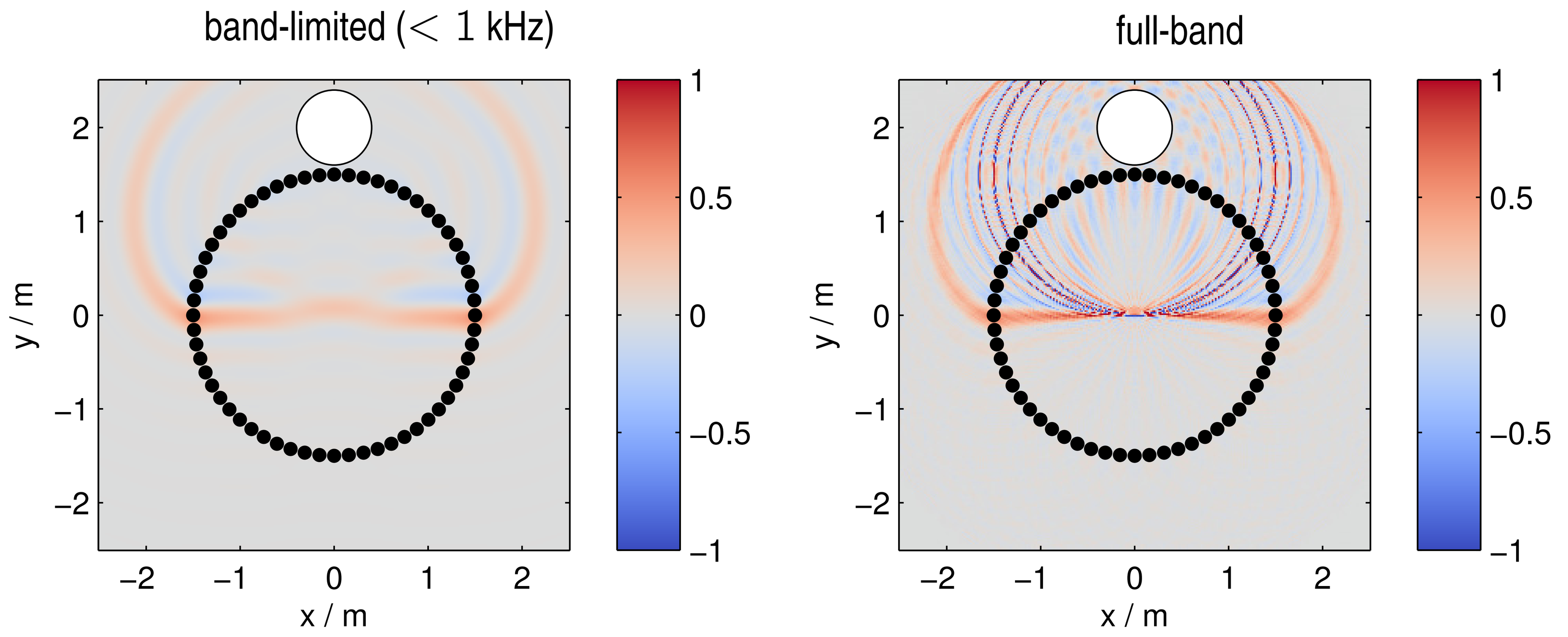
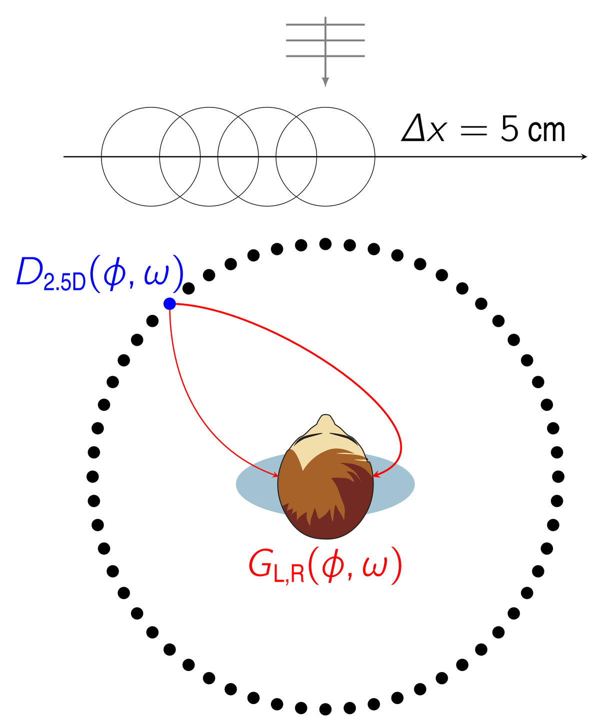


Figure: Wide-band sound fields

Listening Examples

- ear signals simulated for a virtual NFC-HOA system ($r_0 = 1.5$ m, $N_{\mathrm{loudspeaker}} = 60$)
- incident plane wave ($\phi_{\mathrm{PW}} = -\frac{\pi}{2}$)
- moving cylindrical scatterer ($y = 2$ m, $a = 0.4$ m)
- driving signals filtered with HRTFs
- computed for every 5 cm and cross-faded
- `http://spatialaudio.net/sfs_scattering_object`



References

[1] M. S. Gordon and L. D. Rosenblum, "Perception of sound-obstructing surfaces using body-scaled judgments," *Ecol. Psychol.*, vol. 16, no. 2, pp. 87–113, 2004.

[2] M. Vorländer, *Auralization*. Springer, 2007.

[3] N. Tsingos and J.-D. Gascuel, "Fast rendering of sound occlusion and diffraction effects for virtual acoustic environments," in *Proc. of 104th Audio Eng. Soc. Convention*, Amsterdam, The Netherlands, 1998.

[4] D. T. Murphy and M. J. Beeson, "Modelling spatial sound occlusion and diffraction effects using the digital waveguide mesh," in *Proc. of 24th Audio Eng. Soc. Intl. Conference on Multichannel Audio, The New Reality*, Banff, Canada, 2003.

[5] J. Daniel, "Spatial sound encoding including near field effect: Introducing distance coding filters and a viable, new Ambisonic format," in *Proc. of 23rd Auido Eng. Soc. Intl. Conference on Signal Processing in Audio Recording and Reproduction*, Helsingør, Denmark, 2003.

[6] J. Ahrens, *Analytic Methods of Sound Field Synthesis*. Springer, 2012.