Evaluation Strategies for the Optimization of Line Source Arrays

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Recent Trends for Line Source Array Applications

Curved LSA	Curved LSA	Straight LSA
-intensity shading by curving band-zoning/array morphing	-curving and electronic beam forming (FIR/IIR)	-electronic beam forming (FIR)
e.g. Meyer Sound MAPP XT e.g. L-ACOUSTICS SoundVision	e.g. EASE Focus FIR Maker e.g. Martin Audio Display e.g. Duran Audio AXYS with Digital Directivity Synthesis (DDS)$\longrightarrow$ now with JBL	e.g. EAW Resolution

Optimization Method

Complex-Directivity Point Source Model (CDPS) [Mey84, vB00, Fei09]

$$P(m,f) = \sum_{i=1}^{i=L\,N} \underbrace{D(i,f)}_{\text{FIR-Filter}} \cdot \underbrace{H_{\text{post}}(\beta(m,i),f) \cdot \frac{e^{-j\frac{2\pi f}{c}|x_m - x_{0,i}|}}{4\pi\,|\mathbf{x}_m - \mathbf{x}_{0,i}|} \cdot \frac{\Lambda_{y,\text{LSA}}}{L}}_{G(m,i,f)} .$$

Least Squares Optimization / **Pressure Matching** (DDS like) [vB00, Col14] with

-Tikhonov regularization /

energy constraint on the loudspeaker weights [Bet12]

$$\min_{\mathrm{d}(f)} \|\mathbf{G}(f)\mathbf{d}(f) - \mathbf{p}_{\text{des}}(f)\|_2^2 \qquad \text{subject to:} \quad \|\mathbf{d}(f)\|_2^2 \leq D_{\max}^2$$

Other Optimization Approaches

-active noise control, personal audio, multi-zone sound field synthesis [Cho02, Bai14, Col14]

-find minimum of constrained nonlinear multivariable function, Matlab: `fmincon()` [Tho09]

-solve multiobjective goal attainment problems, Matlab: `fgoalattain()` [Tho11, Fei13]

-near field & far field beam forming (DDC like) [vB00, Bai13]

Evaluation Setup

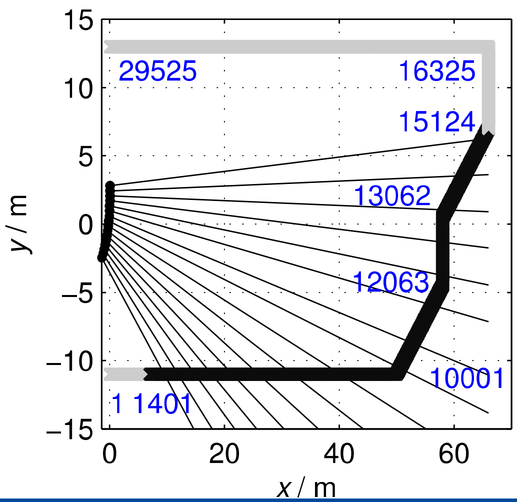
LSA Cabinet Model [Mey84]

height 0.372m, ideal circular / line pistons, ideal X-Over 400 Hz & 1.5 kHz

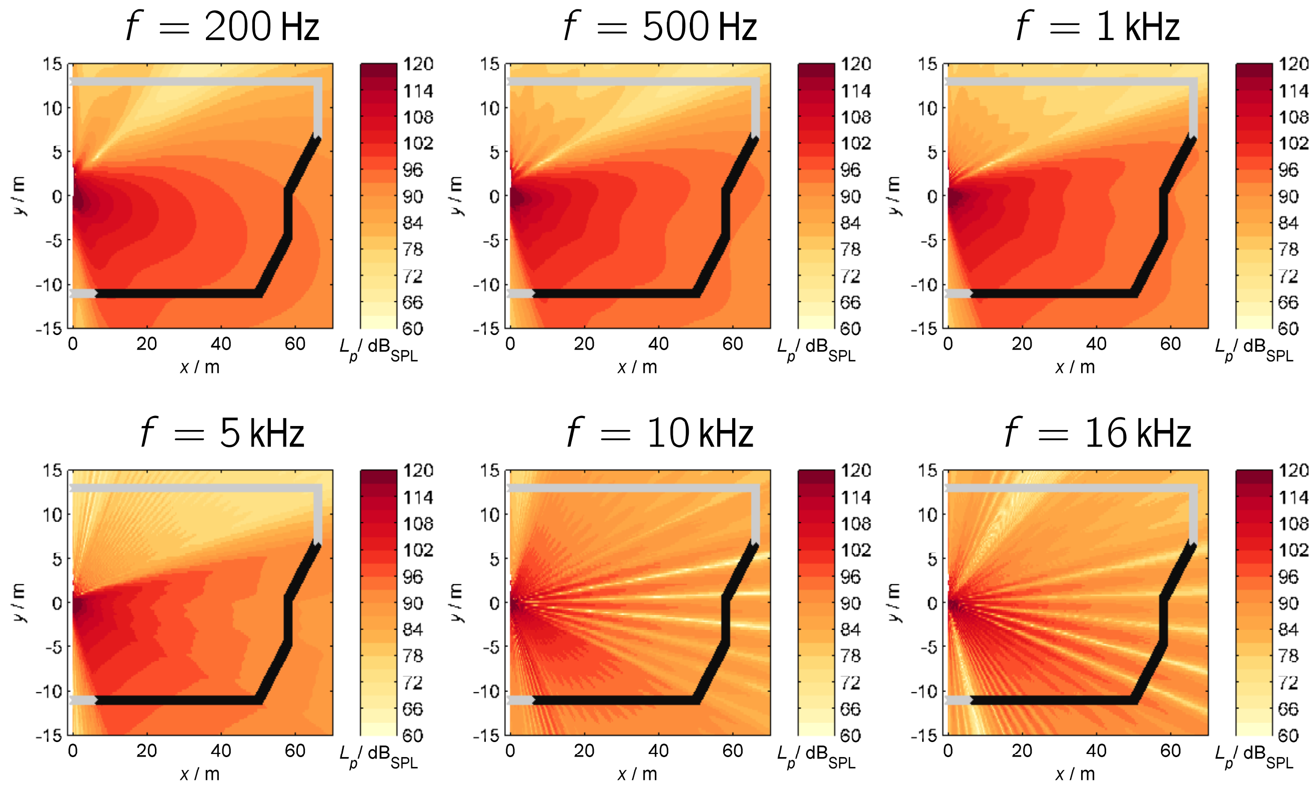
	#	f_{alias}/Hz	diameter/length in inch	Δy in inch	$\text{dB}_{\text{SPL@1W,1m}}$
LF	1	461	12 (circ)	14.65	96
MF	4	1844	3 (circ)	3.66	86
HF	10	4610	1.2 (line)	1.46	112

LSA Model

16 cabinets, length ≈6m, tilt angle +3°, splay angles top to down: 5x2°, 3°, 2°, 6x3°, 2x4°

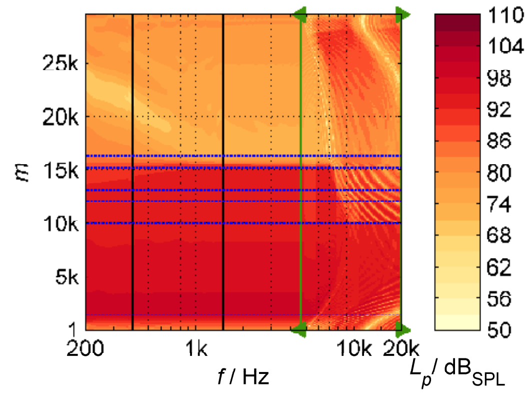


SPL Distribution in xy-Plane

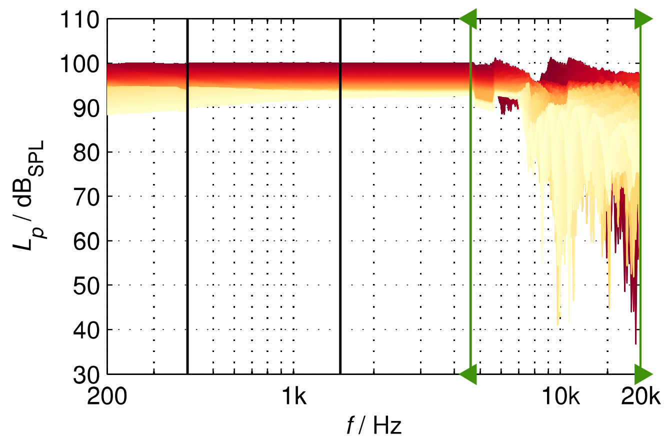


Frequency Responses & Directivity

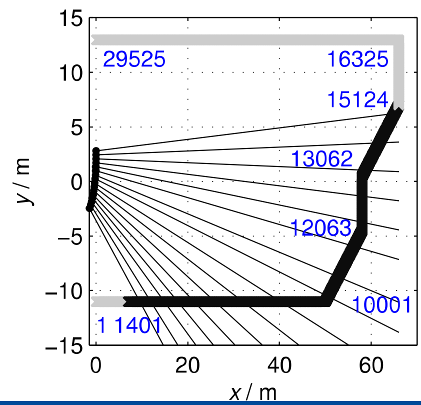
Position Index Plot [Tho09, Fei13]



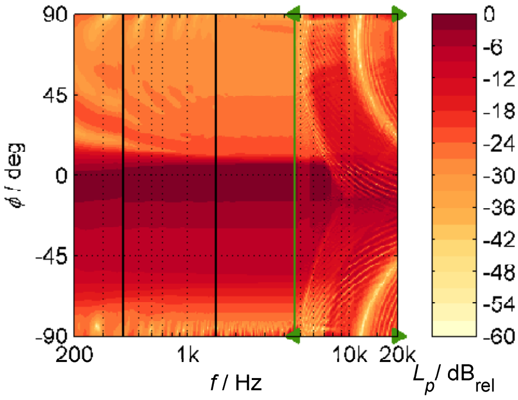
Frequency Responses in Audience Zone



Venue Setup



Farfield Radiation Pattern



Technical Quality: Errors

Absolute error

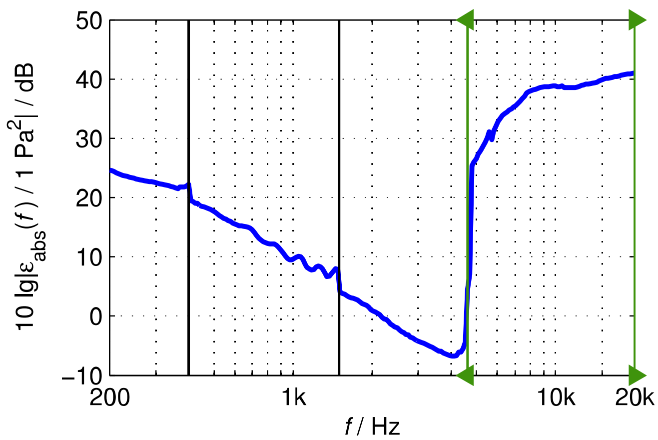
frequency dependent

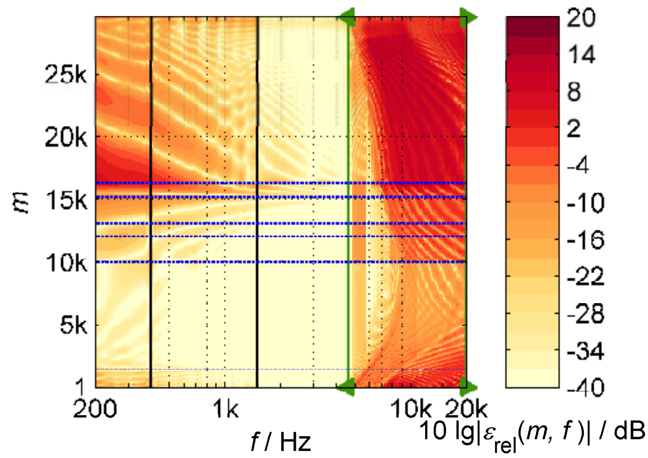
$$\epsilon_{\text{abs}}(f) = \|\mathbf{G}(f)\mathbf{d}(f) - \mathbf{p}_{\text{des}}(f)\|_2^2$$

Relative error

frequency & position dependent

$$\epsilon_{\text{rel}}(m, f) = \left|\frac{P_{\text{des}}(m, f) - P(m, f)}{P_{\text{des}}(m, f)}\right|^2$$





Technical Quality: Acoustic Contrast & Error Distribution

[Cho02, Bai14, Col14]

Acoustic contrast (bright vs. dark zone)

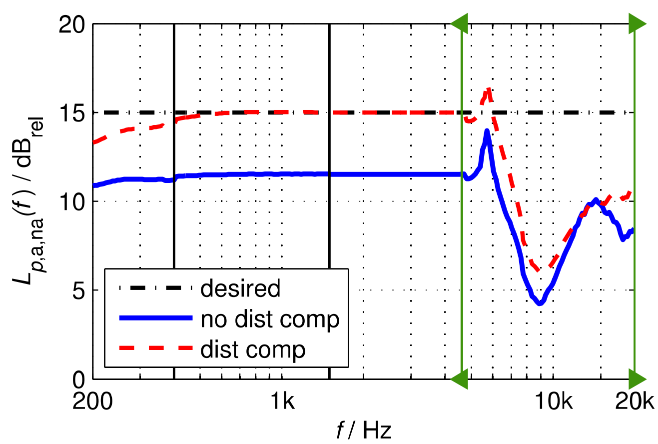
audience vs. non-audience zone

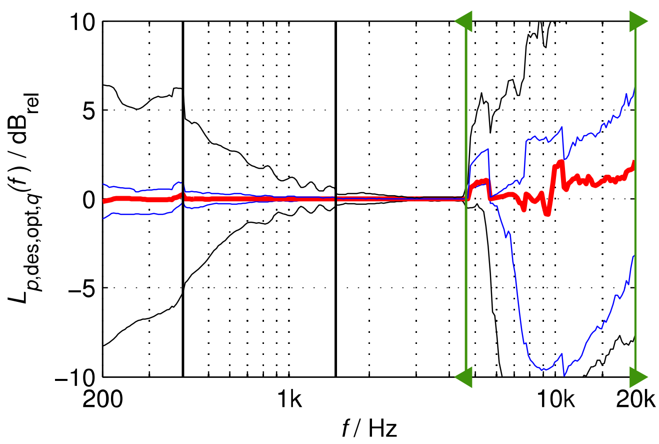
$$L_{p,\text{a,na}}(f) = 10\log_{10}\left(\frac{\frac{1}{M_{\text{a}}}\|\mathbf{p}_{m\in\mathcal{M}_{\text{a}}}(f)\|_2^2}{\frac{1}{M_{\text{na}}}\|\mathbf{p}_{m\in\mathcal{M}_{\text{na}}}(f)\|_2^2}\right)$$

Distribution measure

$q = \{0.05, 0.25, 0.5, 0.75, 0.95\}$ quantiles

$$L_{p,\text{des,opt},q}(f) = \underset{m}{\mathcal{Q}_q}\left[10\log_{10}\left(\frac{|P_{\text{des}}(m, f)|^2}{|P(m, f)|^2}\right)\right]$$

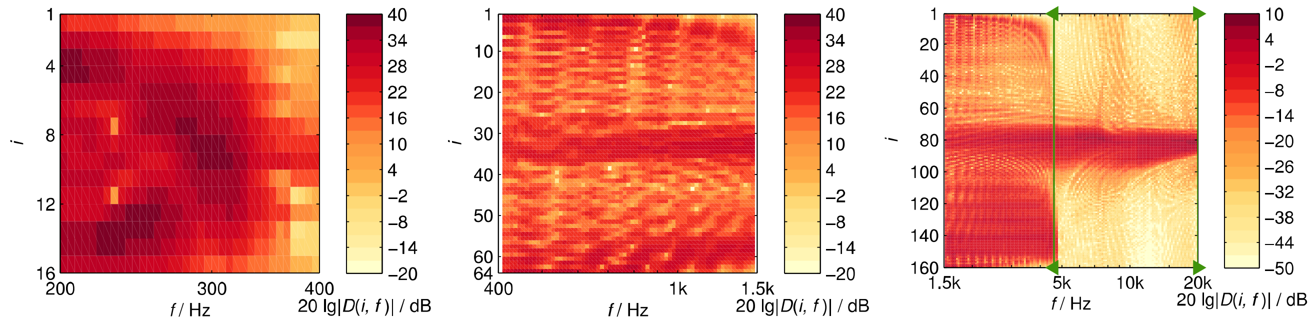




FIR Filters→Driving Function Index Plots [Tho08]

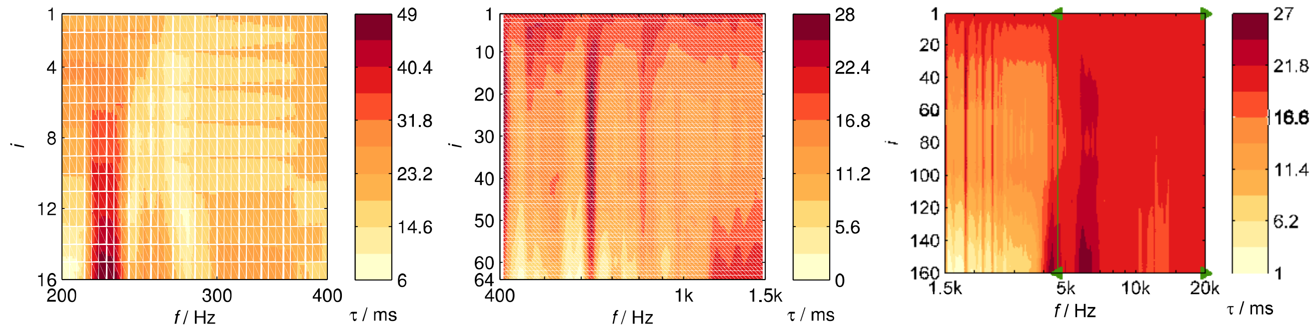
Magnitude in dB

LF MF HF



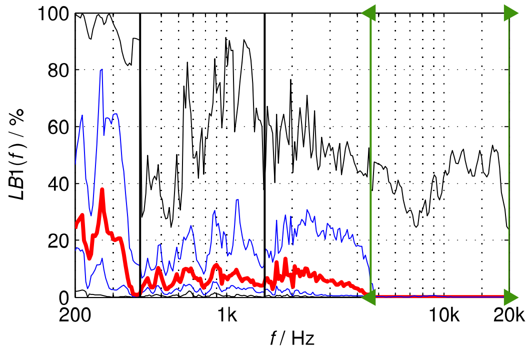
Group Delay in ms

LF MF HF



Technical Quality: Array Effort [Cho02, Bai14, Col14]

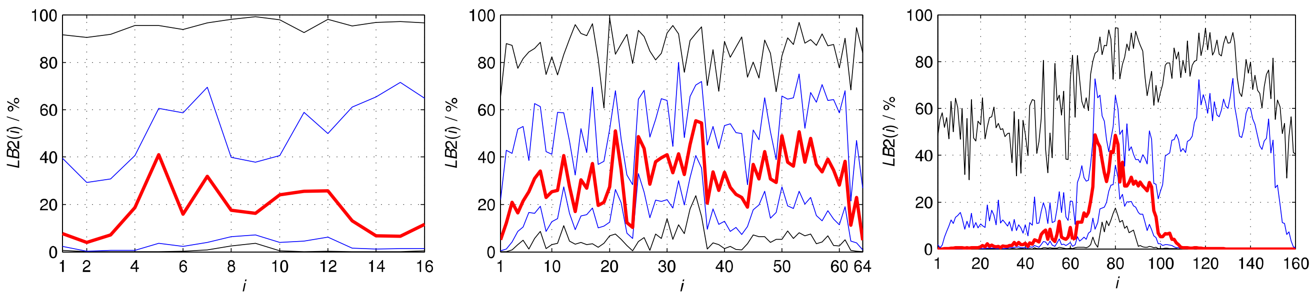
$$LB1(f) = \frac{\mathcal{Q}_q \left[|D(i,f)|^2\right]_i}{\max_i \left[|D(i,f)|^2\right]}$$



q ={0.05, 0.25, 0.5, 0.75, 0.95} quantiles

$$LB2(i) = \frac{\mathcal{Q}_q \left[|D(i,f)|^2\right]_f}{\max_f \left[|D(i,f)|^2\right]}$$

LF MF HF



Conclusion

- LS optimization above spatial aliasing frequency?
- technical error measures give further hints on R&D and optimization algorithm requirements
- usage of smaller waveguides $\longrightarrow$ spatial aliasing shifted to higher frequencies
- phase of optimized sound field?
- what sound fields are needed in terms of perception?

slides @ `http://spatialaudio.net`

References

[Bai13, Bai14, Bet12, Cho02, Col14, Fei09, Fei13, Mey84, Tho08, Tho09, Tho11, Tho13, vB00]

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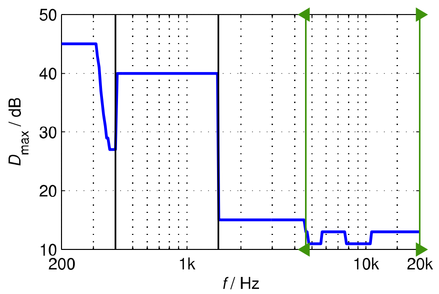
[Tho13] Thompson, A.; Luzarraga, J. (2013): "Drive granularity for straight and curved loudspeaker arrays." In: *Proc. of the Institute of Acoustics*, 35(2).

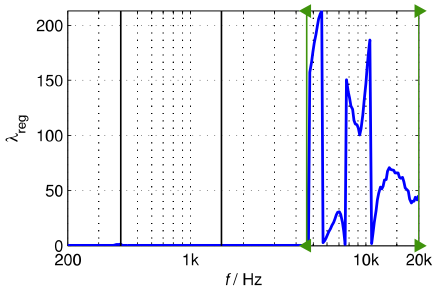
[vB00] van Beuningen, G.W.J.; Start, E.W. (2000): "Optimizing directivity properties of DSP controlled loudspeaker arrays." In: *Proc. of the Institute of Acoustics*, 22(6).

Optimization Parameters

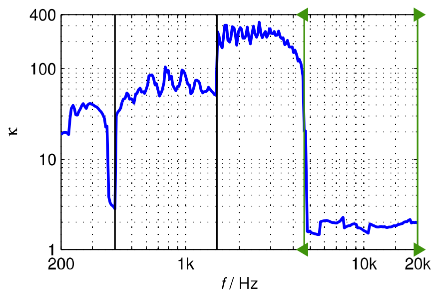
D^2_{max}



regularization value λ_{reg}



condition number κ



$$\mathbf{d}(f, \lambda_{reg}) = [\mathbf{G}(f)^{H}\mathbf{G}(f) + \lambda_{reg}\mathbf{I}_{L\ N}]^{-1}\,\mathbf{G}(f)^{H}\mathbf{p}_{des}(f)$$

Evaluation Setup LSA1

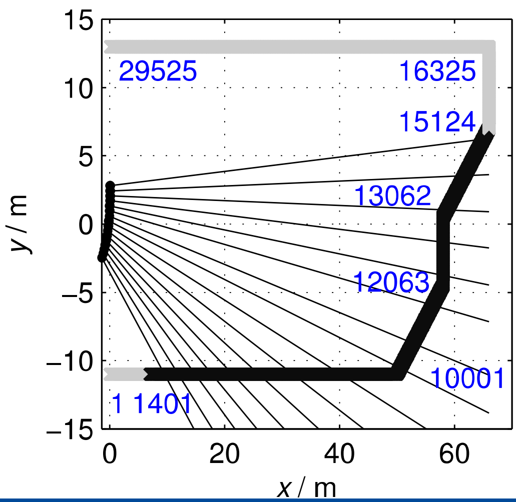
LSA1 Cabinet Model [Mey84]

height 0.372m, ideal circular / line pistons, ideal X-Over 400 Hz & 1.5 kHz

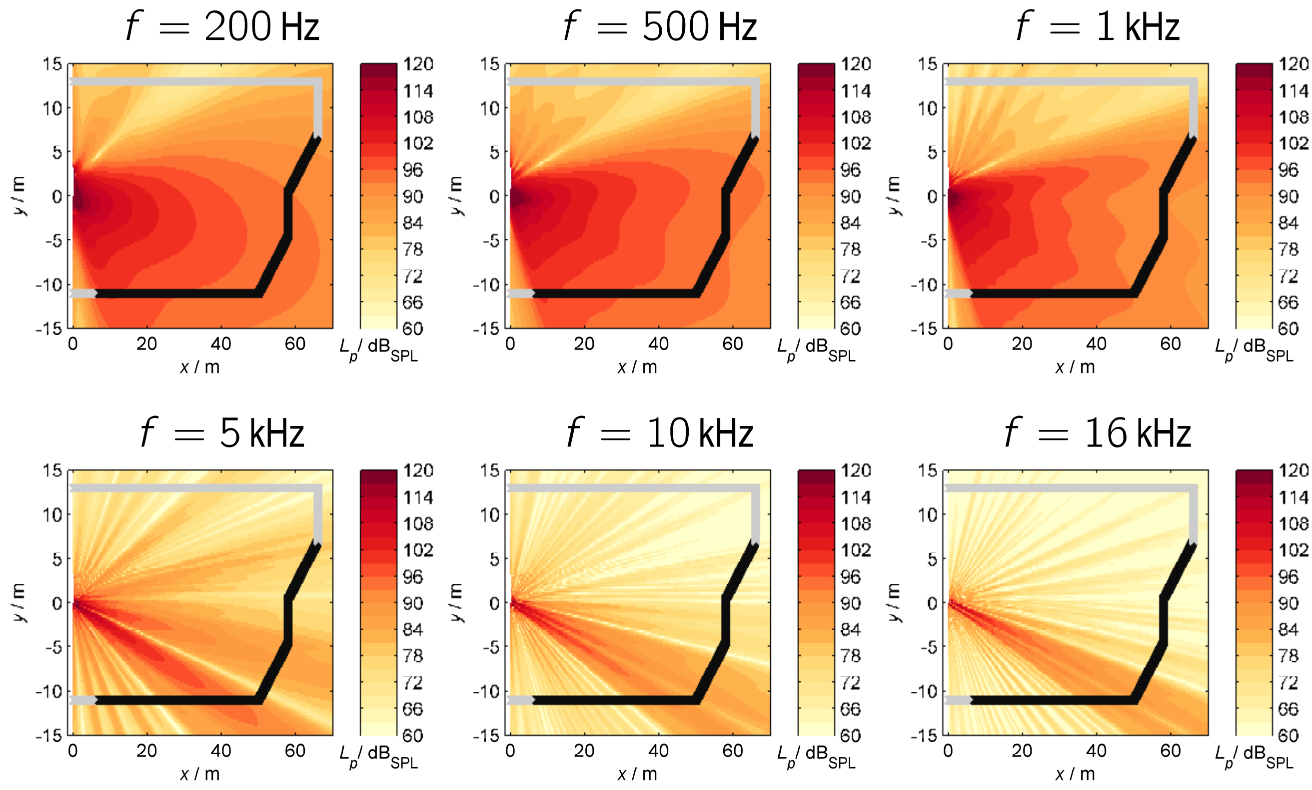
	#	f_{alias}/Hz	diameter/length in inch	Δy in inch	$dB_{SPL@1W,1m}$
LF	1	461	12 (circ)	14.65	96
MF	2	922	6 (circ)	7.32	94
HF	1	461	12 (line)	14.65	112

LSA Model

16 cabinets, length ≈6m, tilt angle +3°, splay angles top/down: 5x2°, 3°, 2°, 6x3°, 2x4°

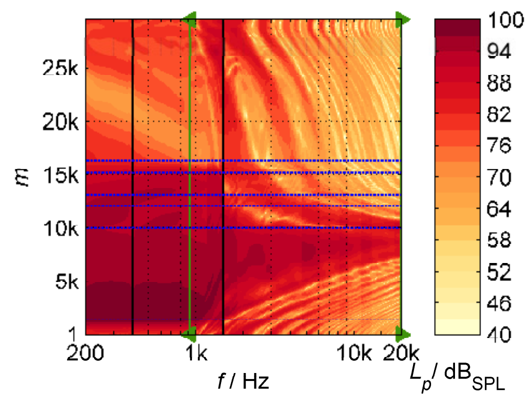


SPL Distribution in xy-Plane

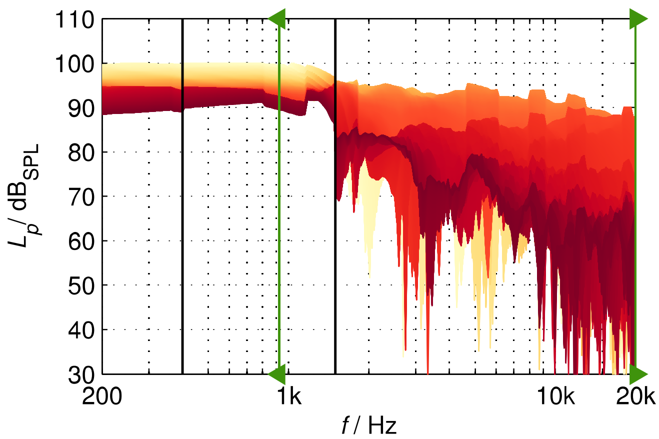


Frequency Responses & Directivity

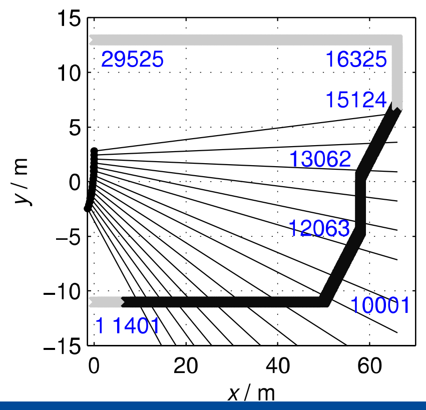
Position Index Plot [Tho09]



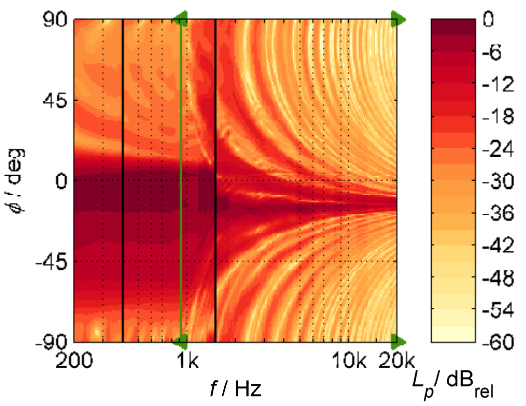
Frequency Responses in Audience Zone



Venue Setup

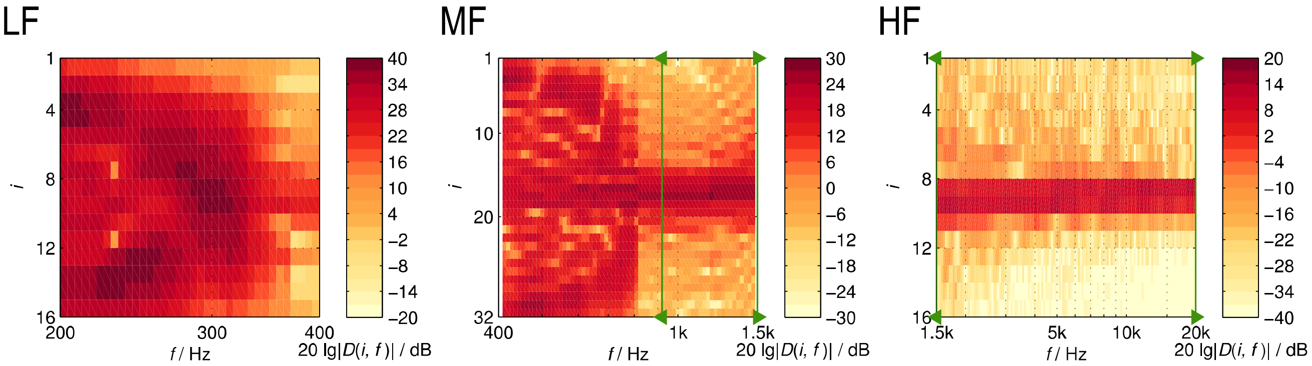


Farfield Radiation Pattern

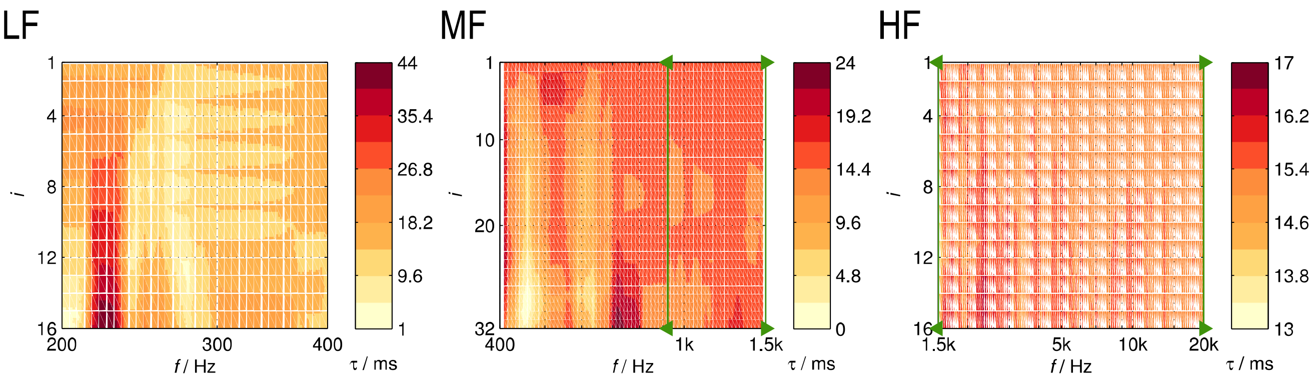


FIR Filters→Driving Function Index Plots

Magnitude in dB



Group Delay in ms



Technical quality: Errors

Absolute error

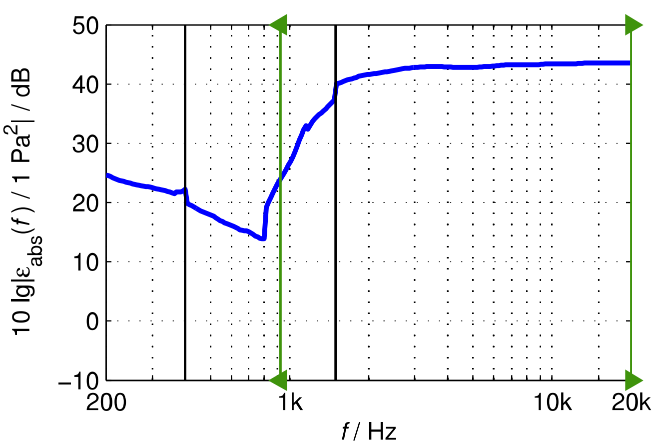
frequency dependent

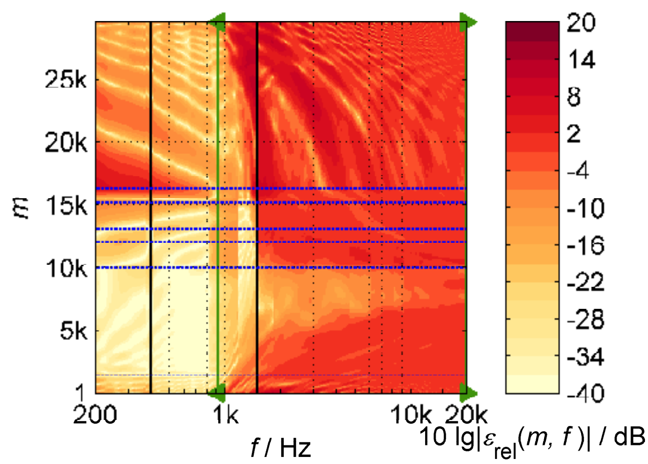
$$\epsilon_{abs}(f) = \|\mathbf{G}(f)\mathbf{d}(f) - \mathbf{p}_{des}(f)\|_2^2$$

Relative error

frequency & position dependent

$$\epsilon_{rel}(m, f) = \left|\frac{P_{des}(m, f) - P(m, f)}{P_{des}(m, f)}\right|^2$$





Technical quality: Acoustic Contrast [Cho02, Bai14, Col14]

Acoustic contrast (bright vs. dark zone)

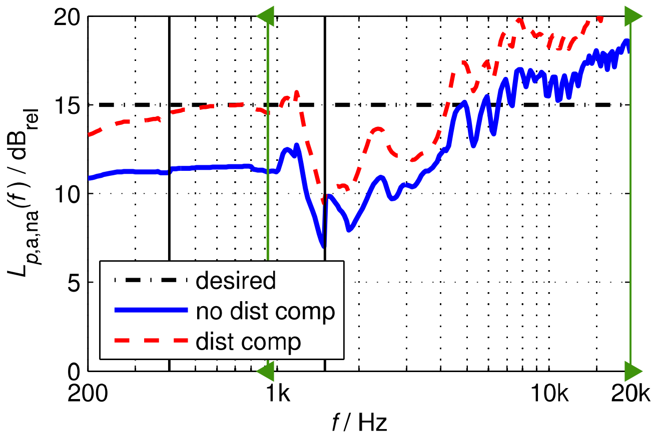
audience vs. non-audience zone

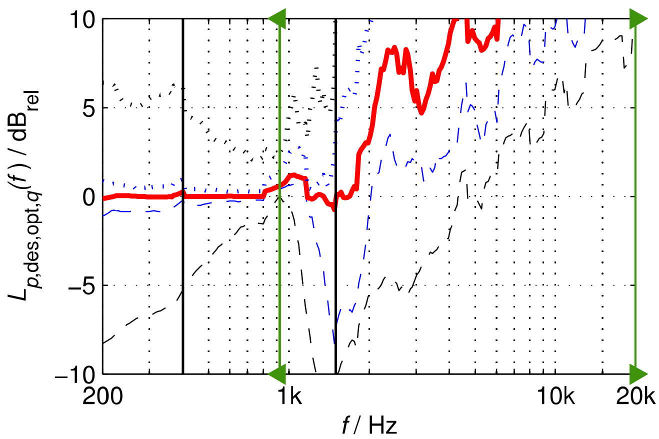
$$L_{p,\mathrm{a,na}}(f) = 10\,\log_{10}\left(\frac{\frac{1}{M_\mathrm{a}}\|\mathbf{p}_{m\in\mathcal{M}_\mathrm{a}}(f)\|_2^2}{\frac{1}{M_\mathrm{na}}\|\mathbf{p}_{m\in\mathcal{M}_\mathrm{na}}(f)\|_2^2}\right)$$

Distribution measure

q ={0.05, 0.25, 0.5, 0.75, 0.95} quantiles

$$L_{p,\mathrm{des,opt},q}(f) = \underset{m}{\mathcal{Q}_q}\left[10\,\log_{10}\left(\frac{|P_\mathrm{des}(m,f)|^2}{|P(m,f)|^2}\right)\right]$$





Technical quality: Array Effort [Cho02, Bai14, Col14]

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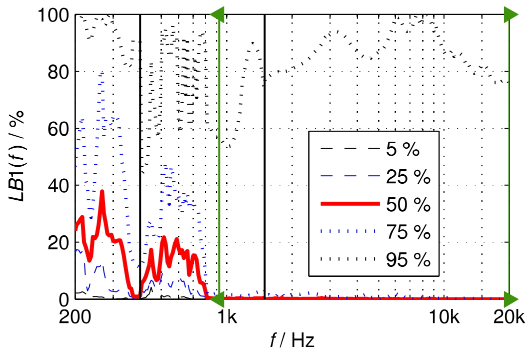
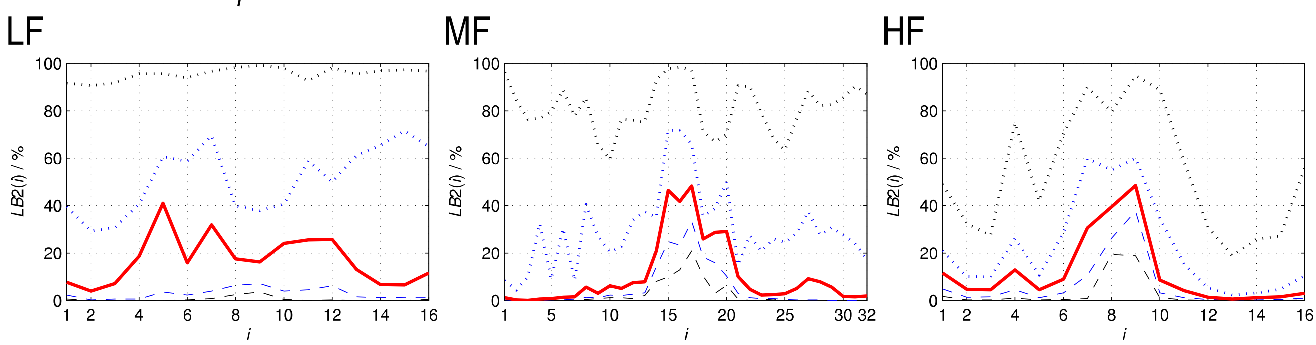


$$LB2(i) = \frac{\underset{f}{\mathcal{Q}_q}\left[|D(i,f)|^2\right]}{\underset{f}{\max}\left[|D(i,f)|^2\right]}$$



Optimization Parameters

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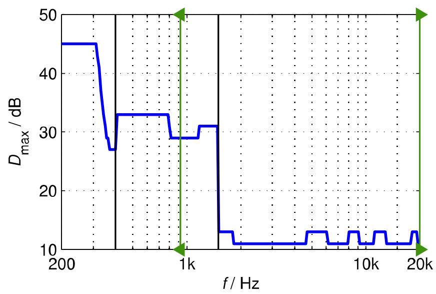
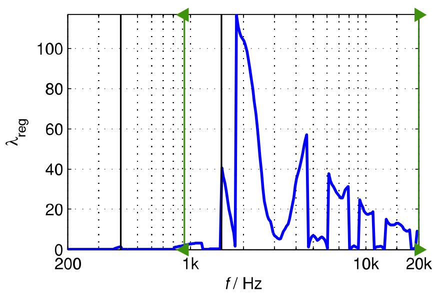


regularization value λ_{reg}



condition number κ