Universität Rostock Traditio et Innovatio

Institute of Communications Engineering

On Spatial-Aliasing-Free Sound Field Reproduction using Infinite Line Source Arrays

Frank Schultz, Till Rettberg, Sascha Spors

University of Rostock

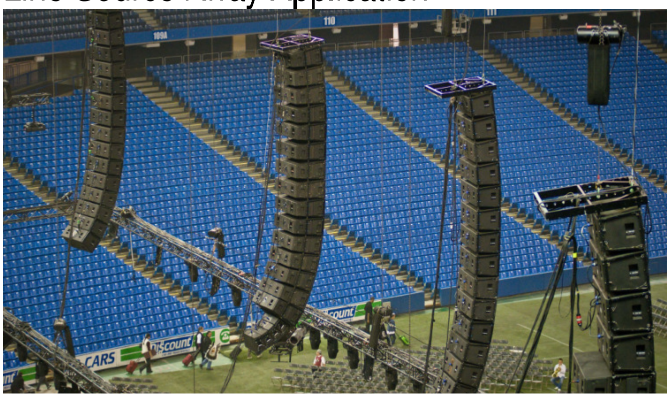
Institute of Communications Engineering

136th AES Convention, Berlin

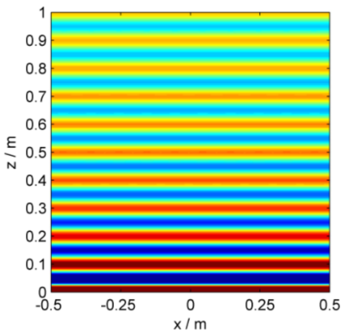
2014-04-29 10:00, paper session P11 "'Spatial Audio"', #9078

Introduction

Line Source Array Application

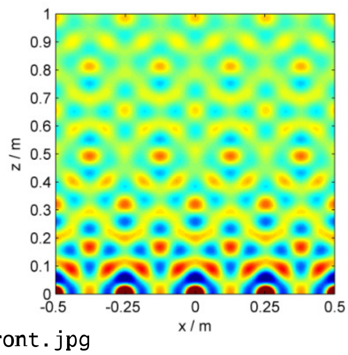


No spatial aliasing



Line Source Array Element

Spatial aliasing

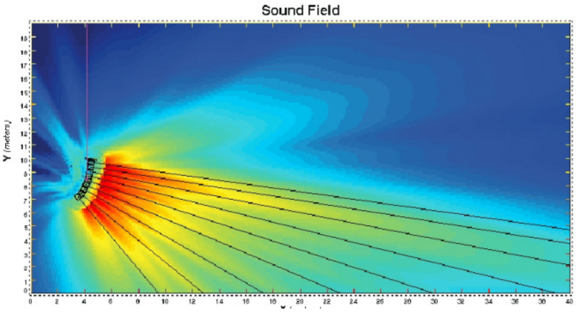


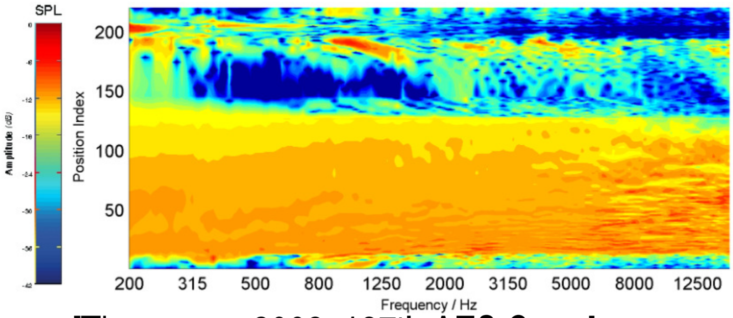
http://www.jblpro.com/press/jan09/JBL_IntlVerTec.jpg
http://www.turbosound.com/public/images/product_zoom/TFS-900H_front.jpg
http://www.turbosound.com/public/images/news_img_thumbs/TFS-900H-dendritics-assembly-thumb.jpg

Line Source Array Prediction

[Feistel, 2009, JAES **57**(6)]

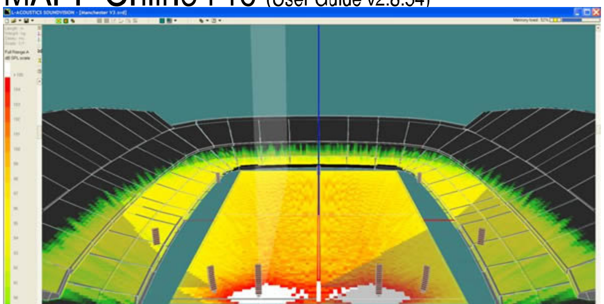
$$\underbrace{P(\mathbf{x},\omega)}_{\text{sound pressure}} = \sum_{n=1}^{N} \underbrace{D(\mathbf{x_{0,n}},\omega)}_{\text{filter}} \underbrace{A_n(\mathbf{x},\mathbf{x_{0,n}},\omega)}_{\text{directivity}} \underbrace{\frac{e^{-j\frac{\omega}{c}|\mathbf{x}-\mathbf{x_{0,n}}|}}{4\pi|\mathbf{x}-\mathbf{x_{0,n}}|}}_{\text{monopole}}$$



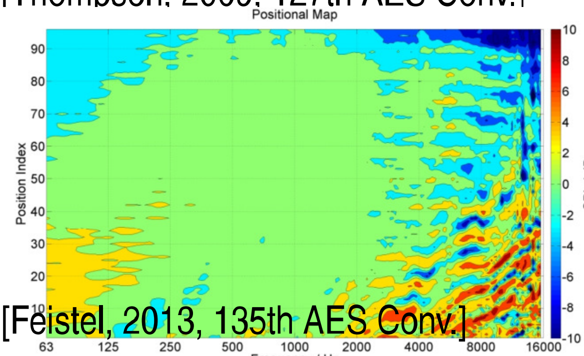


MAPP Online Pro (User Guide v2.8.54)

[Thompson, 2009, 127th AES Conv.]



Sound Vision
http://www.ratsound.com/cblog/uploads/soundvision/MainBack.jpg



[Feistel, 2013, 135th AES Conv.]

Wavefront Sculpture Technology® (WST)

[Heil, 1992, 92nd AES Conv.]

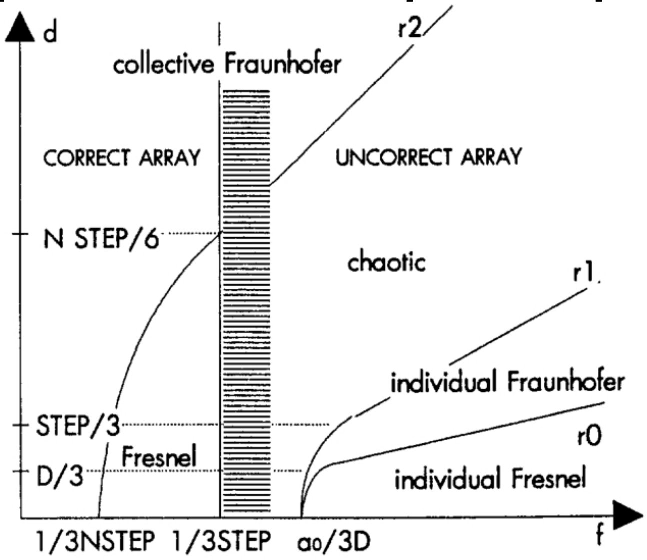
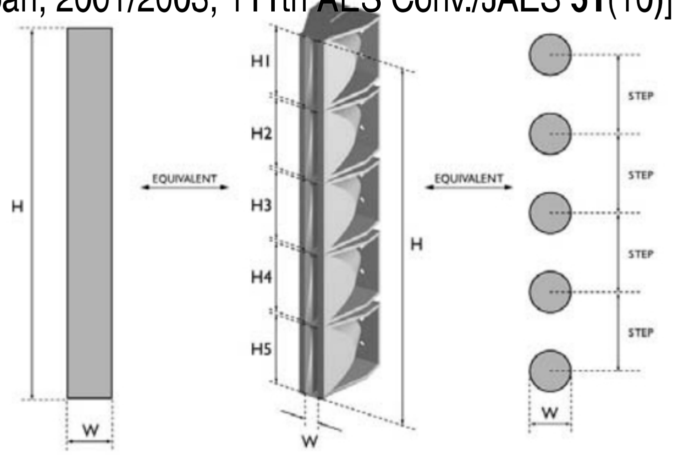
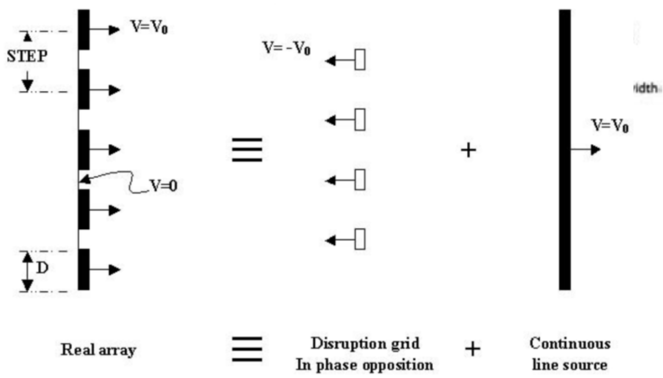


Fig 16. Border lines in the plane (d,f)

[Urban, 2001/2003, 111th AES Conv./JAES **51**(10)]





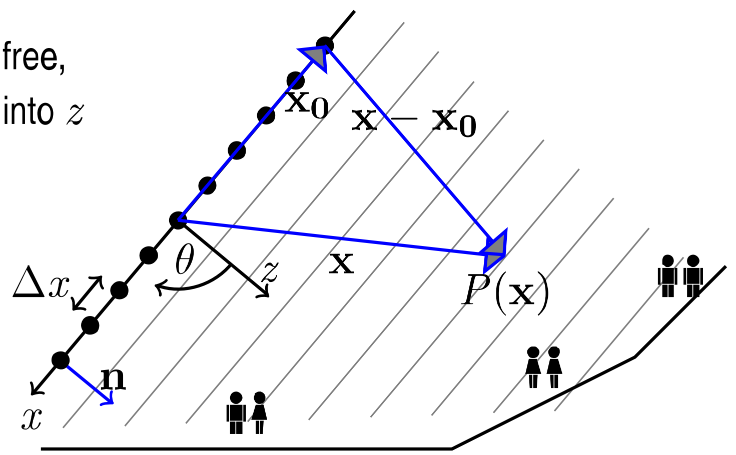
[Ureda, 2004, JAES **52**(5)]

Problem Formulation

$$\underbrace{P(\mathbf{x},\omega)}_{\text{sound pressure}} = \sum_{n=1}^{N} \underbrace{D(\mathbf{x_{0,n}},\omega)}_{\text{filter}} \underbrace{A_n(\mathbf{x},\mathbf{x_{0,n}},\omega) \frac{\mathrm{e}^{-\mathrm{j}\frac{\omega}{c}|\mathbf{x}-\mathbf{x_{0,n}}|}}{4\pi|\mathbf{x}-\mathbf{x_{0,n}}|}}_{\text{loudspeaker}}$$

$$\underbrace{P(\mathbf{x},\omega)}_{\text{sound pressure}} = \int_{-\infty}^{+\infty} \underbrace{D_{\text{Sampled}}(\mathbf{x_0},\omega)}_{\text{driving function}} \cdot \underbrace{G(|\mathbf{x}-\mathbf{x_0}|,\omega)}_{\text{loudspeaker}} \, \mathrm{d}x_0$$

Aim: spatial-aliasing free, cylindrical wavefront into z



Signal Processing Model for Sound Field Synthesis

- **Continuous** problem formulation with **monopoles**

$$D(\mathbf{x_0}) \longrightarrow \circledast \longrightarrow P(\mathbf{x}), \quad \uparrow G(\mathbf{x},\mathbf{0})$$

$$\underbrace{P(\mathbf{x},\omega)}_{\text{sound pressure}} = \int_{-\infty}^{+\infty} \underbrace{D(\mathbf{x_0},\omega)}_{\text{driving function}} \cdot \underbrace{G(|\mathbf{x}-\mathbf{x_0}|,\omega)}_{\text{monopole}} \, \mathrm{d}x_0$$

- Interpretation as a **spatial convolution** along x_0

$$P(\mathbf{x},\omega) = D(\mathbf{x},\omega) *_{x_0} G(|\mathbf{x}-\mathbf{0}|,\omega)$$

- This corresponds to a **multiplication** in the k_x-domain

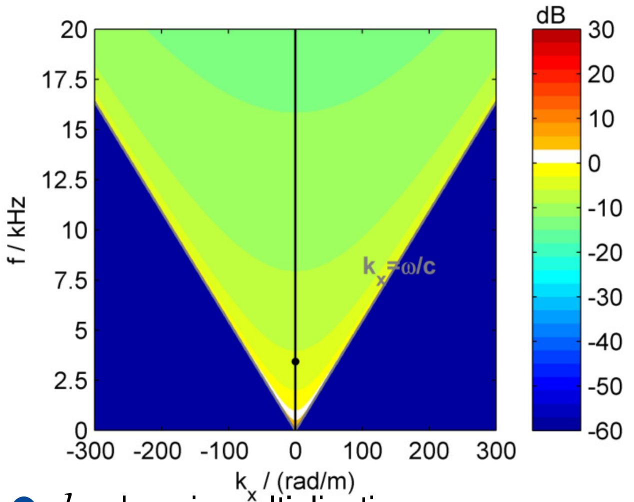
$$P(k_x,0,z,\omega) = D(k_x,0,z,\omega) \cdot G(k_x,0,z,\omega)$$

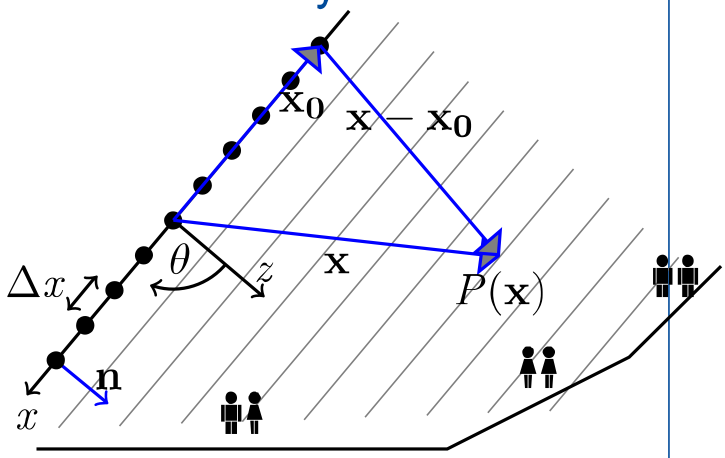
using the one-dimensional spatial Fourier transform along x_0

$$P(k_x,0,z,\omega) = \int_{-\infty}^{+\infty} P(x,0,z,\omega)\,\mathrm{e}^{+\mathrm{j}\,k_x x}\mathrm{d}x$$

[Ahrens, 2010, IEEE Audio **18**(8)]

Signal Processing Model for Sound Field Synthesis





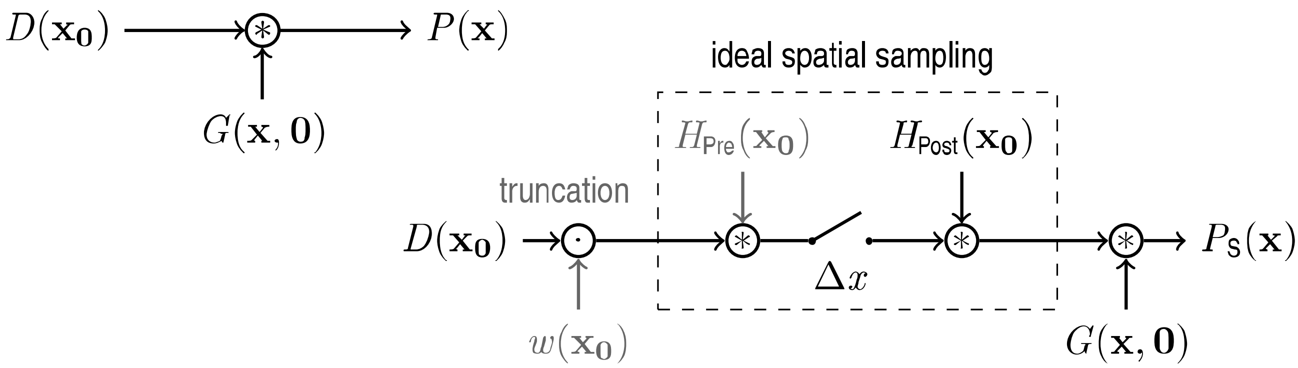
- k_x-domain multiplication

$$P(k_x, 0, z_{\text{ref}}, \omega) = D(k_x, 0, z_{\text{ref}}, \omega) \cdot G(k_x, 0, z_{\text{ref}}, \omega)$$

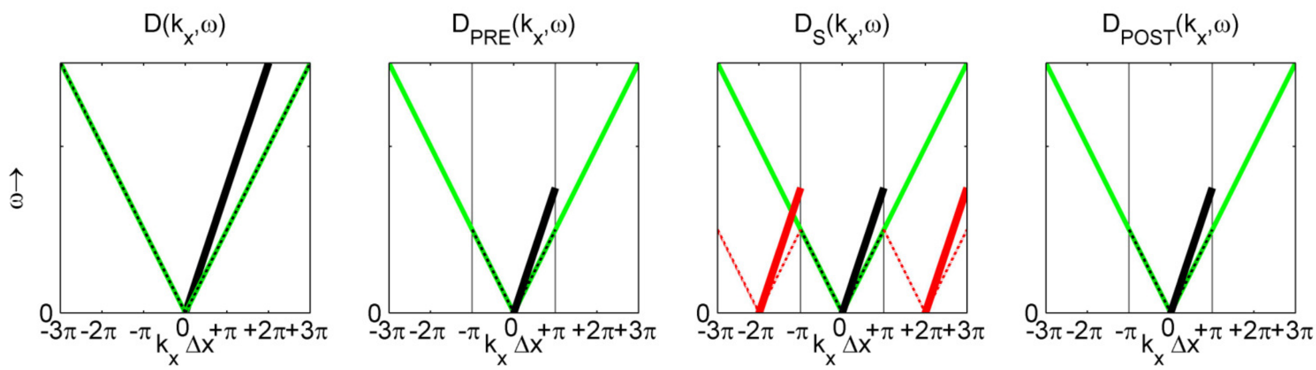
- Dispersion relation for a 2.5D wave propagation problem, $k_x = \frac{\omega}{c} \sin\theta$

$$\left(\frac{\omega}{c}\right)^2 = k_x^2 + k_z^2 \qquad \text{we want: } k_x = 0$$

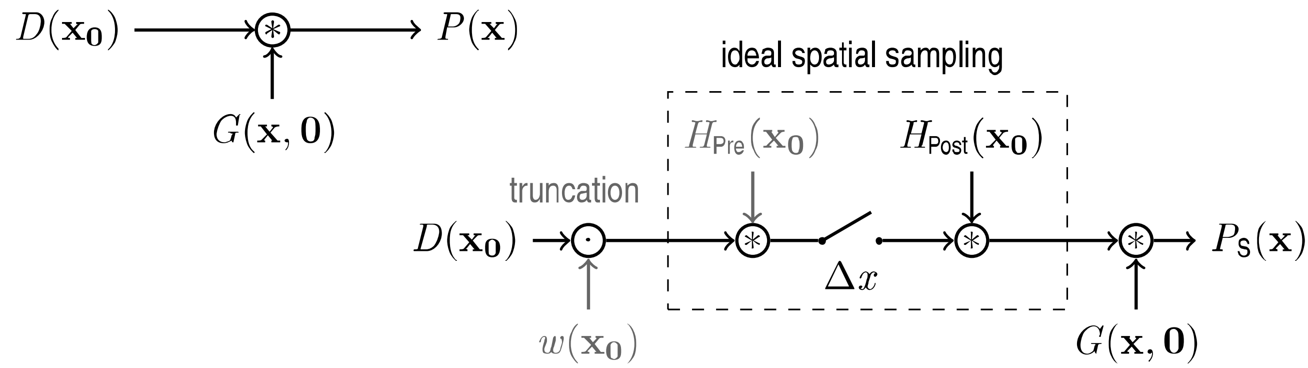
Baseband Sampling for Spatial Signals



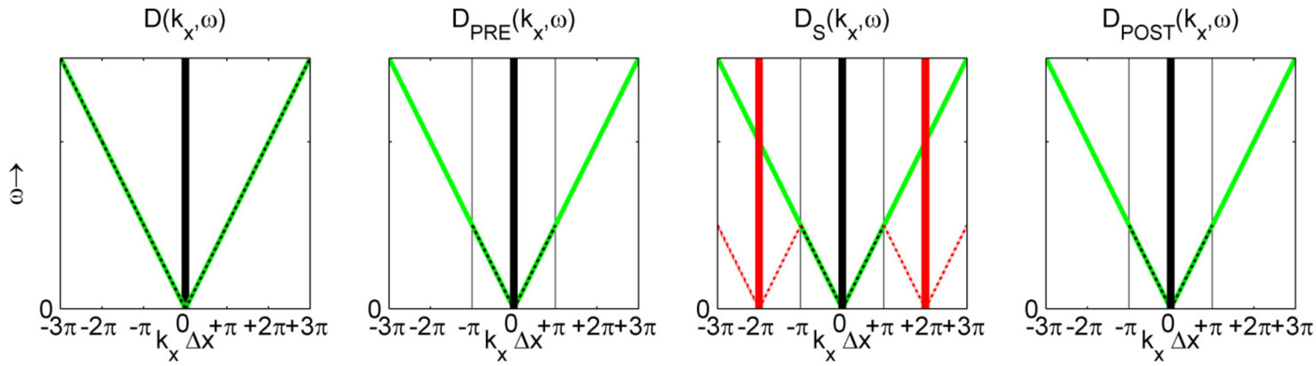
Δx ○—● $\Delta k_x = \frac{2\pi}{\Delta x}$



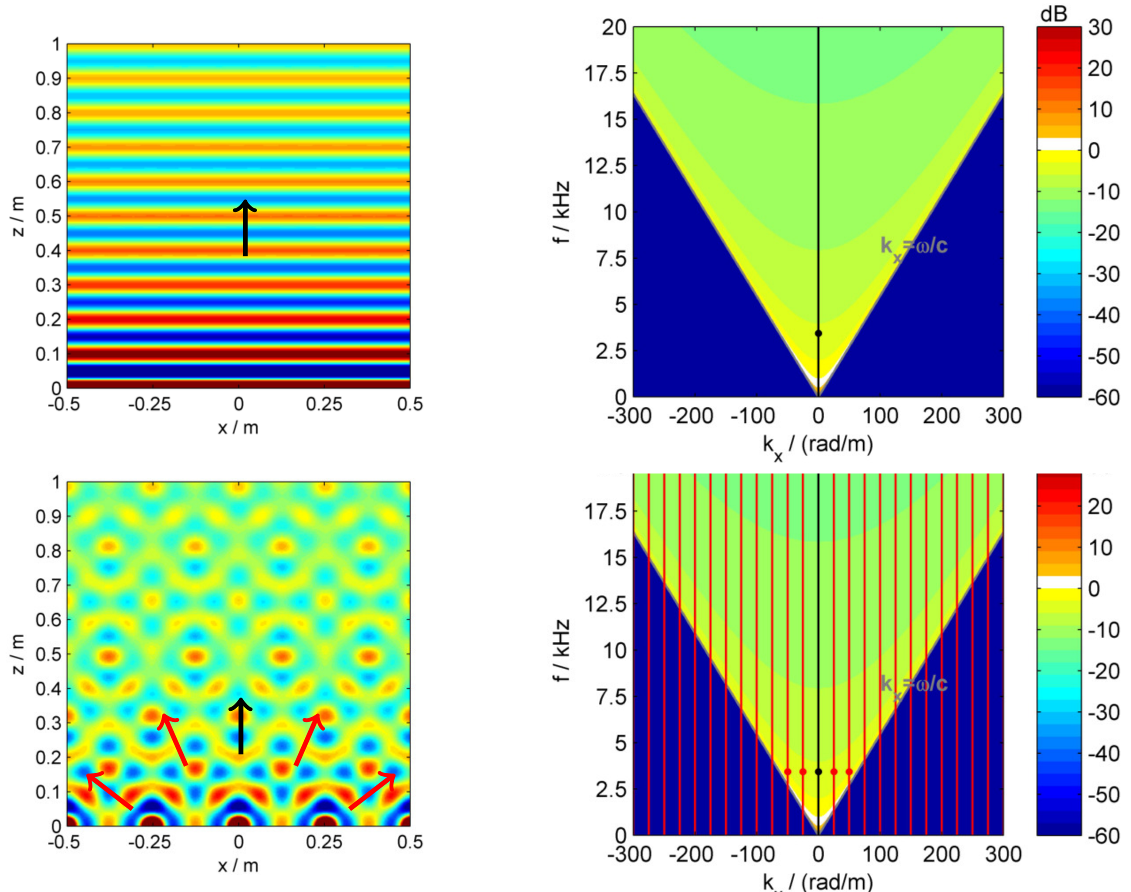
Baseband Sampling for Spatial Signals



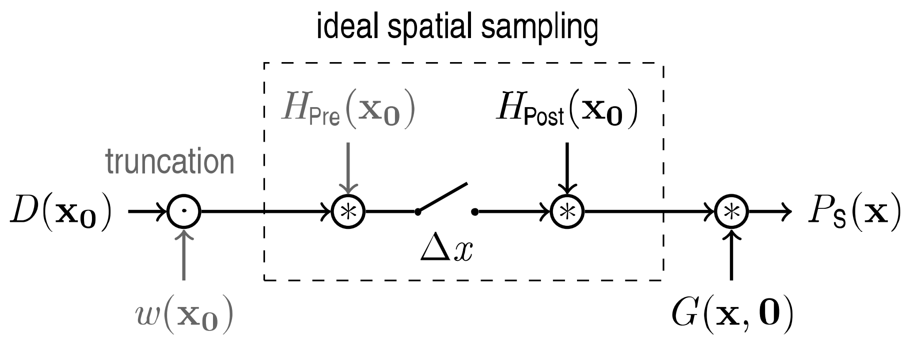
$$\Delta x \quad \Delta k_x = \frac{2\pi}{\Delta x}$$

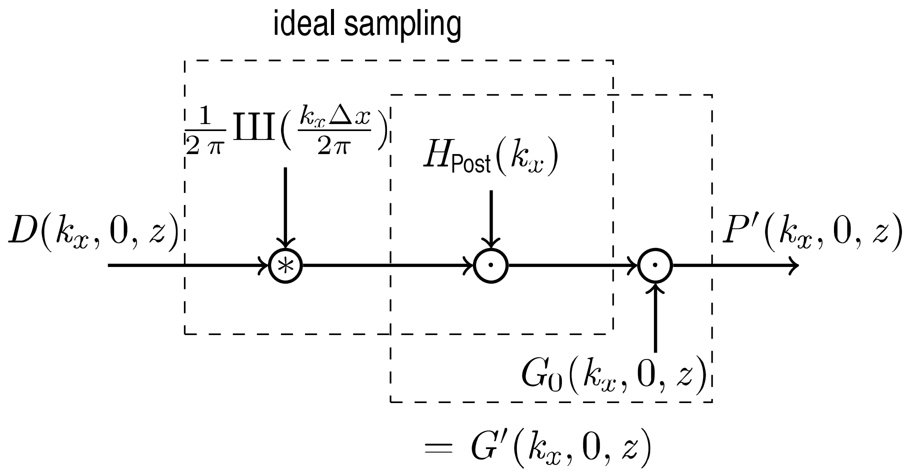


Spatial Aliasing due to missing Spatial Postfilter



Baseband Sampling for Spatial Signals





Use the Loudspeaker as the Spatial Postfilter

model $H_{\text{Post}}(k_x)$ with the farfield directivities of a loudspeaker

farfield directivities have spatial lowpass characteristics

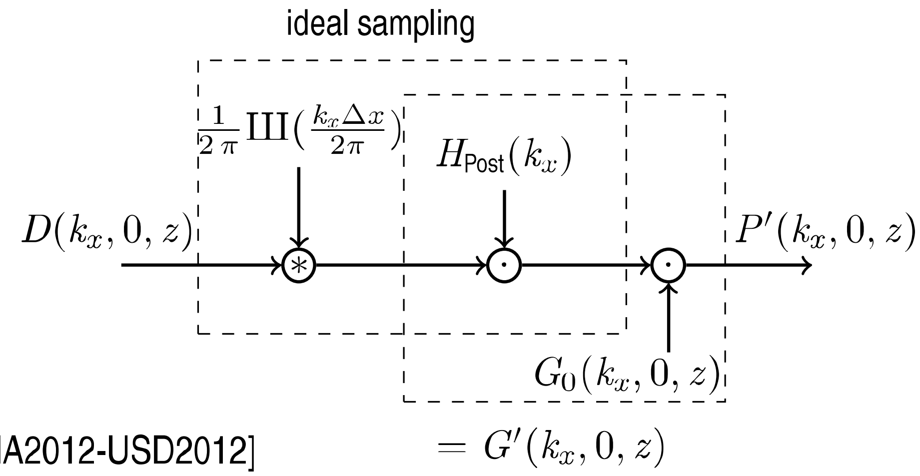
circular piston with radius r_0

$$H_{\text{Circ}}(k_x) = \frac{2\, J_1(\frac{\omega}{c}\, \sin\theta\, r_0)}{\frac{\omega}{c}\, \sin\theta\, r_0}$$

$$k_x = \frac{\omega}{c}\, \sin\theta$$

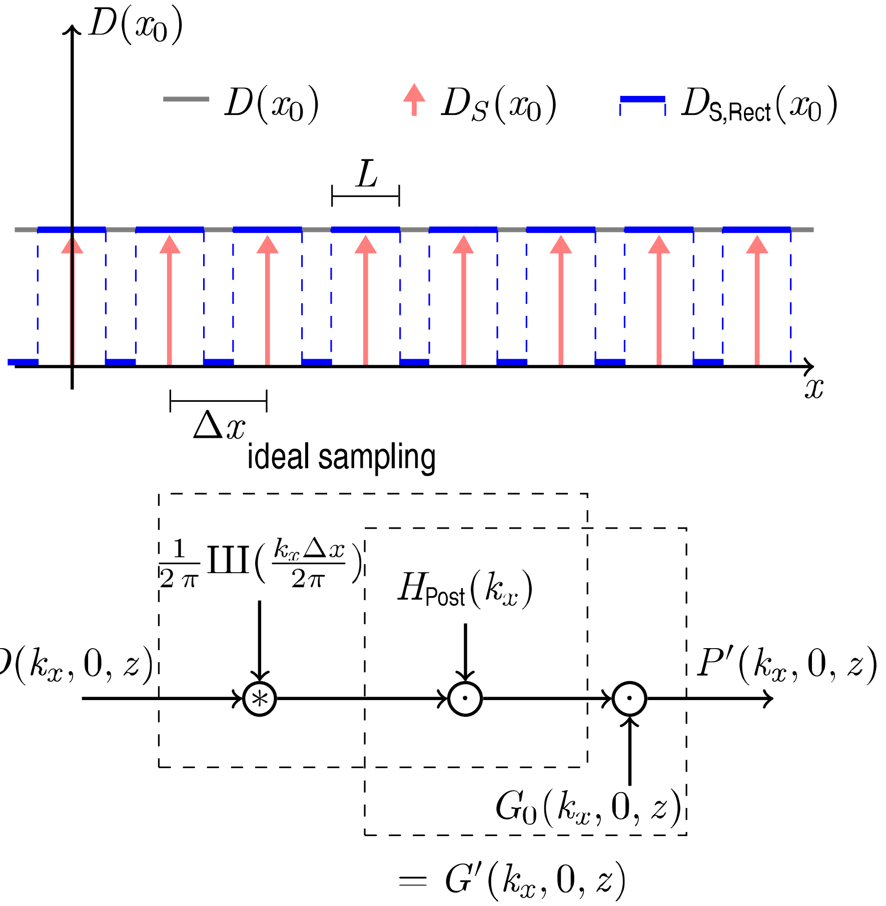
line piston with length L

$$H_{\text{Rect}}(k_x) = \frac{\sin\left(\frac{\omega}{c}\, \sin\theta\, \frac{L}{2}\right)}{\frac{\omega}{c}\, \sin\theta\, \frac{L}{2}}$$



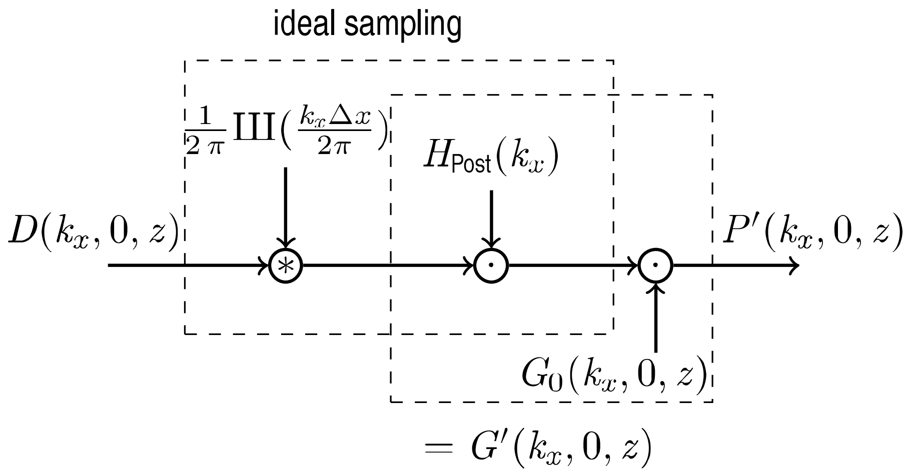
[Firtha, 2012, ISMA2012-USD2012]

Waveguide as a Spatial Lowpass Filter

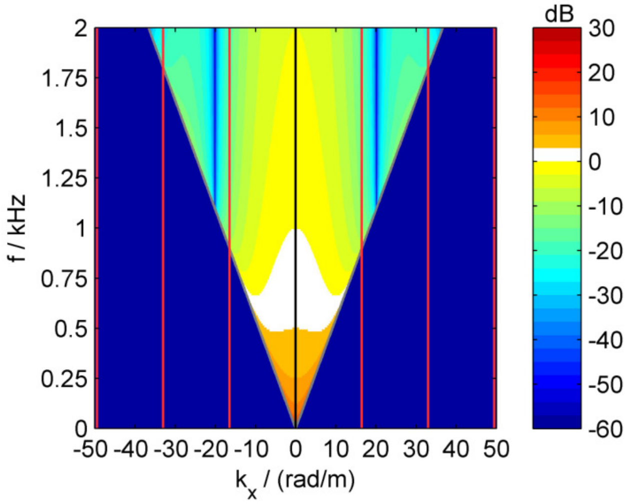


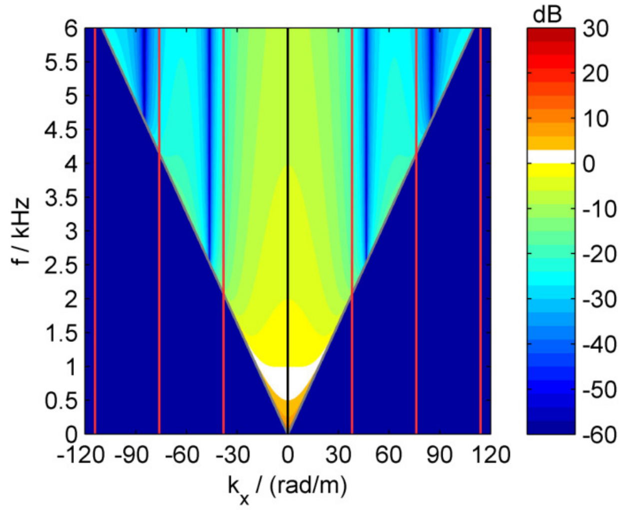
Line Array Prediction vs. Signal Model

$$\underbrace{P(\mathbf{x}, \omega)}_{\text{sound pressure}} = \sum_{n=1}^{N} \underbrace{D(\mathbf{x_{0,n}}, \omega)}_{\text{filter}} \underbrace{A_n(\mathbf{x}, \mathbf{x_{0,n}}, \omega)}_{\text{directivity}} \underbrace{\frac{\mathrm{e}^{-\mathrm{j}\,\frac{\omega}{c}\,|\mathbf{x}-\mathbf{x_{0,n}}|}}{4\,\pi\,|\mathbf{x}-\mathbf{x_{0,n}}|}}_{\text{monopole}}$$



Circular Piston Model





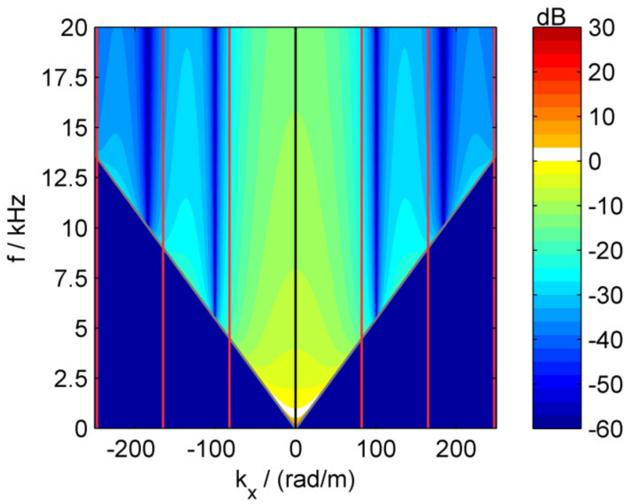
$d = \Delta x = 15"$
suitable for lowest frequencies < 500Hz

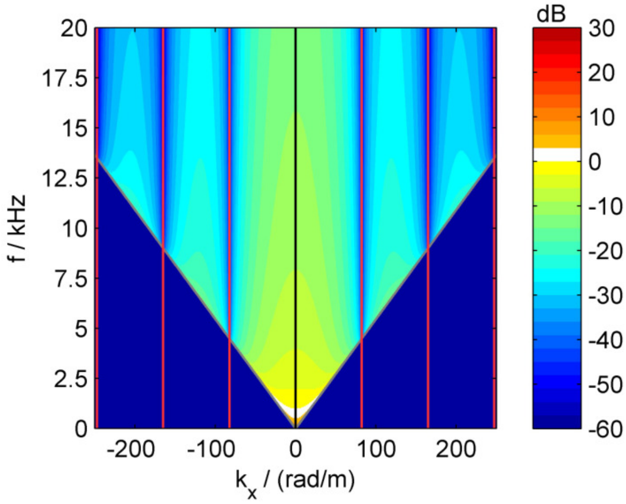
$d = \Delta x = 6.5"$
suitable for mid frequencies < 1.5kHz

speaker's diameter d

http://www.electrovoice.com/downloadfile.php?f=XLC_Brochure_FI.pdf

Circular vs. Line Piston Model





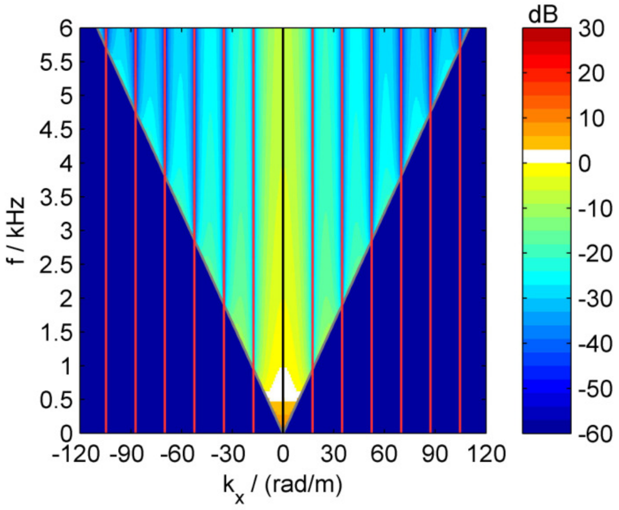
circular piston
$d = \Delta x = 3"$

$$H_{\text{Circ}}(k_x) = \frac{2\,J_1(\frac{\omega}{c}\,\sin\theta\,r_0)}{\frac{\omega}{c}\,\sin\theta\,r_0}$$

line piston (waveguide)
$L = \Delta x = 3"$

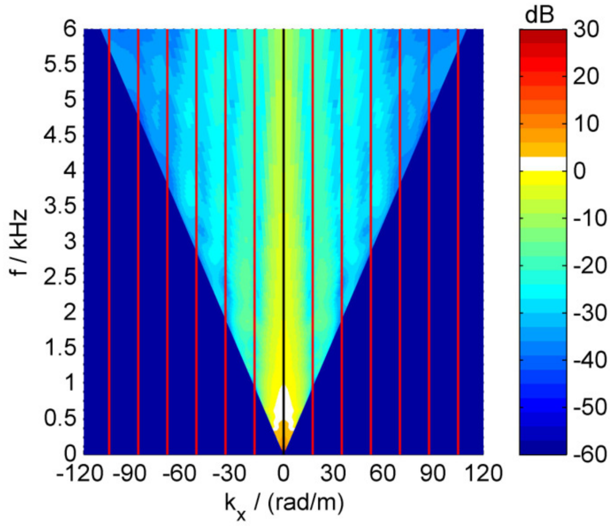
$$H_{\text{Rect}}(k_x) = \frac{\sin\left(\frac{\omega}{c}\,\sin\theta\,\frac{L}{2}\right)}{\frac{\omega}{c}\,\sin\theta\,\frac{L}{2}}$$

Waveguide Model and Measurement



ideal waveguide model

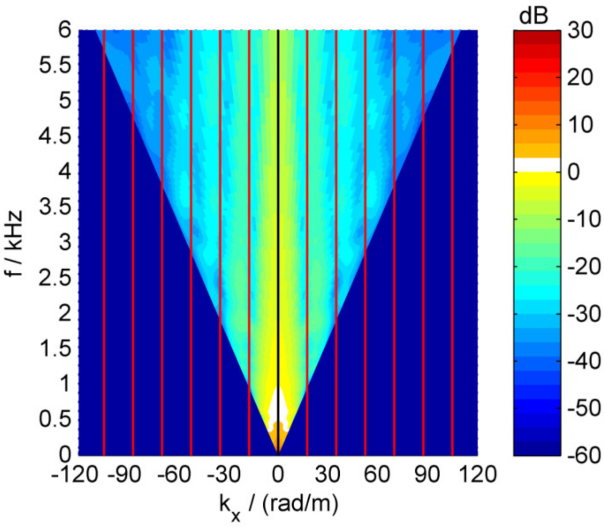
$L = \Delta x = 36$cm

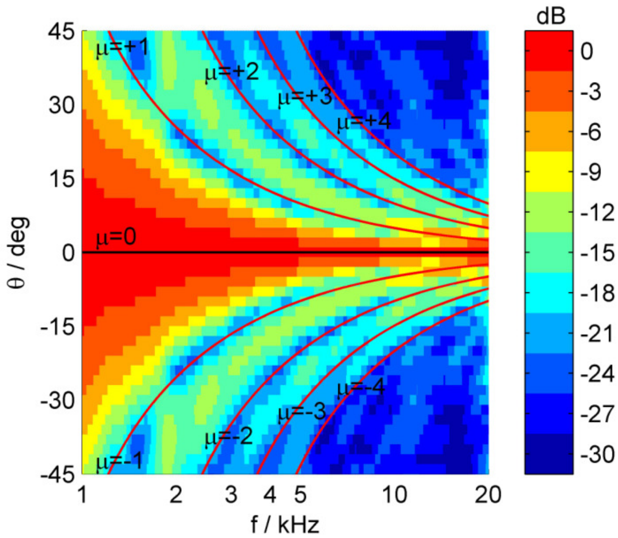


waveguide measurement

$L = \Delta x = 36$cm

Waveguide Measurement: Isobars





$$k_x = \frac{2\,\pi\,f}{c}\,\sin\theta$$

Conclusion

WST criteria I & II proved with sound field synthesis and spatial sampling theory

Loudspeakers act as a spatial lowpass filter

Spatial-aliasing-free sound field with a quasi-continuous line source array

- no gaps between waveguides
- waveguide should match ideal line piston as best as possible

$\Rightarrow$ perfect spatial lowpass filter

slides of this talk available @ `http://spatialaudio.net/`

Schultz, F.; Rettberg, T.; Spors, S. (2014): "On Spatial-Aliasing-Free Sound Field Reproduction using Infinite Line Source Arrays". In *Proc. of 136th Aud. Eng. Soc. Conv., Berlin.* #9078.