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Generation of multiple sound zones by spatial filtering in wavenumber domain using a linear array of loudspeakers

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Presentation contents

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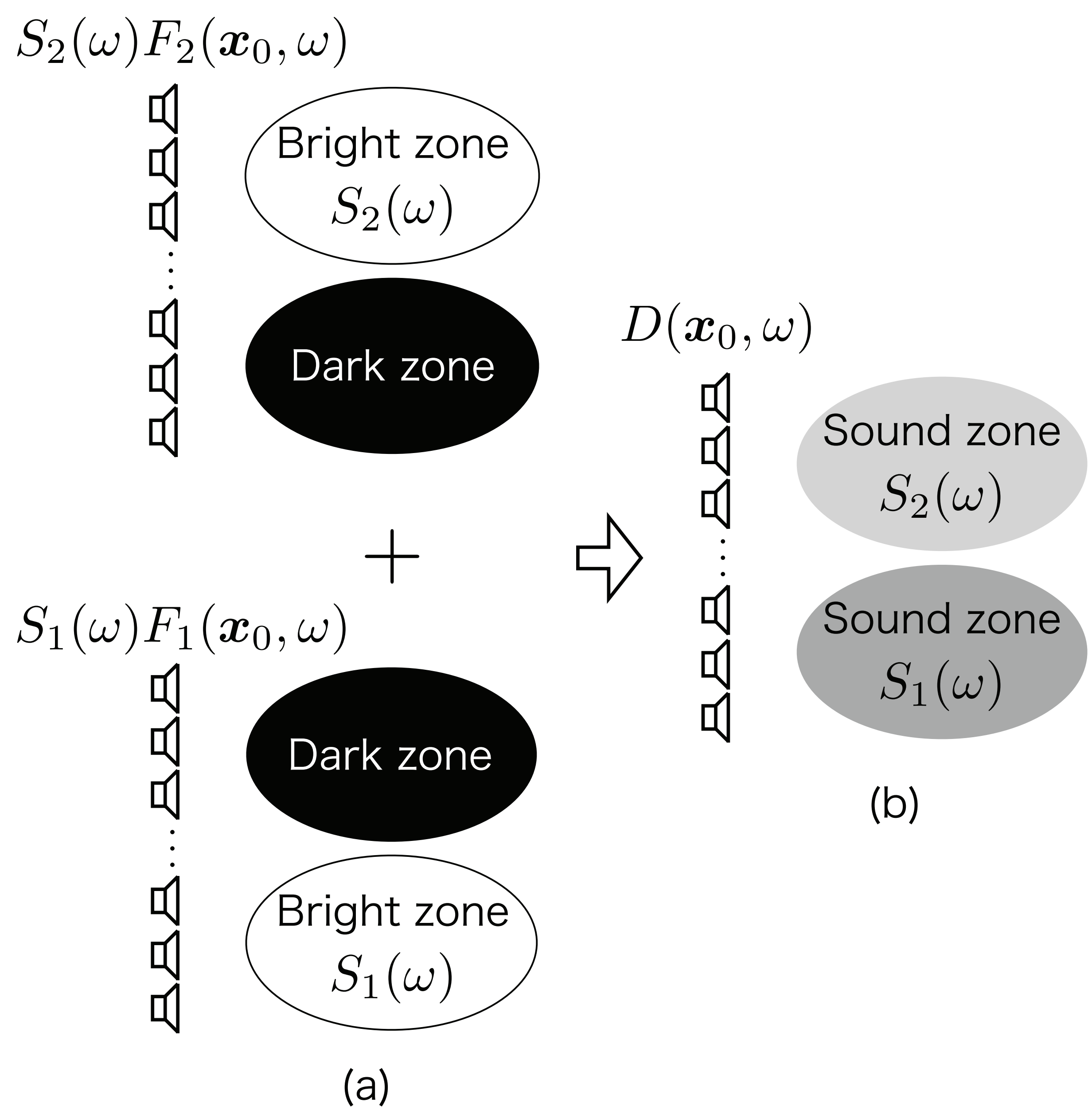
  - Acoustically bright zone or multi-zones generation using loudspeakers
- Purpose
  - Conventional methods and their problems
  - Novel approach
- Proposed method
  - Basic theory : Spectral division method (SDM)
  - Analytically-derived spatial filters in wavenumber domain
  - Computer simulations
  - Demonstrations
- Concluding remarks

Introduction

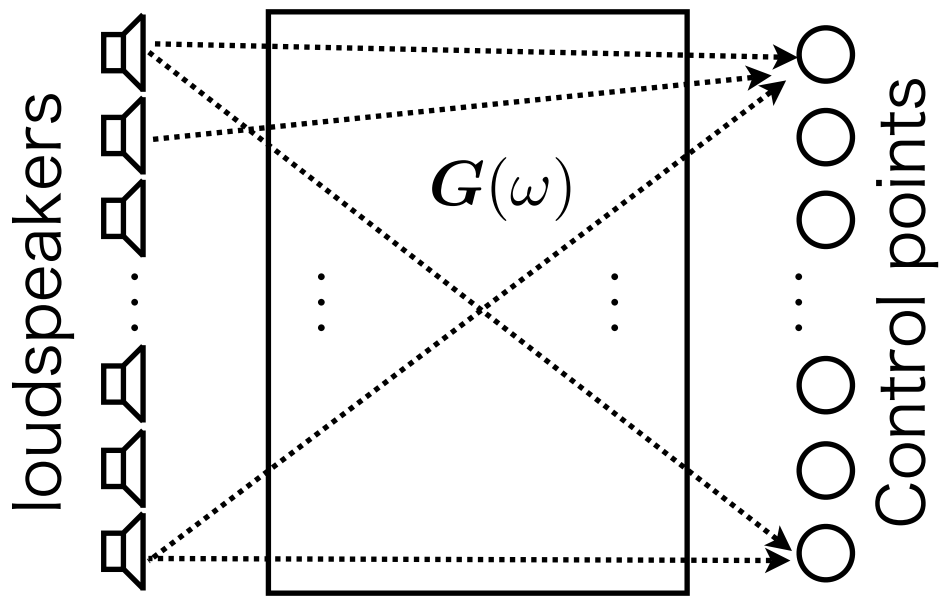
- Generation of acoustically bright and dark zones using an array of loudspeakers
  - (a) generating bright and dark zones
  - (b) multiple spots generation
  - Applications
    - Personal audio system
    - Multiple-language guide system
    - Virtual reality applications

without headphone



Previous methods and their problems

- Most methods based on multiple points control
  - Principle (e.g. J.-W. Choi *et al*. in *JASA*, 2002.)
    - Numerical calculation of the inverse of the spatial correlation matrix
  - Problems
    - Quite unstable
    - Iterative calculation for deciding regularization parameter



- Energy difference maximization (EDM)
  - Principle (M. Shin *et al*. in *JASA*, 2010.)
    - Numerical calculation of the eigenvector of the spatial correlation matrix
  - Problem
    - Iterative calculation for deciding tuning factor

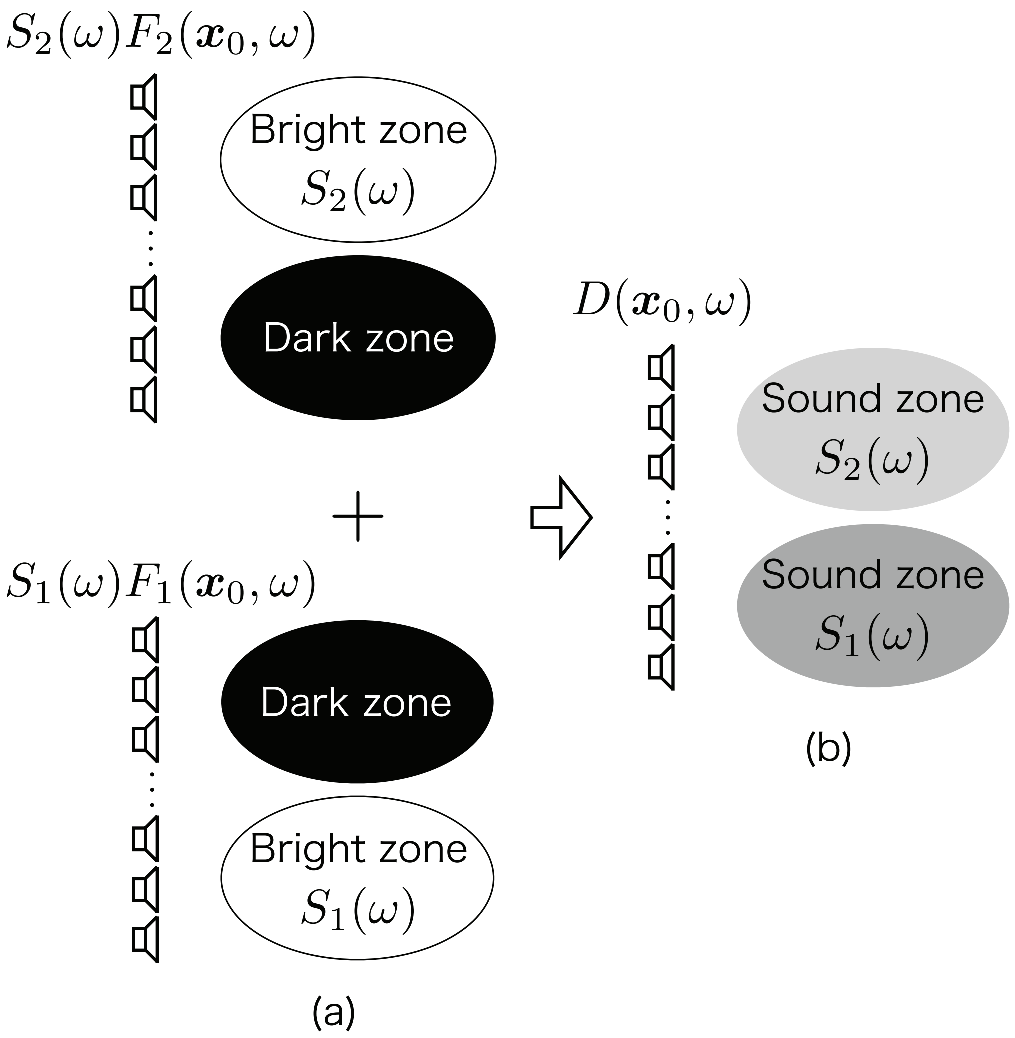
Novel approach

- Problems of conventional methods
  - Unstable
  - Iterative calculation
- 3 characteristics of proposed method
  - Analytically derived stable filters
  - No iterative calculation
  - Implemented by using actual 64 loudspeakers
- Nomenclature
  - Sound source signal : $S(\omega)$
  - Driving signals of loudspeakers
    - (a) Generating bright and dark zone

$$D(\boldsymbol{x}_0,\omega) = S_1(\omega)F_1(\boldsymbol{x}_0,\omega)$$

    - (b) Generating multiple sound zones

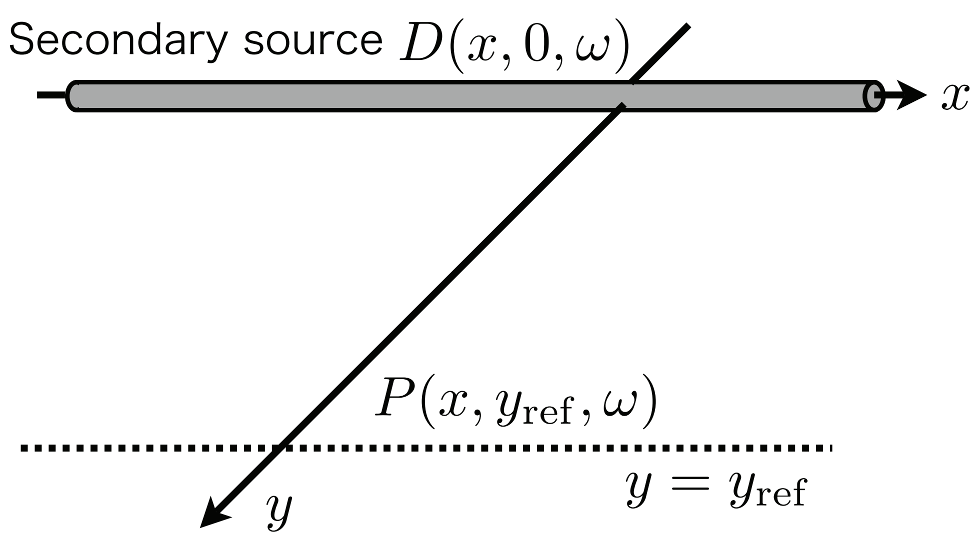
$$D(\boldsymbol{x}_0,\omega) = \sum_{i=1}^{M} S_i(\omega)F_i(\boldsymbol{x}_0,\omega)$$



How to calculate?

Basic theory

- Spectral division method (SDM) (J. Ahrens *et al*. in *IEEE ASLP*., 2010.)
  - Sound field reproduction using planer or linear arrays of loudspeakers
    - Driving signals of secondary sources are analytically derived
    - Acoustical single layer potential in a plane



$$P(\boldsymbol{x}, \omega) = \int_{-\infty}^{\infty} D(\boldsymbol{x}_0, \omega) G_{\mathrm{3D}}(\boldsymbol{x} - \boldsymbol{x}_0, \omega) d x_0$$

    - Spatial Fourier transform along with x–axis

$$\tilde{P}(k_x, y, \omega) = \tilde{D}(k_x, \omega) \cdot \tilde{G}(k_x, y, \omega)$$

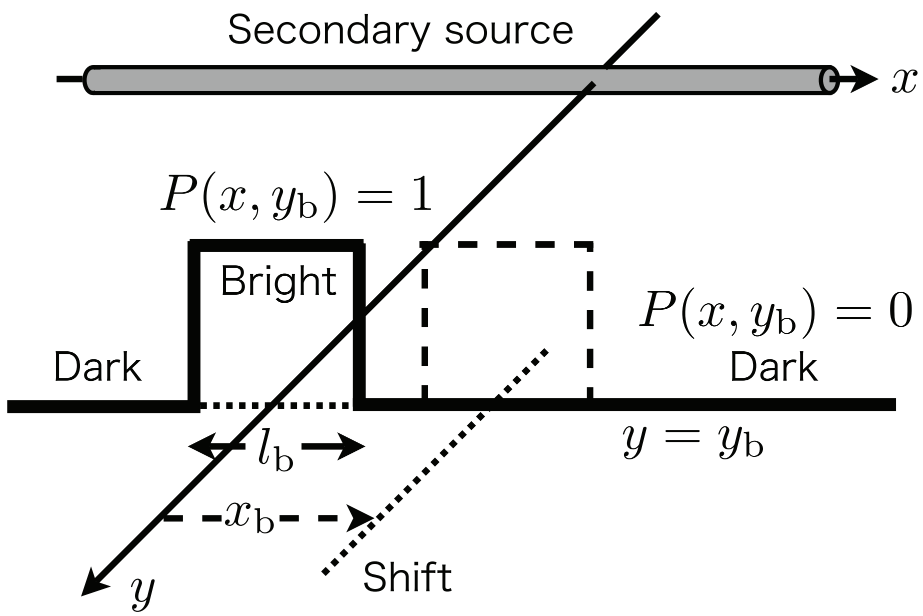
    - Driving signals of secondary sources

$$\tilde{D}(k_x, \omega) = \frac{\tilde{P}(k_x, y_{\mathrm{ref}}, \omega)}{\tilde{G}(k_x, y_{\mathrm{ref}}, \omega)} \quad \xrightarrow{\mathcal{F}_x^{-1}} \quad D(x, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{\tilde{P}(k_x, y_{\mathrm{ref}}, \omega)}{\tilde{G}(k_x, y_{\mathrm{ref}}, \omega)} e^{-j k_x x} d k_x$$

    - Driving signals in each wavenumber domain is completely orthogonal each other and much stable rather than multiple points control

Proposed method

- Analytically derived spatial filters in wavenumber domain
  - Spatial filters in wavenumber domain



$$\tilde{F}(k_x, \omega) = \frac{\tilde{P}(k_x, y_{\mathrm{ref}}, \omega)}{\tilde{G}(k_x, y_{\mathrm{ref}}, \omega)}$$

$$\left.\begin{array}{l} P(x, y_{\mathrm{ref}}, \omega) = 1 \\ P(x, y_{\mathrm{ref}}, \omega) = 0 \end{array}\right\}$$ Modeled by Rectangular window

$$P(x, y_{\mathrm{b}}) = \Pi\left(\frac{x}{l_{\mathrm{b}}}\right) = \begin{cases} 1, & \text{for } |x| \le l_{\mathrm{b}}/2 \\ 0, & \text{elsewhere} \end{cases} \quad \xrightarrow{\mathcal{F}_x} \quad \tilde{P}(k_x) = l_{\mathrm{b}} \operatorname{sinc}\left(\frac{k_x l_{\mathrm{b}}}{2\pi}\right)$$

- Shift theorem introduced to shift rectangular window along with x–axis

$$\tilde{P}_{\mathrm{shift}}(k_x) = \tilde{P}(k_x) \exp(jk_x x_b) = l_{\mathrm{b}} \operatorname{sinc}\left(\frac{k_x l_{\mathrm{b}}}{2\pi}\right) \exp(jk_x x_b)$$

- Spatial filters for generating bright and dark zones

$$\tilde{F}(k_x, \omega) = \frac{l_{\mathrm{b}} \operatorname{sinc}(k_x l_{\mathrm{b}}/2\pi) \exp(jk_x x_{\mathrm{b}})}{\tilde{G}(k_x, y_{\mathrm{b}}, \omega)}$$

Arbitrary length : l_{b}
Arbitrary position : $[x_{\mathrm{b}}, y_{\mathrm{b}}]^{\mathrm{T}}$

Computer simulations

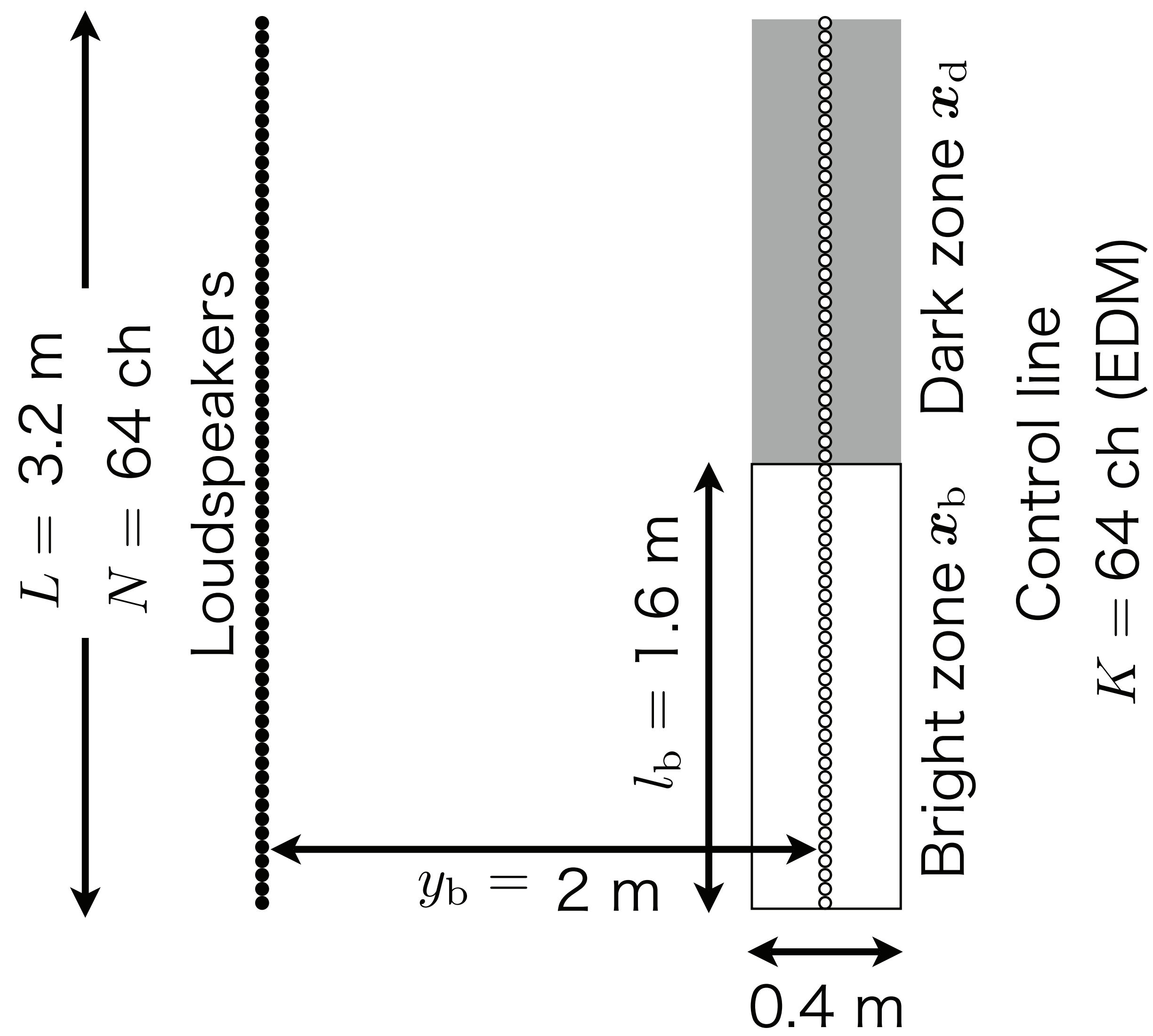
- Simulation condition
  - Speed of sound : 343.25 m/s
  - distance between adjacent loudspeakers : 0.05 m
  - Tuning factor for EDM : 0.9999

- Evaluation values
  - Sound pressure level

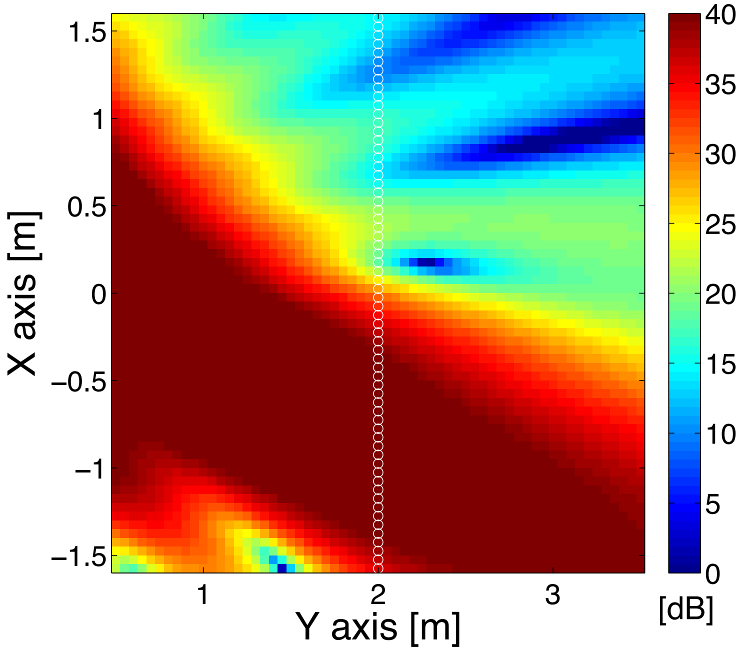
$$P_{\mathrm{SPL}}(\boldsymbol{x},\omega) = 10\log_{10}\left|\hat{P}(\boldsymbol{x},\omega)\right|^2$$

  - Bright to dark ratio

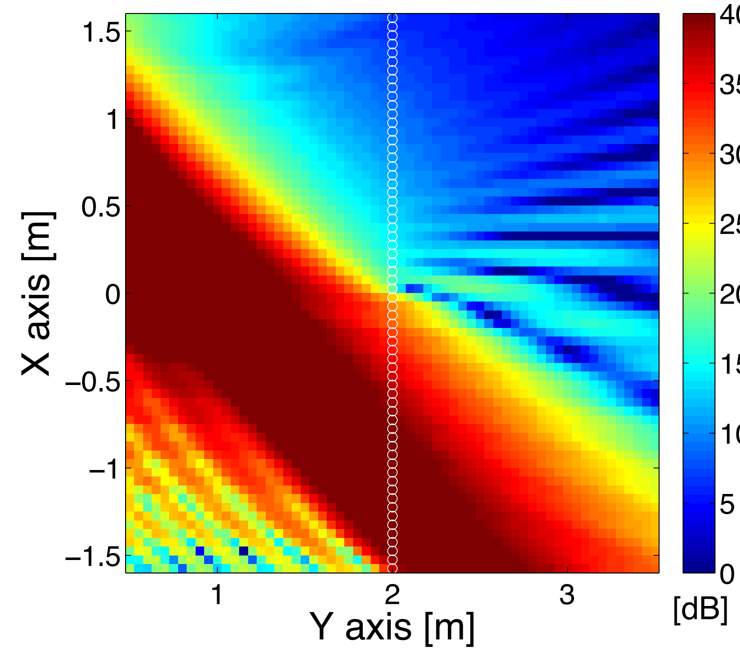
$$BDR(\omega) = 10\log_{10}\frac{\sum_{\boldsymbol{x}_\mathrm{b}}\left|\hat{P}(\boldsymbol{x}_\mathrm{b},\omega)\right|^2}{\sum_{\boldsymbol{x}_\mathrm{d}}\left|\hat{P}(\boldsymbol{x}_\mathrm{d},\omega)\right|^2}$$



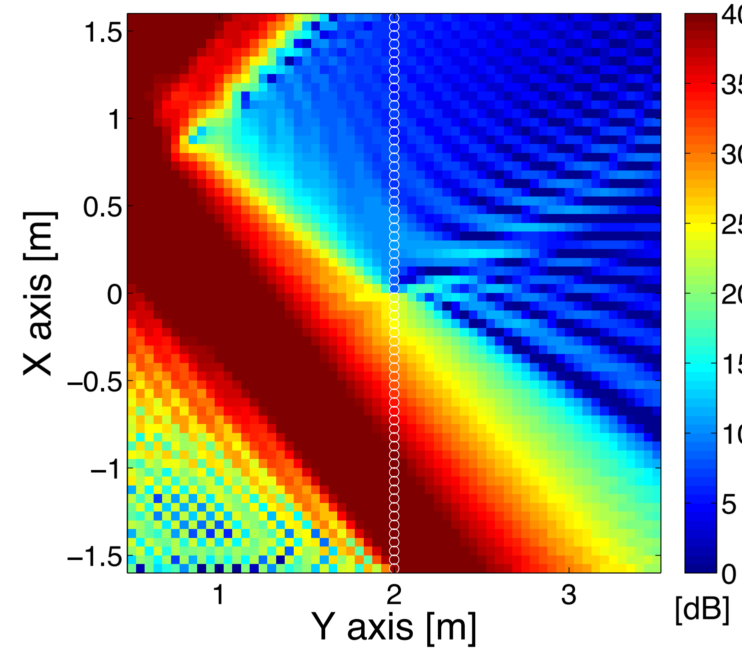
Simulation results : $P_{\mathrm{SPL}}(\boldsymbol{x})$



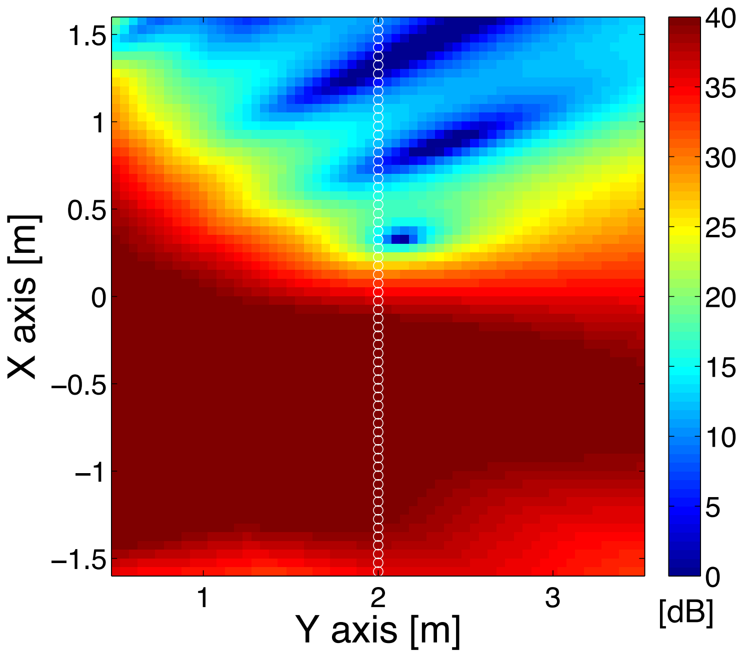
EDM (500 Hz)



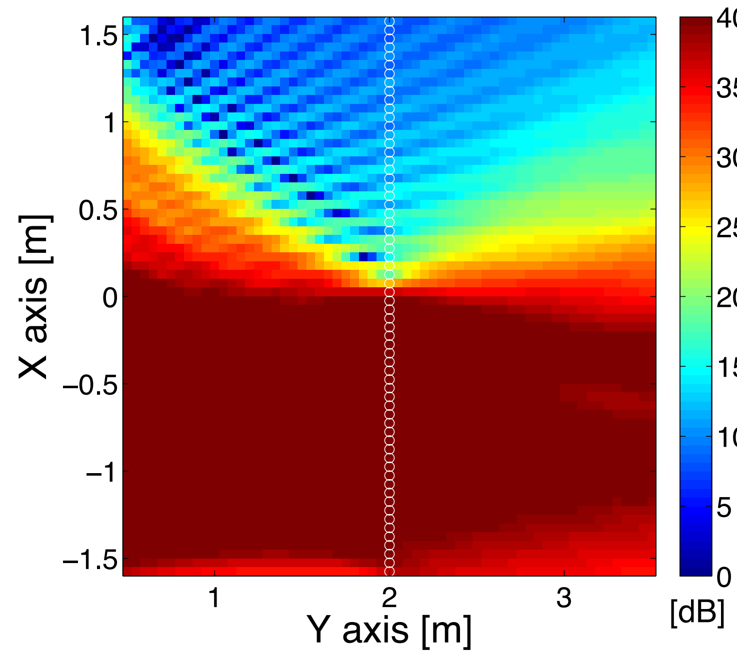
EDM (2 kHz)



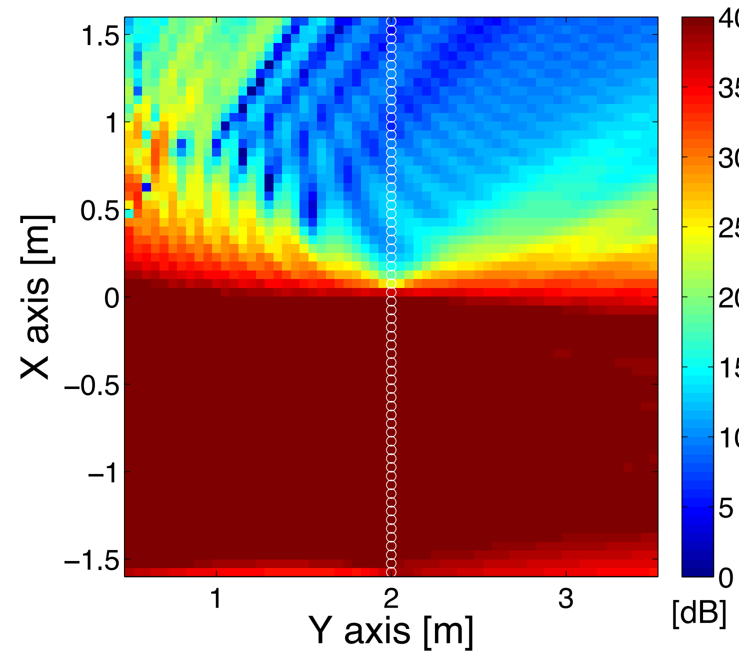
EDM (5 kHz)



Proposed (500 Hz)

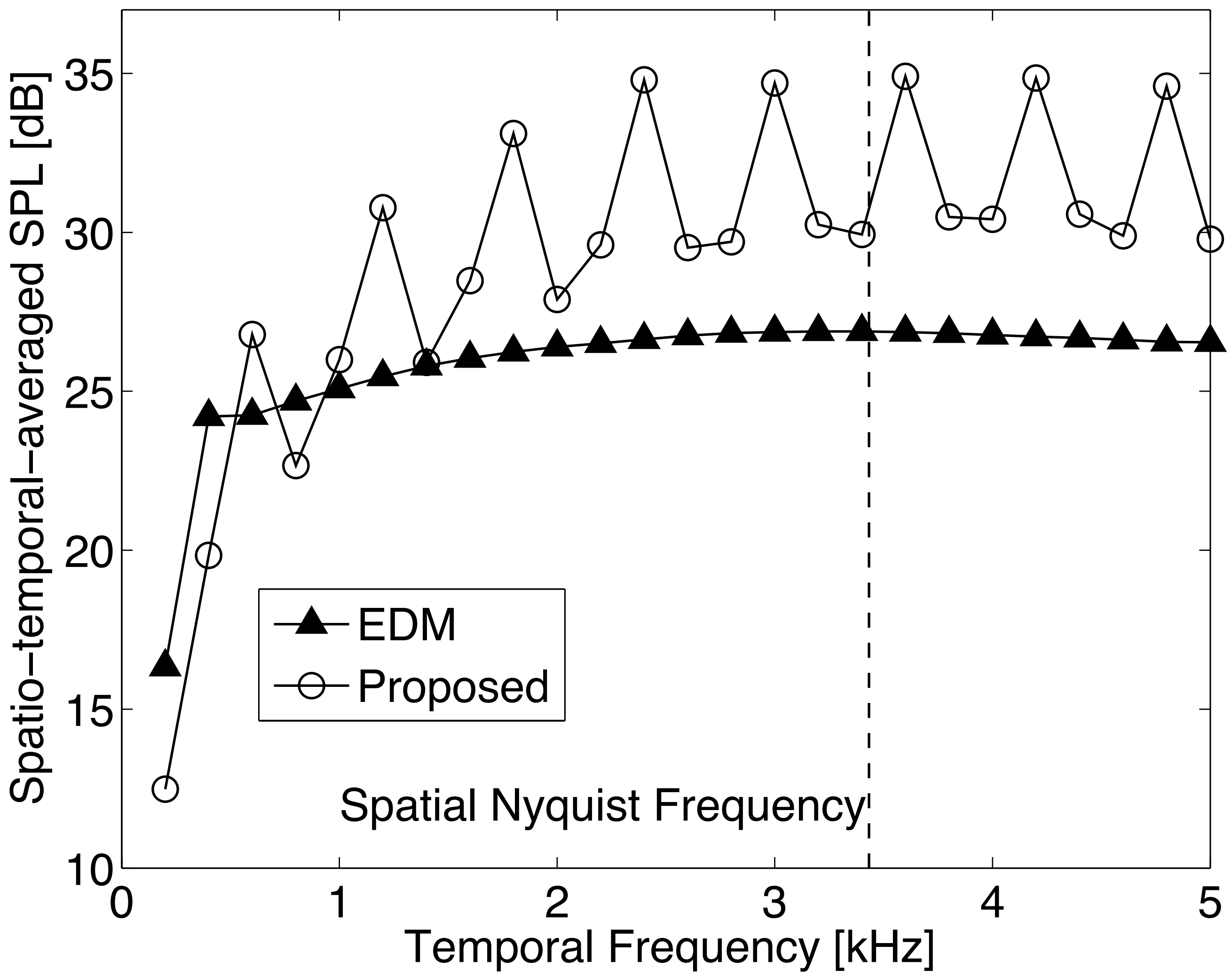


Proposed (2 kHz)



Proposed (5 kHz)

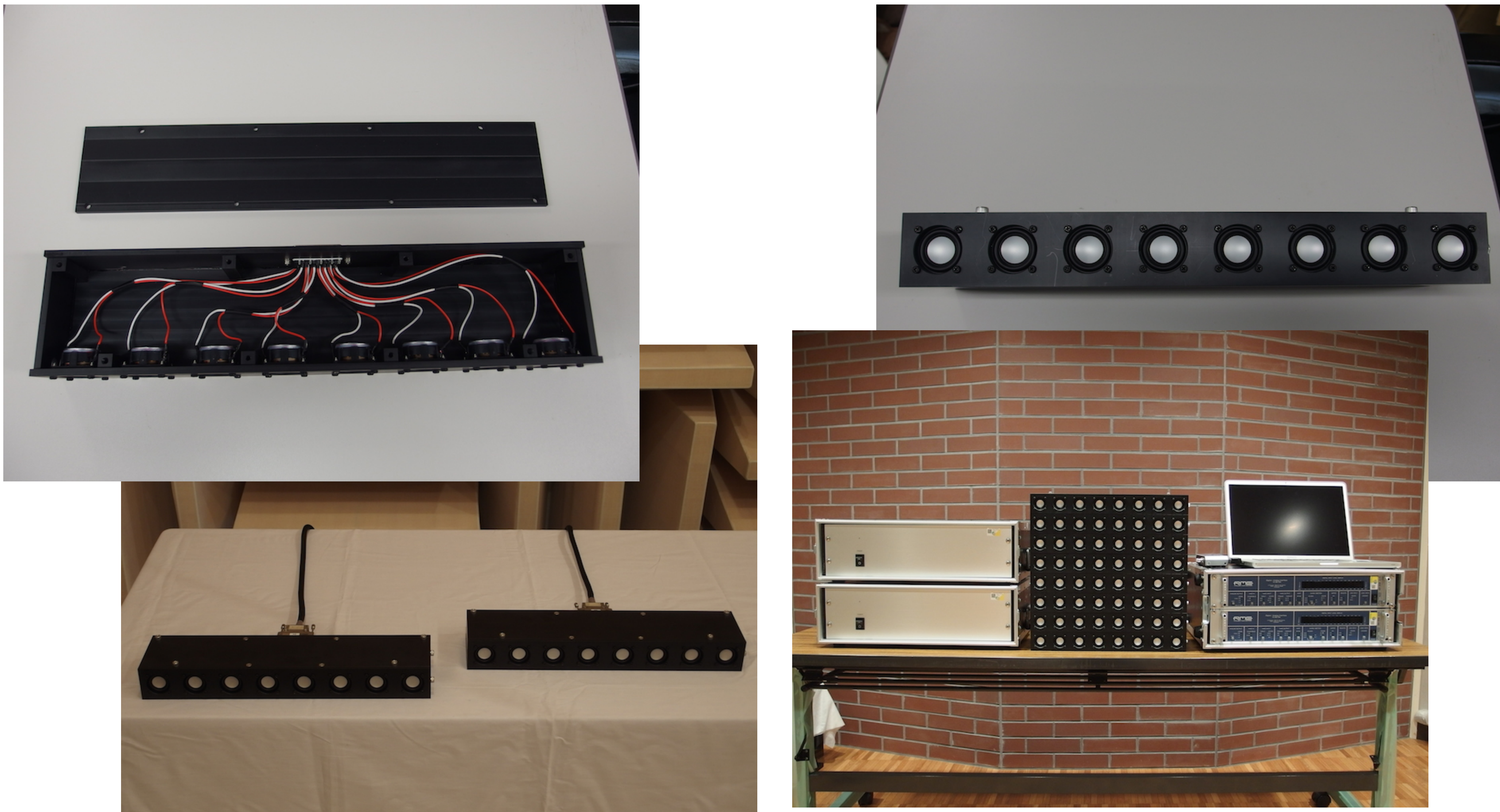
Simulation results : BDR

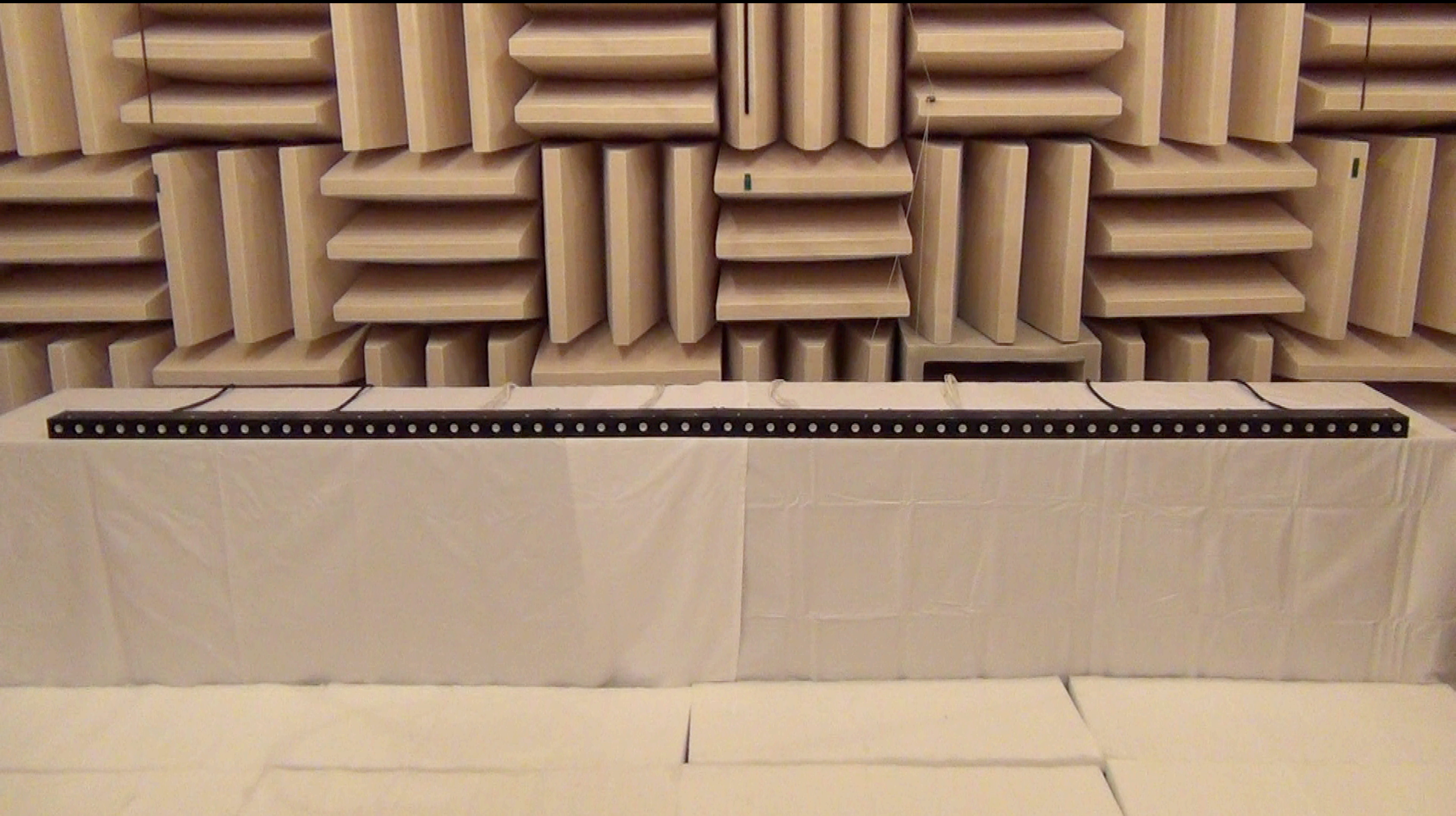


$$BDR(\omega) = 10\log_{10}\frac{\sum_{\boldsymbol{x}_{\mathrm{b}}}\left|\hat{P}(\boldsymbol{x}_{\mathrm{b}},\omega)\right|^2}{\sum_{\boldsymbol{x}_{\mathrm{d}}}\left|\hat{P}(\boldsymbol{x}_{\mathrm{d}},\omega)\right|^2}$$

DEMO 1
implemented by PureData

DEMO 2
implemented by actual linear array of loudspeakers





Concluding remarks

- Acoustically bright zone or multi-zones generation using loudspeakers
  - Analytically derived stable filters
  - No iterative calculation
  - Implemented by using an actual linear array of 64 loudspeakers

Grazie mille!!

- Acknowledgement
  - This study is partly supported by Grant-in-Aid for Young Scientists B (No. 25871208) from JSPS