Beamforming using two rigid circular loudspeaker arrays: Numerical simulations and experiments

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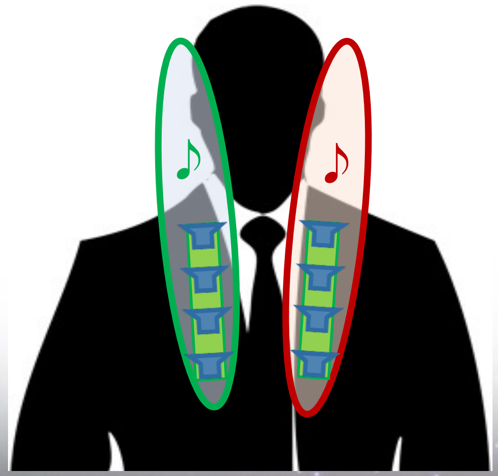
AUDIO ENGINEERING CONVENTION

Introduction

- Beamforming
  - Well studied & widely used on microphone array, antenna, and loudspeaker array.

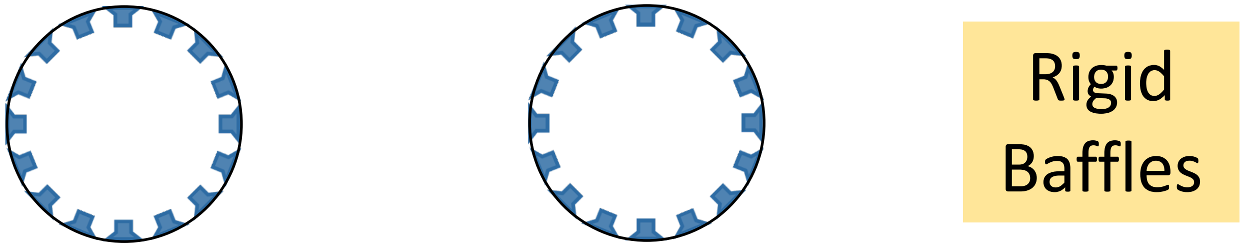
- Application with Loudspeaker Array
  - Personal Audio
  - Broadcasting

  etc.



Introduction

- Two Circular Loudspeaker Arrays (2CLA)



Our previous study:

Yi Ren and Yoichi Haneda, "Two-dimensional exterior sound field reproduction using two rigid circular loudspeaker arrays," *The Journal of the Acoustical Society of America*, 148(4), pp. 2236–2247, 2020.

  - Sound field reproduction using 2CLA
  - Investigations on array shape (radius, distance, etc.)

Introduction

This work:

Discuss the 2CLA model in beamforming **(2D field)**

- beam pattern, directivity index, beam width, and side lobe level in comparisons with CLA
- performance in different look directions
- effect on array radius and distance
- 3D field experiments in an anechoic chamber

Beamforming Method

MVDR beamformer (frequency domain)

- one constraint point at the look direction.

- regularization for suppressing maximum filter gain under 0 dB

$$\mathbf{w} = \frac{\mathbf{R}^{-1}\mathbf{C}^{\mathrm{H}}}{\mathbf{C}\mathbf{R}^{-1}\mathbf{C}^{\mathrm{H}}}\mathbf{f}$$

where $\mathbf{R} = \mathbf{G}^{\mathrm{H}}\mathbf{G} + \lambda\mathbf{I}$, λ: regularization parameter;

$\mathbf{w} \in \mathbb{C}^{L\times 1}$: filter, L: number of loudspeakers;

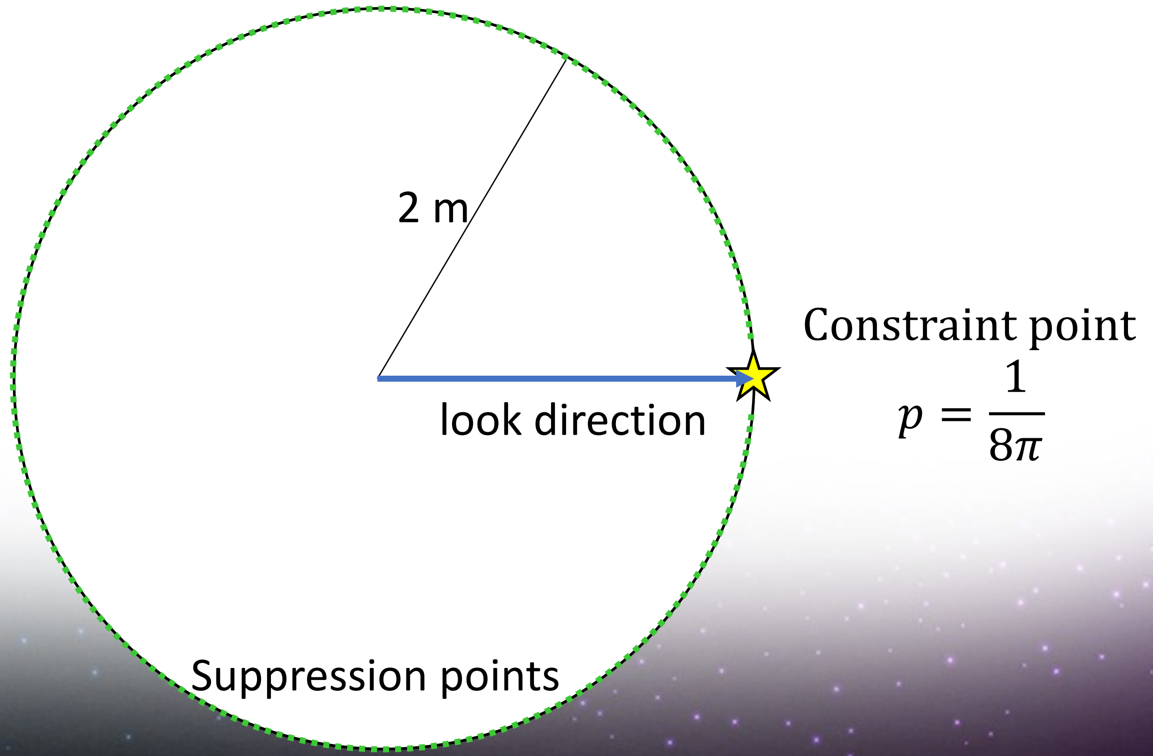
$\mathbf{C} \in \mathbb{C}^{M_{\mathrm{C}}\times L}$: transfer functions of constraint points, $\mathbf{f} \in \mathbb{C}^{M_{\mathrm{c}}\times 1}$: constraint value of constraint points, M_{s}: number of constraint point;

$\mathbf{G} \in \mathbb{C}^{M_{\mathrm{s}}\times L}$: transfer functions of suppression points, M_{c}: number of suppression point;

• The constraint point and suppression points were on a circle with radius of 2 m.
• Number of suppression points: $M_s = 143$
• Constraint value: $\mathbf{f} = 1/(4\pi\times 2)$ distance attenuation

Filter Design

- The constraint point and suppression points were on a circle with radius of 2 m.
- Number of suppression points: $M_{\mathrm{s}} = 143$
- Constraint value: $\mathbf{f} = 1/(4\pi\times 2)$ distance attenuation

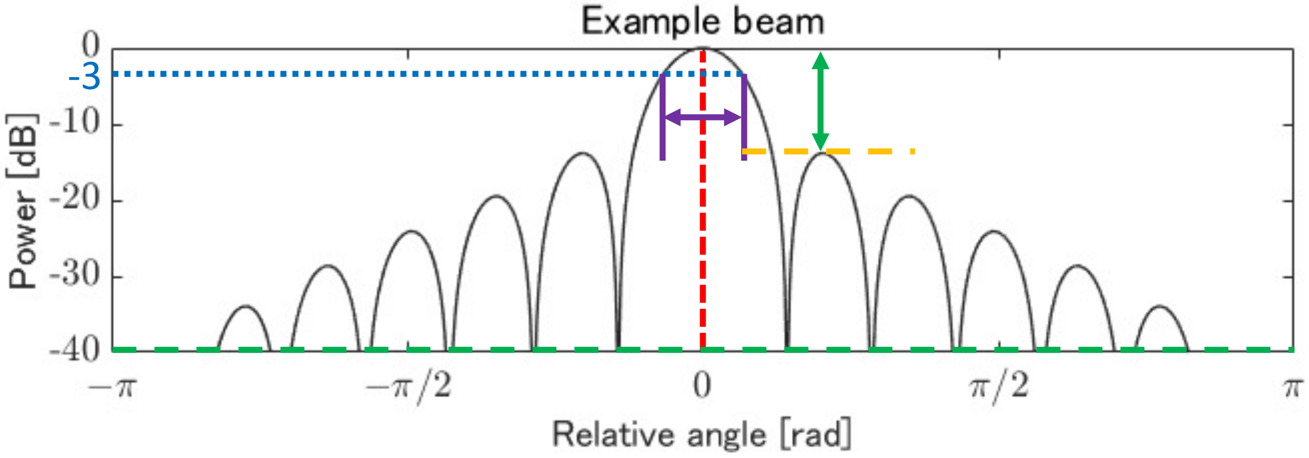


Performance

- Directivity Patterns
  - Normalized to maximum of 0 dB
- Directivity Index (DI)

$$\mathrm{DI}(\omega)\ [\mathrm{dB}] = 10\log_{10}\frac{2\pi\left\|P_{\varphi}(\omega)\right\|^2}{\int_0^{2\pi}\left\|P_{\phi}(\omega)\right\|^2 d\phi}$$

  - The power of the look direction
- Beam Width (BW)
  - Half power (-3 dB) beam width of the main lobe
  - The narrowness of the main beam
- Side Lobe Level (SLL)
  - The maximum level of the side lobe
  - Relative to the main lobe

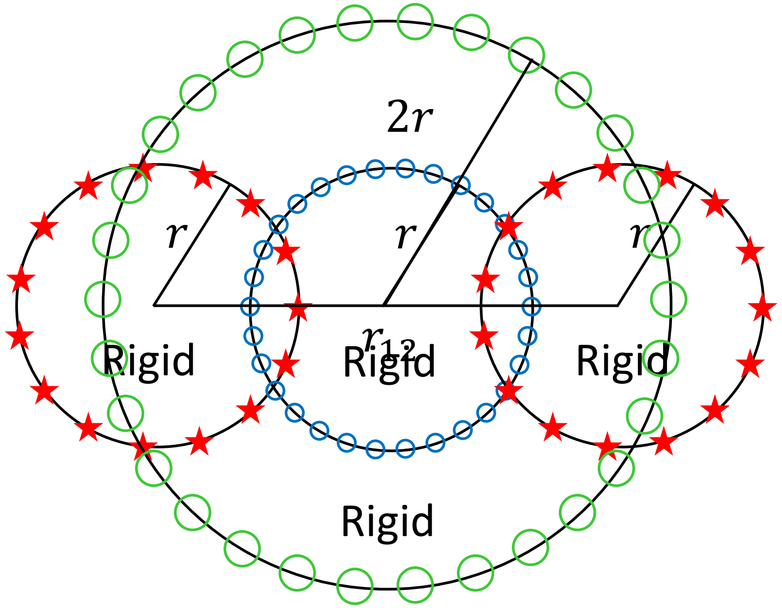


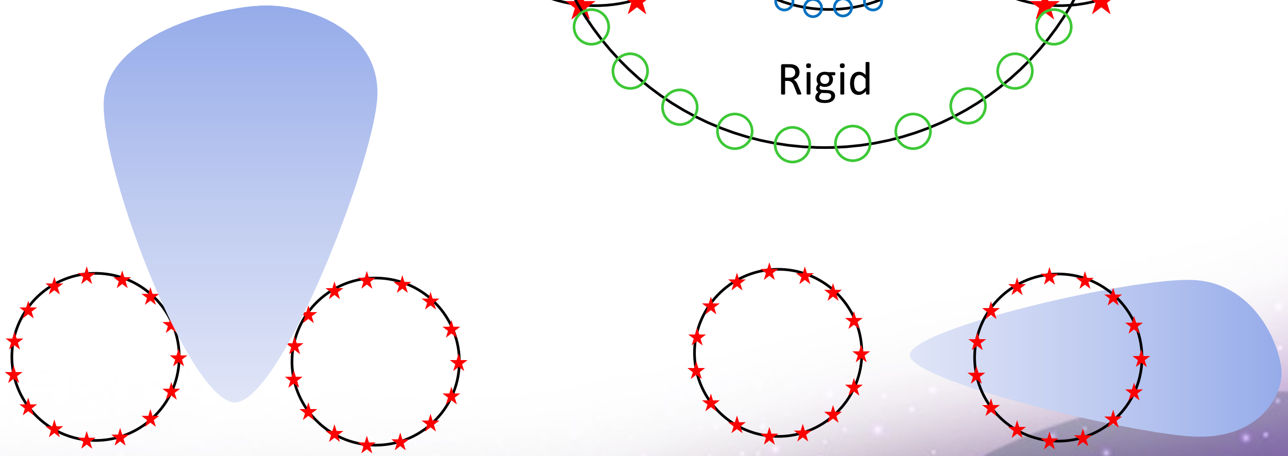
I. Comparison with CLA

- Numerical simulations comparing 2CLA to CLA
- Number of loudspeakers: $L = 30$
- 2CLA ★
  - Radii: $r_{0,1} = r_{0,2} = r = 0.15$ m
  - Distance between centers: $r_{12} = 0.5$ m
- CLA

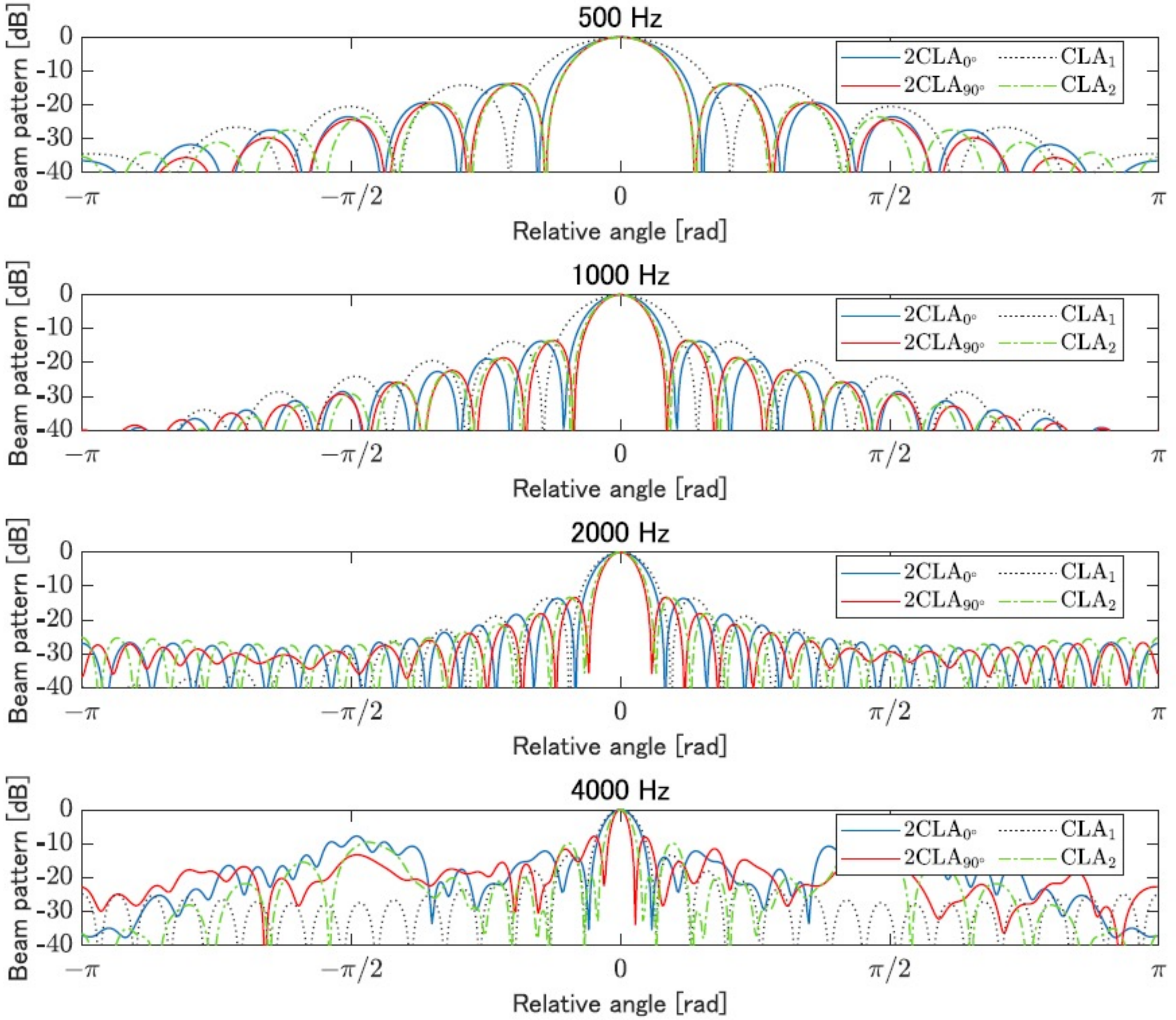
  CLA_1 ○
  - Radius: $r_0 = r = 0.15$ m

  CLA_2 ○
  - Radius: $r_0 = 2r = 0.3$ m
  - Same loudspeaker distance as 2CLA





$2CLA_{90°}$ (Look direction $\varphi = 90°$) $2CLA_{0°}$ (Look direction $\varphi = 0°$)

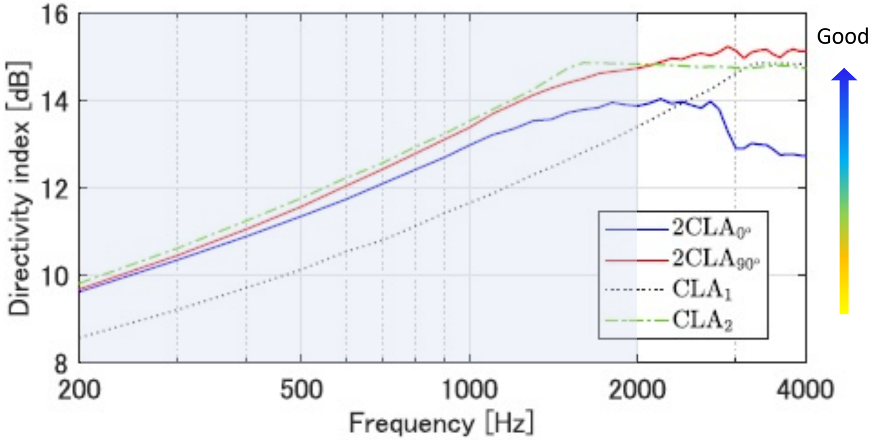


Directivity Pattern

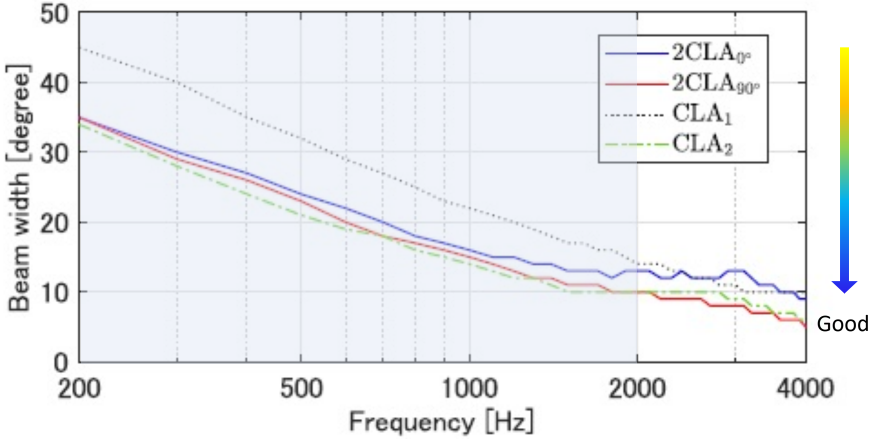
500, 1000, 2000 Hz:
Performance
$2CLA \approx CLA_2 > CLA_1$

4000 Hz:
Aliasing on
2CLA and CLA_2

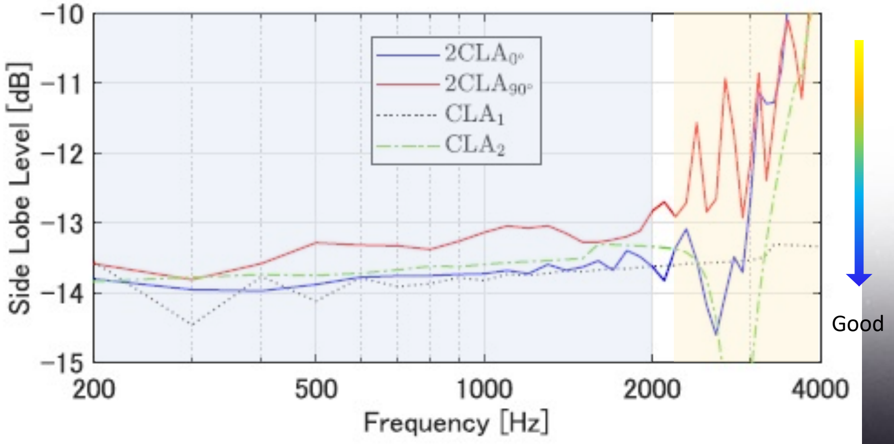
DI



BW



SLL



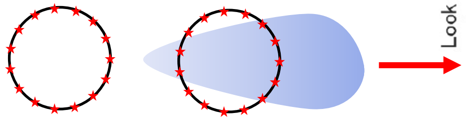
Below 2000 Hz:
2CLA outperforms CLA_1
on DI and BW,
no obvious difference on SLL

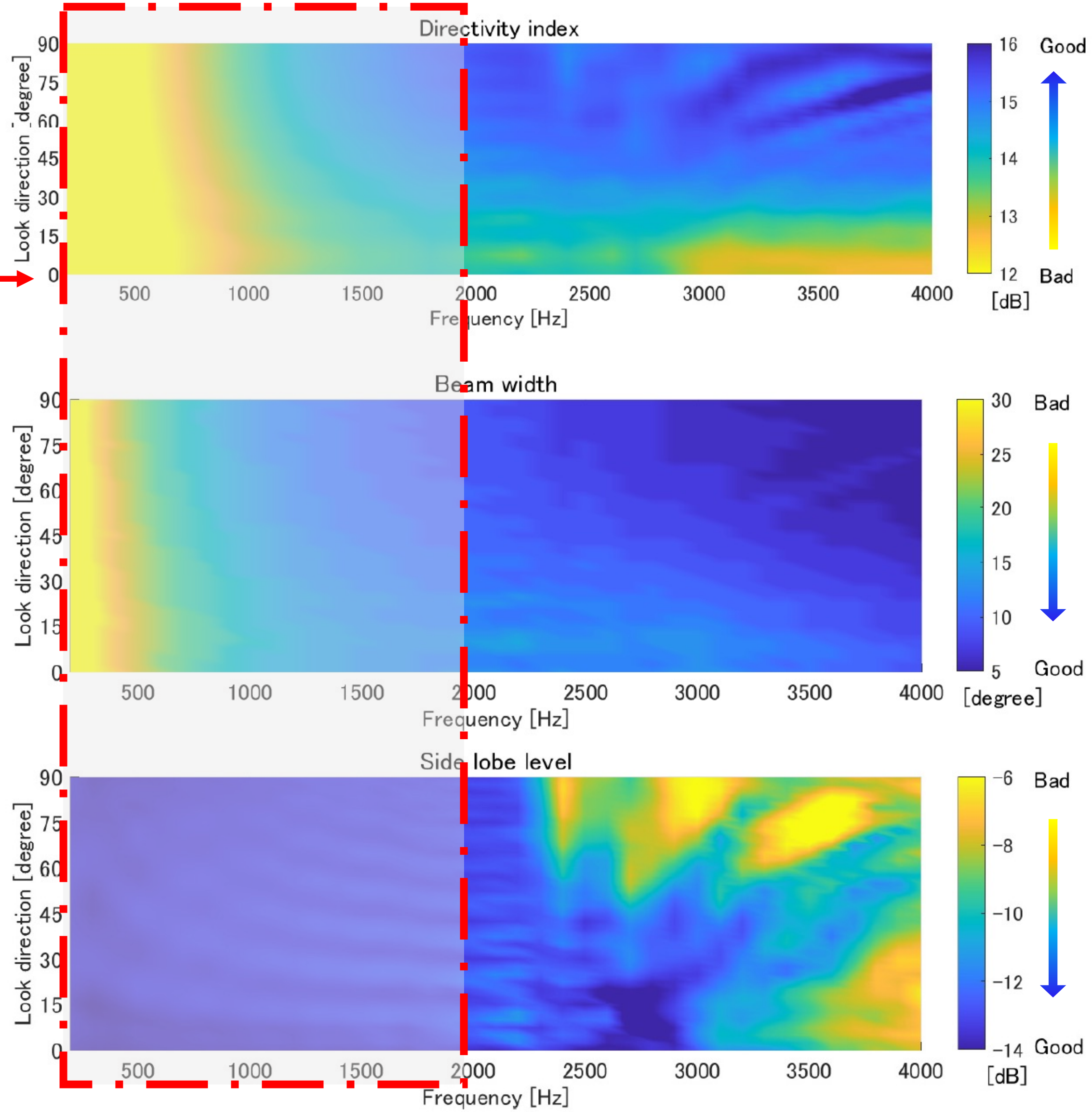
Above 2000 Hz:
2CLA and CLA_2 get high SLL
(because of aliasing)

II. Direction dependence

- Look direction φ
  - From 0° to 90°

Same 2CLA model



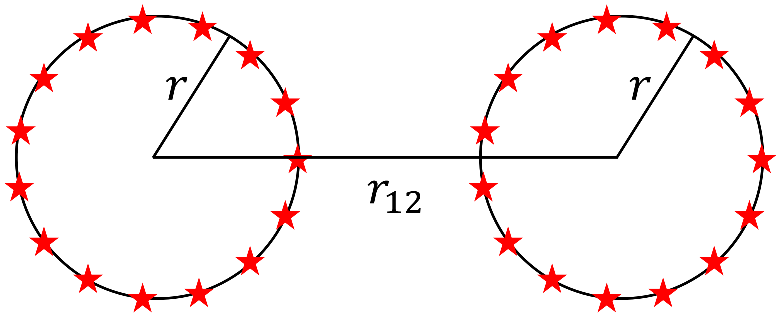


Below 2000 Hz:
little direction dependence

Above 2400 Hz:
Look direction $\varphi \rightarrow 90°$
Narrower beam with high SLL

III. Radius and distance factor

- Two factors of 2CLA:
  - radius r
  - distance r_{12}



In our previous study:

Yi Ren and Yoichi Haneda, "How the distance and radius of two circular loudspeaker arrays affect sound field reproduction and directivity controls," in *Proc. 23rd International Congress on Acoustics*, 2019.

The performance of 2CLA is highly related to the two factors.

Here, we made a more detailed investigation:

$r \in \{0.05, 0.1, 0.15, \ldots, 0.95\}, r_{12} \in \{r + 0.05, r + 0.1, \ldots, 1\}$

Frequency @1000 Hz

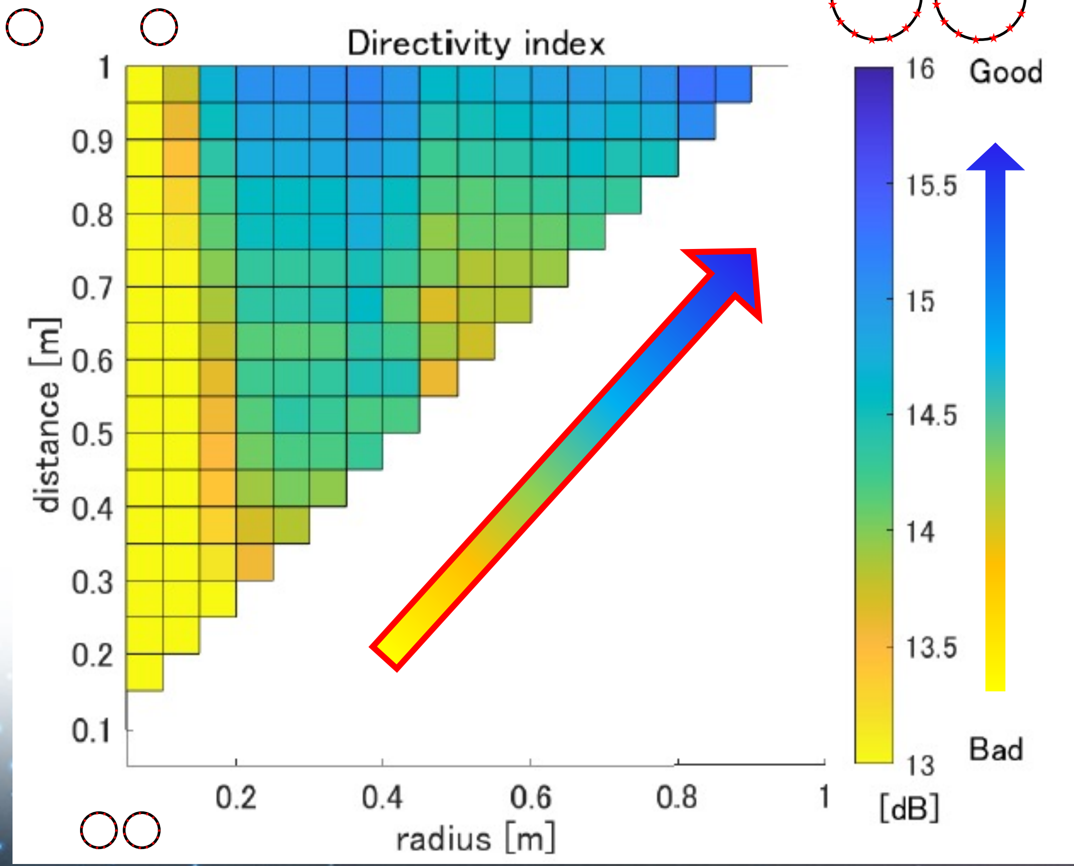
DI

small radius
short distance

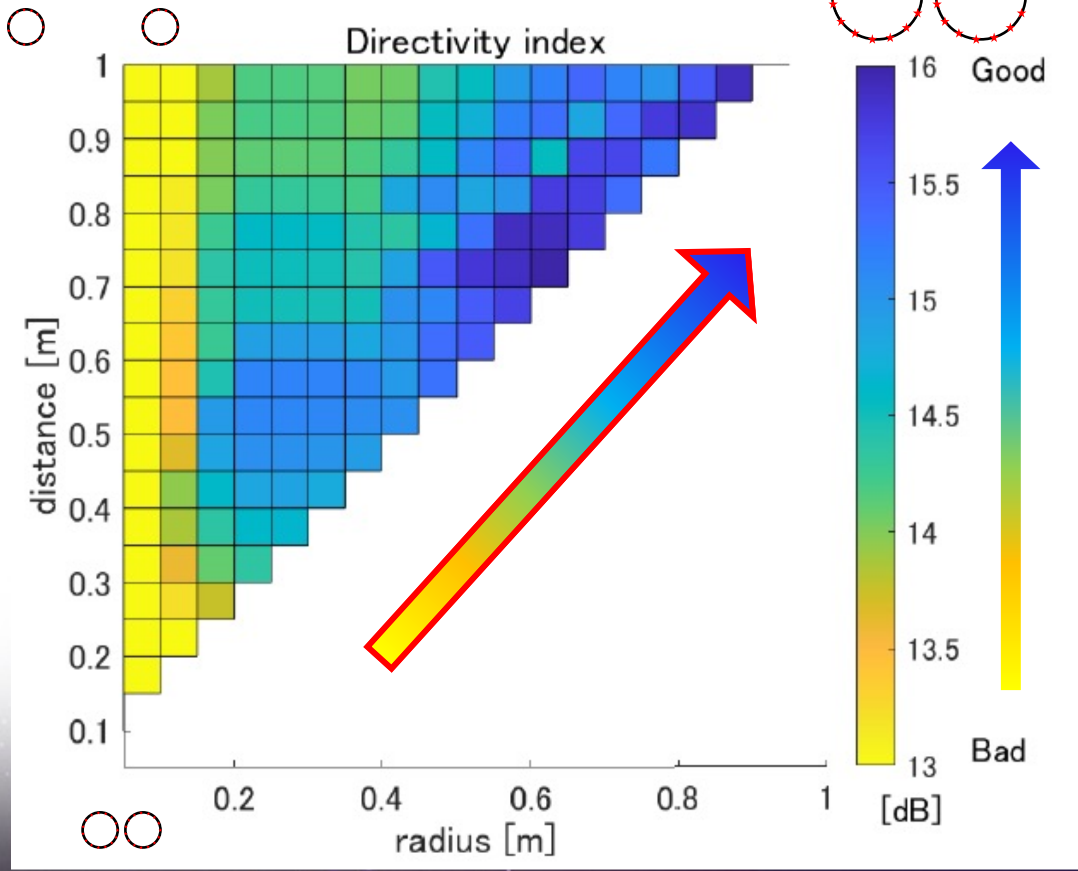
small radius
long distance

large radius
long distance

Look direction $\varphi = 0°$



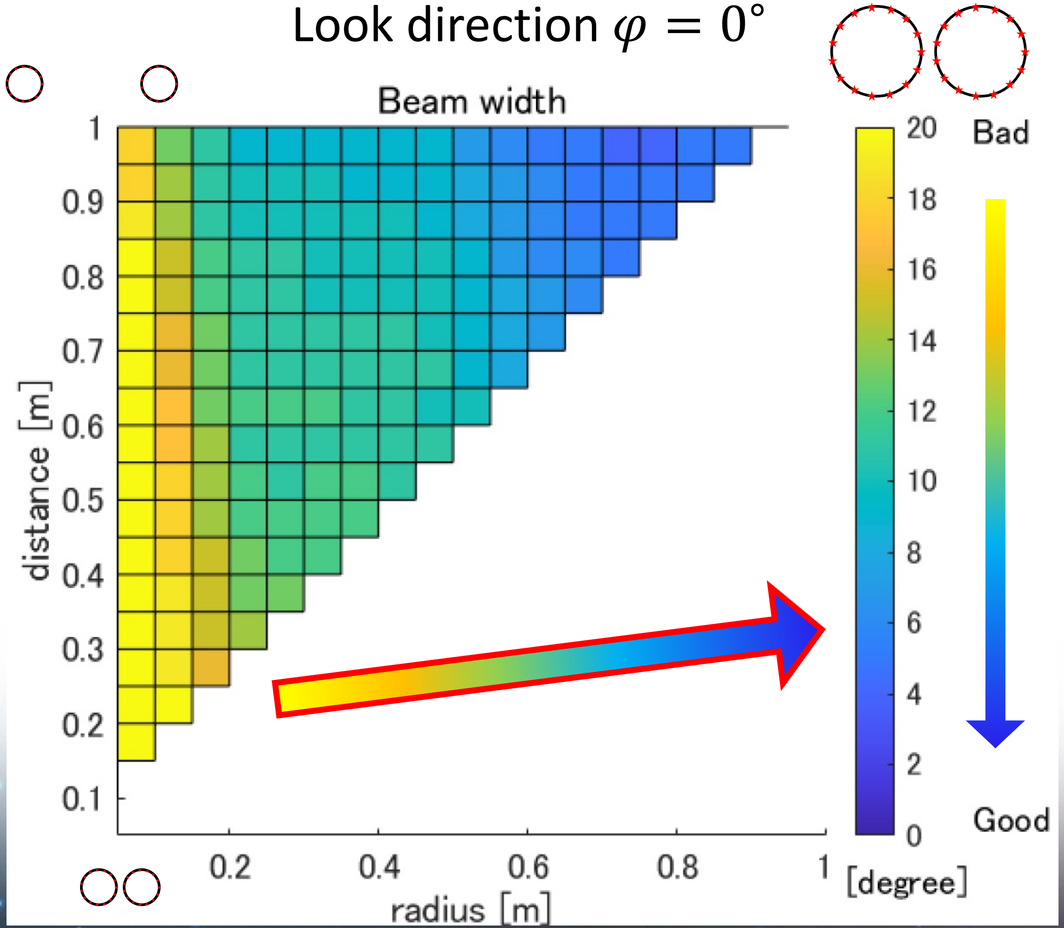
Look direction $\varphi = 90°$



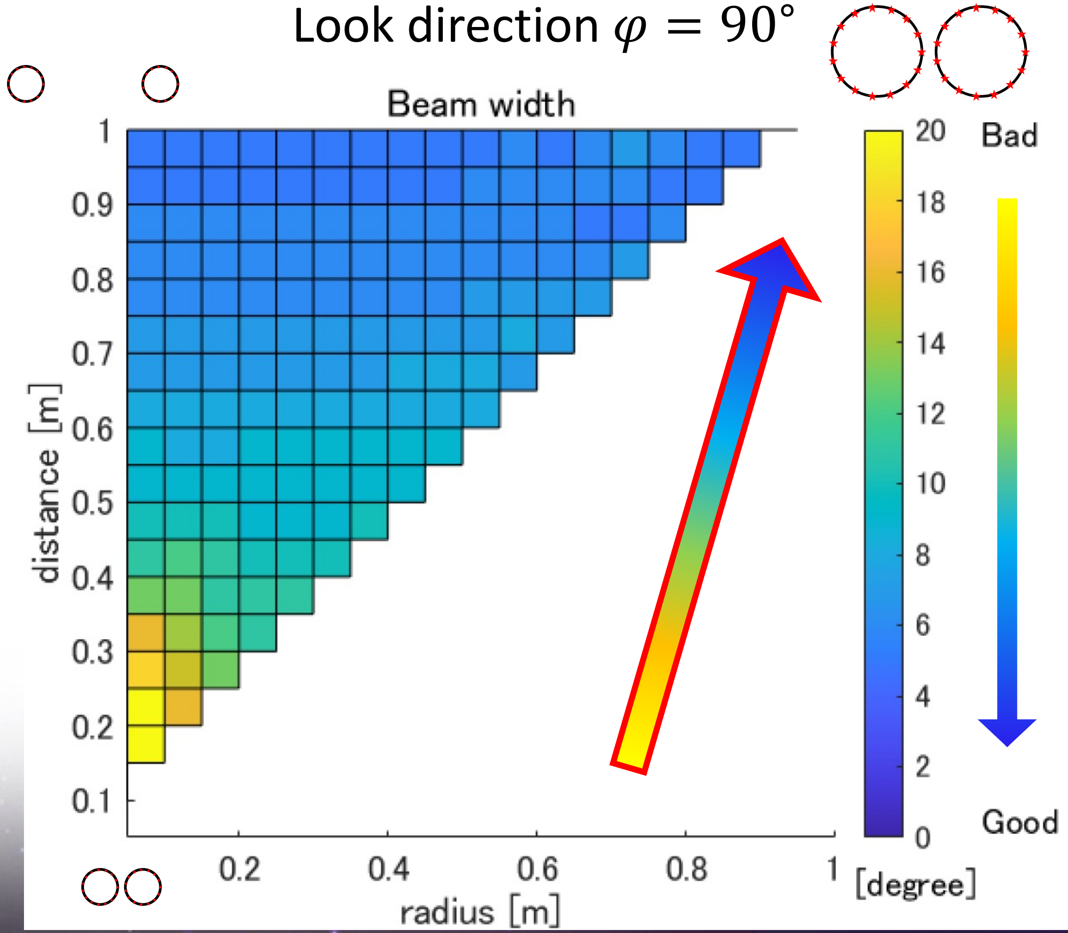
BW

For DI and BW:
larger radius and distance make a better performance
AGREES WITH PREVIOUS STUDY

Look direction $\varphi = 0^\circ$

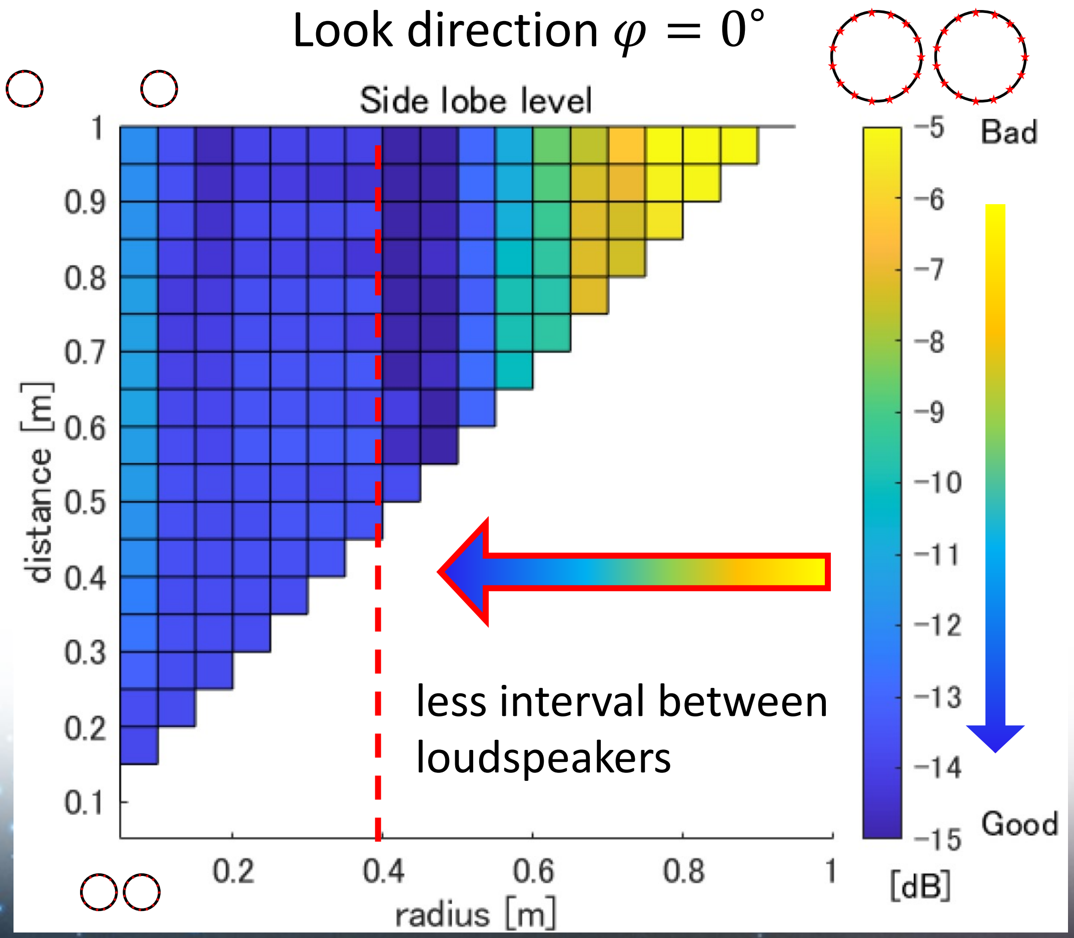


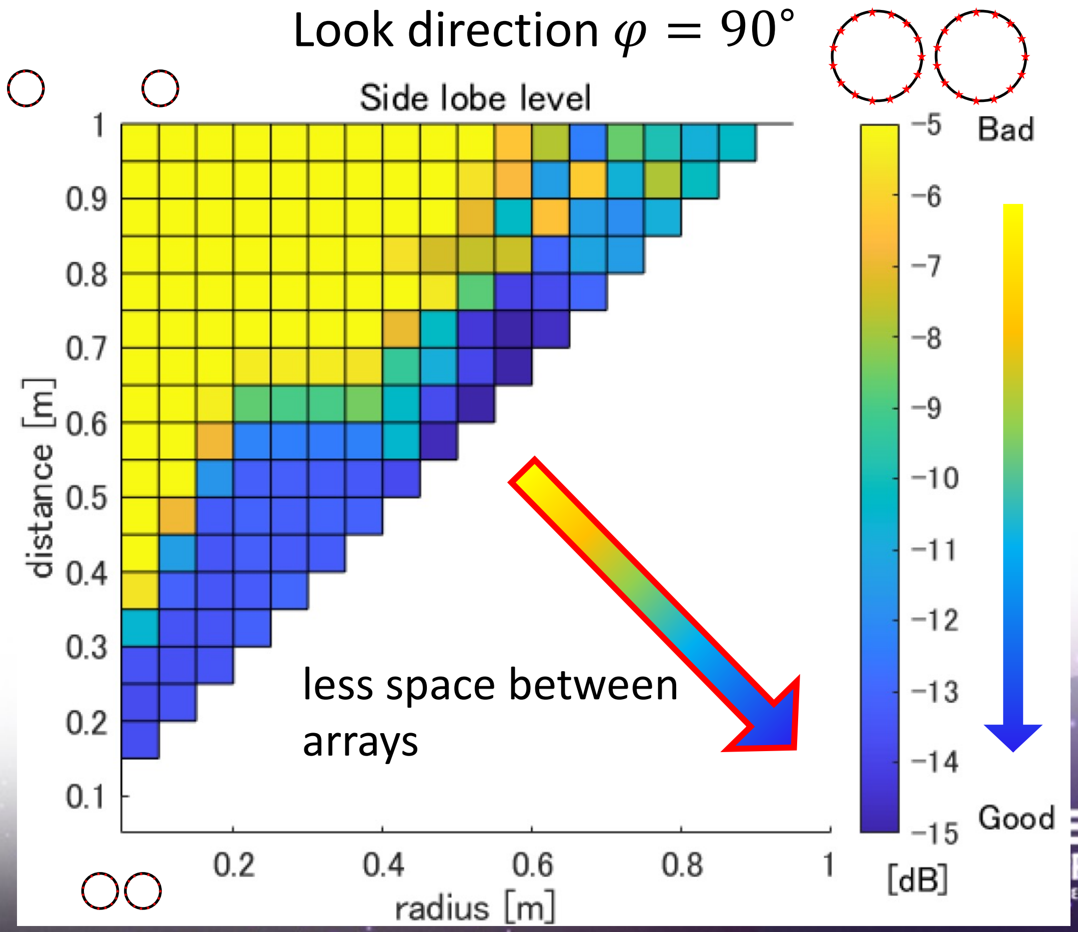
Look direction $\varphi = 90^\circ$



SLL

$\varphi = 0°$: large radius causes high SLL (aliasing)
$\varphi = 90°$: large inter-array space causes high SLL





IV. Experiment in 3D field

Two $r = 0.15$ m cylindrical loudspeaker arrays, height 0.576 m

Number of loudspeaker: 15×2

Distance $r_{12} = 0.5$ m

Anechoic chamber

- 48 microphones on an 120° curve

with a radius of 1.5 m

- Rotated and measured three times

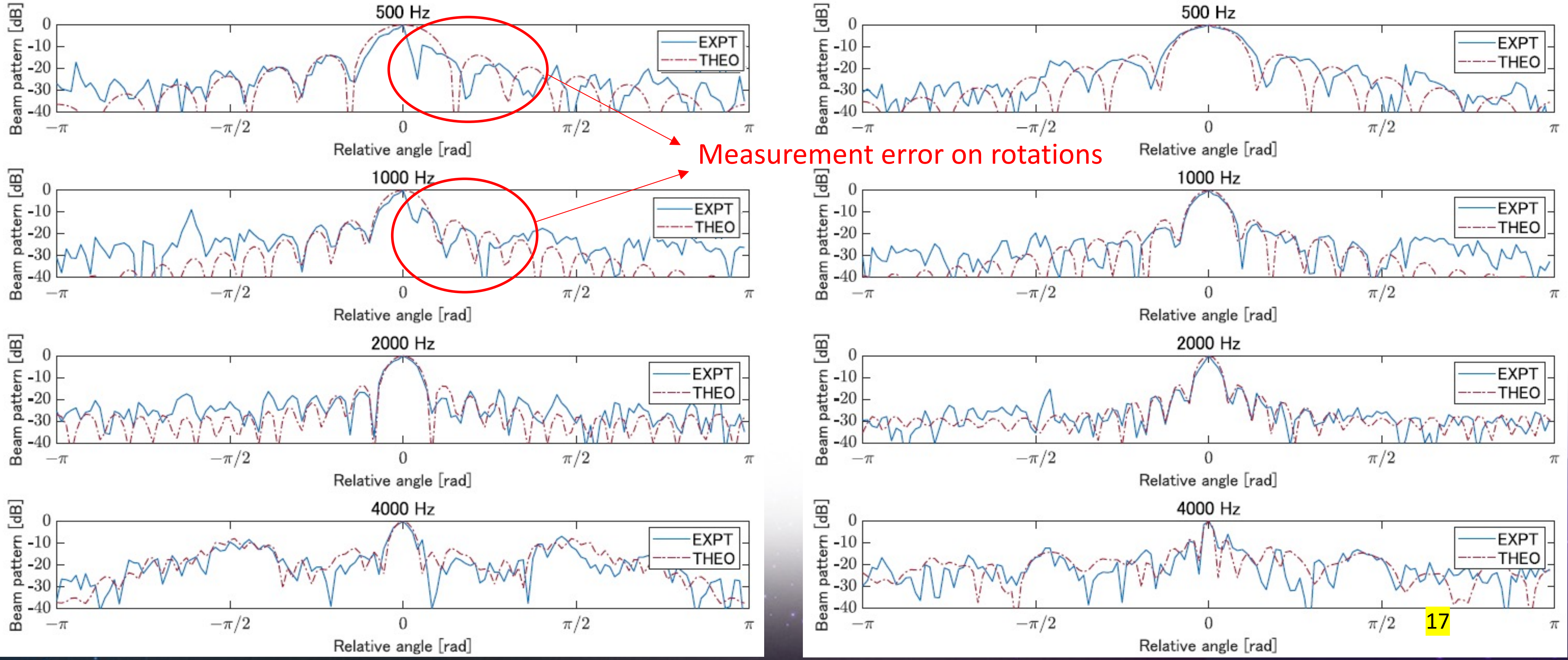
→ a full circle

- Calibrated and normalized

Experimental results (EXPT) ≈ theoretical results (THEO)

- Proposed method works for cylindrical arrays in 3D fields.

Look direction $\varphi = 0°$ | Look direction $\varphi = 90°$



Conclusion

- A detailed investigation on MVDR beamforming using a 2CLA model
- Numerical simulation results:
  - 2CLA outperform a same-sized CLA at low frequencies but with a higher risk of aliasing.
  - No obvious look-direction dependence at low frequencies.
  - A large radius factor can lead to aliasing.
- Experiment results:
  - Proposed method can be implemented in 3D sound fields.

Thanks for listening!