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Focused source reproduction using rigid elliptical loudspeaker array

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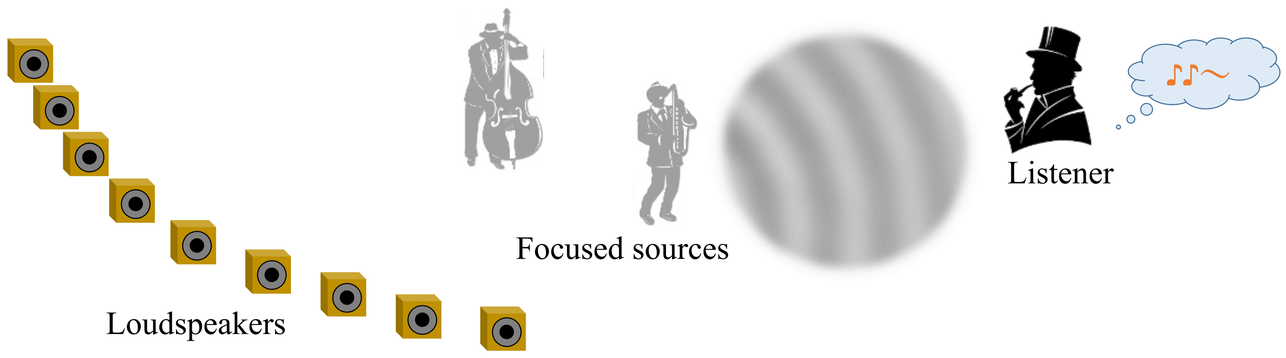
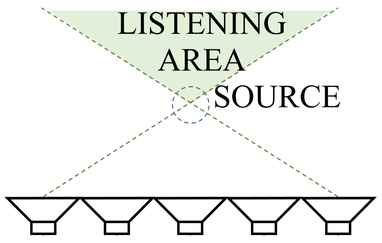
1. Background

- **Focused (Virtual) source reproduction**
  - To reproduce radiating sources in front of loudspeakers.
  - Possible applications:
    - reproduction of voice/musical instruments
    - entertainment/true 3D audio

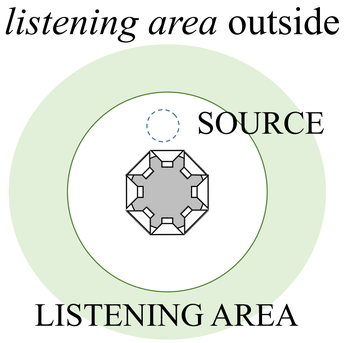


2. Conventional Studies

Linear loudspeaker array (LLA)
- Wave Field Synthesis (WFS), etc.
- Well-studied
- *Limited listening area* (triangular)



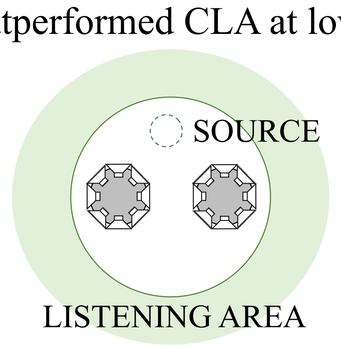
Circular loudspeaker array (CLA)
- Exterior sound field reproduction
- *Unlimited listening area* outside a circular boundary



single scatter
symmetry

Multiple circular loudspeaker array (MCLA)
- Using an *addition theorem.* (Ren+, 2020)
- 2CLA outperformed CLA at low frequencies

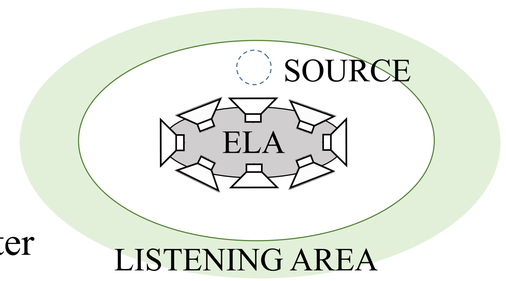
multiple scatter
asymmetry



A further investigation on asymmetric array

3. Elliptical Loudspeaker Array (ELA)

Configuration:
- Rigid array (infinite-length elliptical cylinder)
- Exterior sound field reproduction
- Elliptical boundary



single scatter
asymmetry

Method

Mathieu function* expansion (MFE) based method
- "Ambisonics/mode-matching method for ELA"
- Discussed for interior sound field reproduction[1].
- Details can be found in reference[2].

*wave function in elliptical coordinate system

4. Results

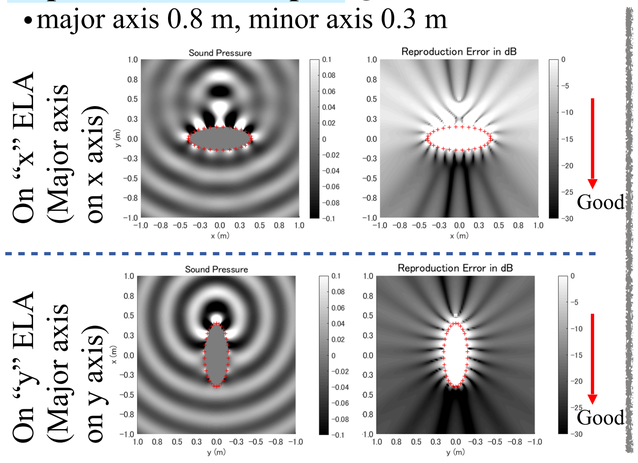
Numerical simulations in 2D space

- **Reproduction examples**
  Sound field and error at 1000 Hz
- **Comparison with CLA & 2CLA**
  200~4000 Hz spatial error
- **Direction dependency**
  Test with target sources in various directions
- **Array Dimension**
  Further investigation on how the array dimensions* matter

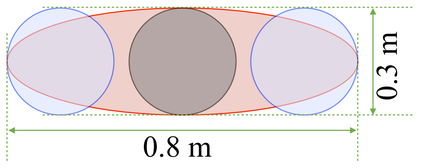
*axis length and flattening

Number of loudspeakers $\mathscr{L} = 30$ and
Target source position (0 m, 0.5 m) for all experiments

- **Reproduction examples** @1000 Hz
  - major axis 0.8 m, minor axis 0.3 m

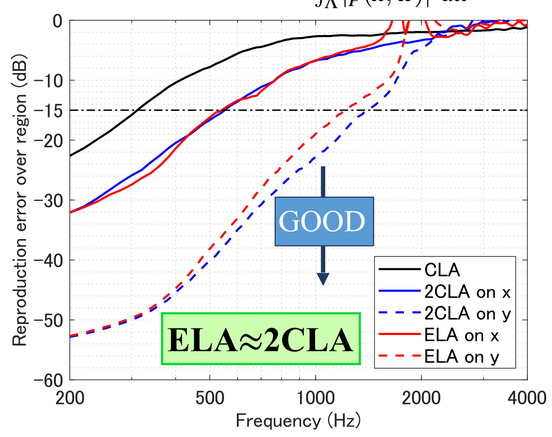


- **Comparison with CLA and 2CLA**
  - ELA, major 0.8 m / minor 0.3 m
  - CLA
    0.15 m radius
    *same "height" as ELA
  - 2CLA
    0.15 m radius
    0.5 m distance
    *same "width" as ELA



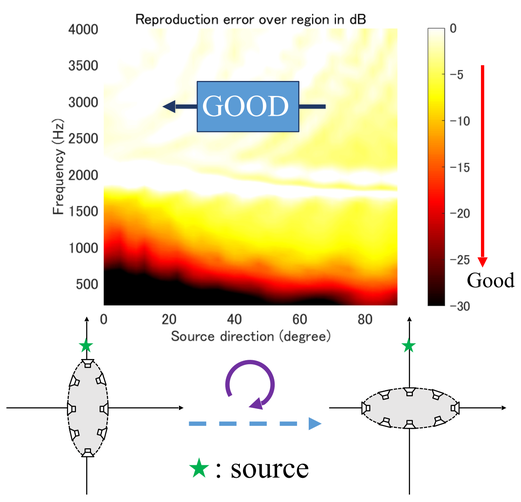
Error in listening area Λ

$$\varepsilon_\Lambda(\omega) = 10\log_{10}\frac{\int_\Lambda |\hat{p}(\boldsymbol{x},\omega) - p(\boldsymbol{x},\omega)|^2 d\boldsymbol{x}}{\int_\Lambda |p(\boldsymbol{x},\omega)|^2 d\boldsymbol{x}}$$



- **Direction dependency**
  - ELA 0.8 m / 0.3 m
  - Rotating ELA, source fixed.

Error in listening area



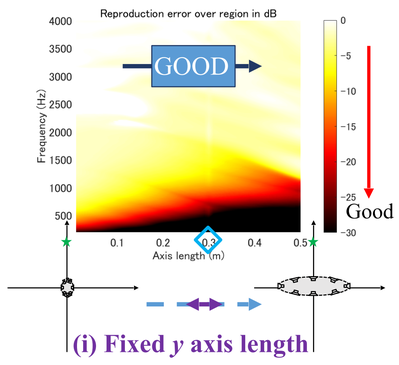
Better at lower angles *Similar to 2CLA*

- **Array dimension**
- **Axis length**

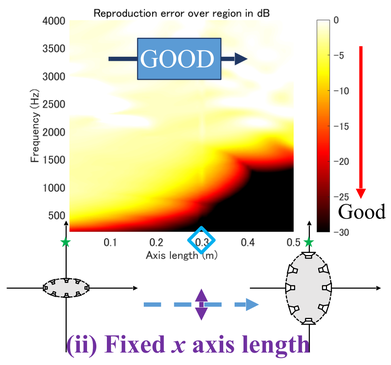
Better with longer axes

◇ in figures: CLA

(i) Axis length perpendicular to source direction
(=x axis for the source, the other axis fixed to 0.3 m)



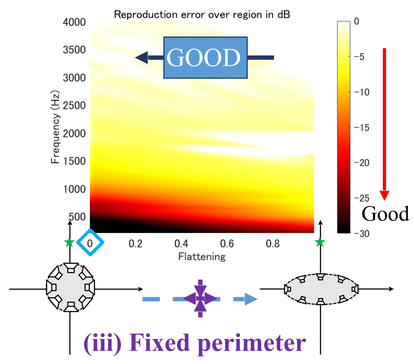
(ii) Axis length in source direction
(=y axis for the source, the other axis fixed to 0.8 m)



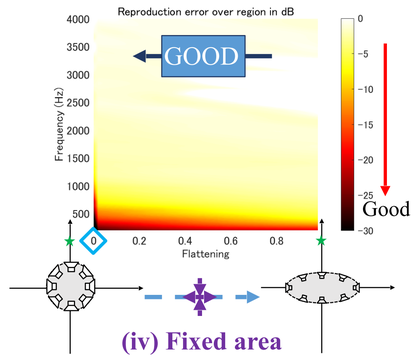
- **Flattening** (*$\mathscr{F} \in [0, 1)$, 0: circle → 1: line)

Better with lower flattening

(iii) Flattening with **fixed perimeter**
(=same loudspeaker interval, same Nyquist frequency)



(iv) Flattening with **fixed area**
(=same quantity of material to build)



5. Summary

Focused source reproduction using ELA
- MFE-based method for exterior field
- Numerical simulations

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- Comparison with CLA & 2CLA: **ELA≈2CLA>CLA**
- Direction dependency
- Array dimension (relation to performance)
  Axis length roughly positive
  Flattening slightly negative

[1] Y. Ren and Y. Haneda, "Two-dimensional sound field reproduction based on Mathieu function expansion", *J. Acoust. Soc. Am.*, Vol. 152, Issue 1, 2022: pp. 416-428.
[2] Y. Ren, *Two-Dimensional Spatial Control using Multiple Circular Loudspeaker Arrays and Elliptical Loudspeaker Array*, PhD Thesis, The University of Eletro-Communications, 2022.