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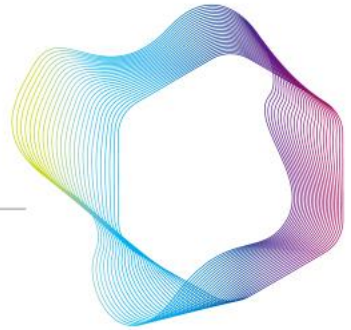

Ear Centering in the Spatial and Transform Domains for Near-Field Head-Related Transfer Functions

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Importance of Near-Field HRTFs

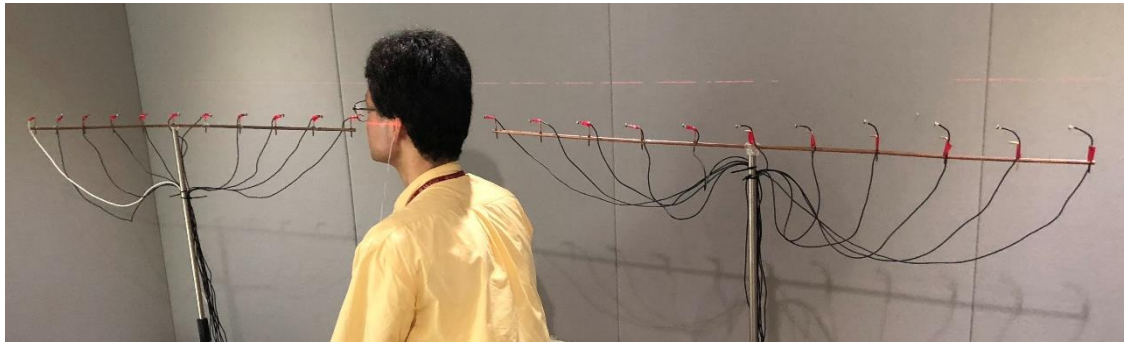
ICA 2022

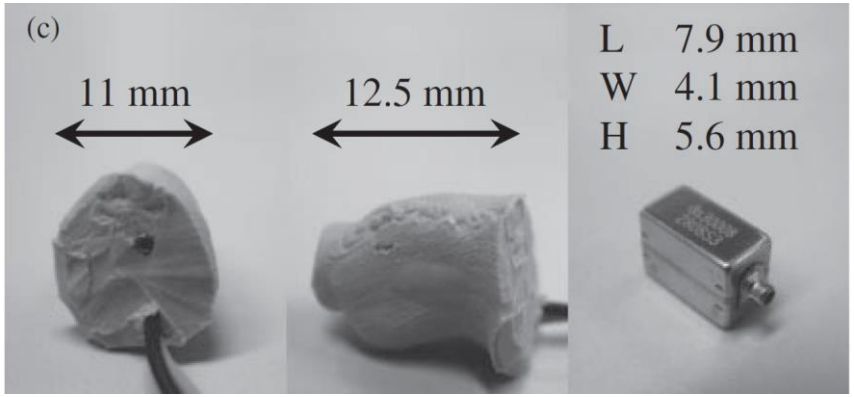
- Sound in the peripersonal space
- Near-field virtual auditory displays
- Auditory attention experiments

[1] S. T. Prepeliţă *et al.*, "Numerical simulations of near-field head-related transfer functions: Magnitude verification and validation with laser spark sources," *J. Acoust. Soc. Am.*, vol. 148, no. 1, pp. 153–166, 2020.
[2] S. Sakamoto *et al.*, "Effects of target speech distance on auditory spatial attention in noisy environments," in *Proc. ICA 2019 and EAA Euroregio*, Aachen, Germany, Sep. 2019, pp. 2177–2181.

Difficulties in Measuring Near-Field HRTFs

- Point sources are still hard to construct





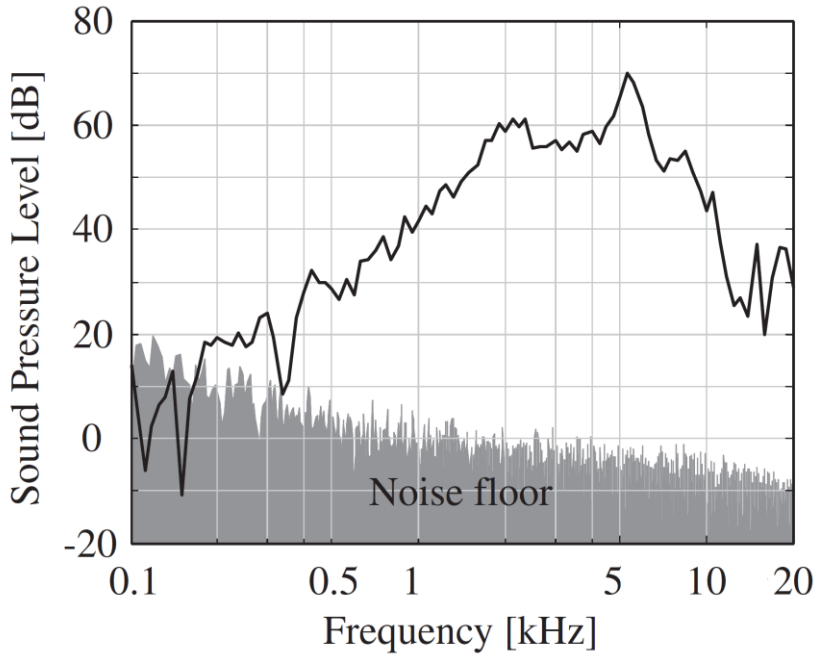


Fig. 3 Frequency response of earplug speaker.

[1] N. Matsunaga and T. Hirahara, "Reexamination of fast head-related transfer function measurement by reciprocal method," *Acoust. Sci. Technol.*, vol. 31, no. 6, pp. 414–416, 2010.

Difficulties in Calculating Near-Field HRTFs

- Numerical acoustics methods might take too long

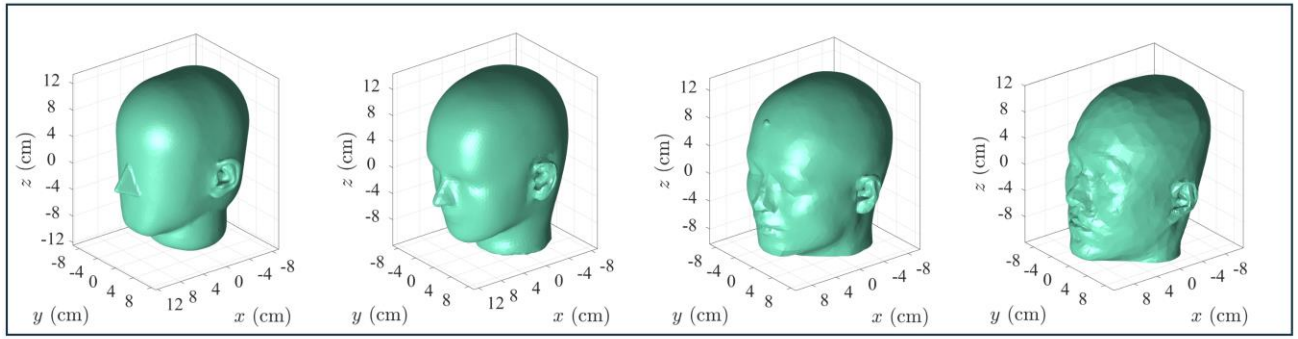


Figure 1. Generic (left) and individual (right) models.

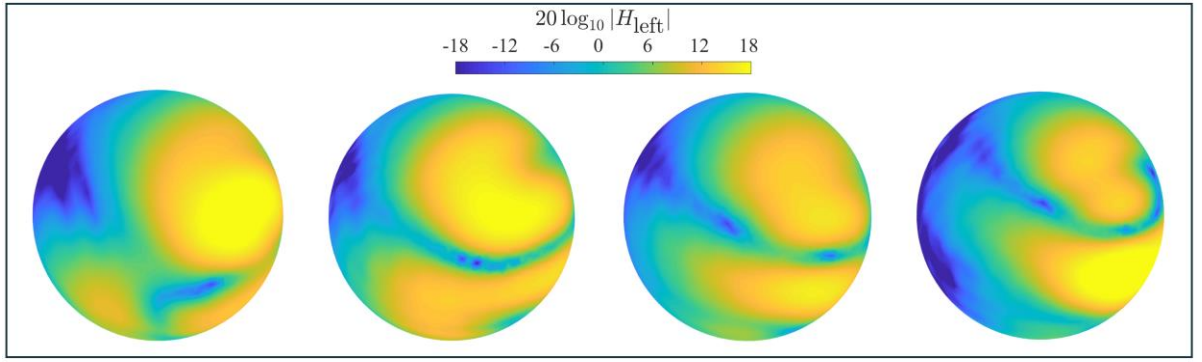


Figure 2. Left-ear HRTFs at 10 kHz for a spherical distribution of sources at 25 cm from the head center.

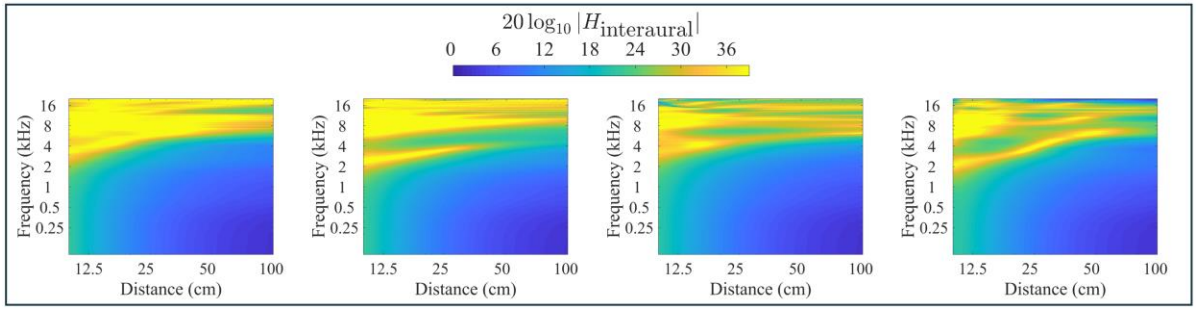
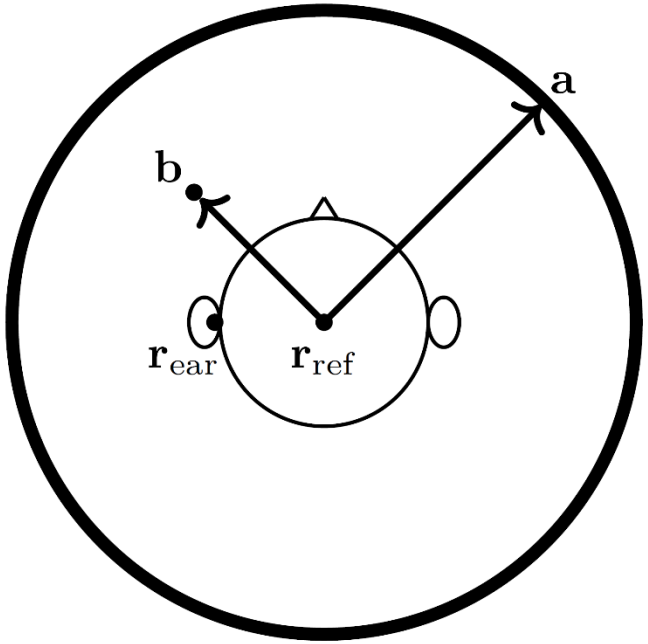


Figure 3. Interaural HRTFs for a distribution of sources along distances at azimuth 100° and elevation 20°.

[1] C. D. Salvador *et al.*, "Dataset of near-distance head-related transfer functions calculated using the boundary element method," *Proc. AES Int. Conf. Spatial Reproduction*, Tokyo, Japan, Aug. 2018.

Near-Field HRTF from Far-field HRTF



At close distances to the head, the distance between the ear and the reference is noticeable.

$$\mathcal{H}(\mathbf{a}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$$

Spatial domain: Azimuth and Elevation

① Spherical Fourier transform

$$\mathcal{H}_{nm}(\|\mathbf{a} - \mathbf{r}_{\text{ref}}\|, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$$

Transform Domain: Indexes *n* and *m*

② Distance-varying filters: $\mathcal{D}_n(\|\mathbf{a} - \mathbf{r}_{\text{ref}}\| \mapsto \|\mathbf{b} - \mathbf{r}_{\text{ref}}\|)$

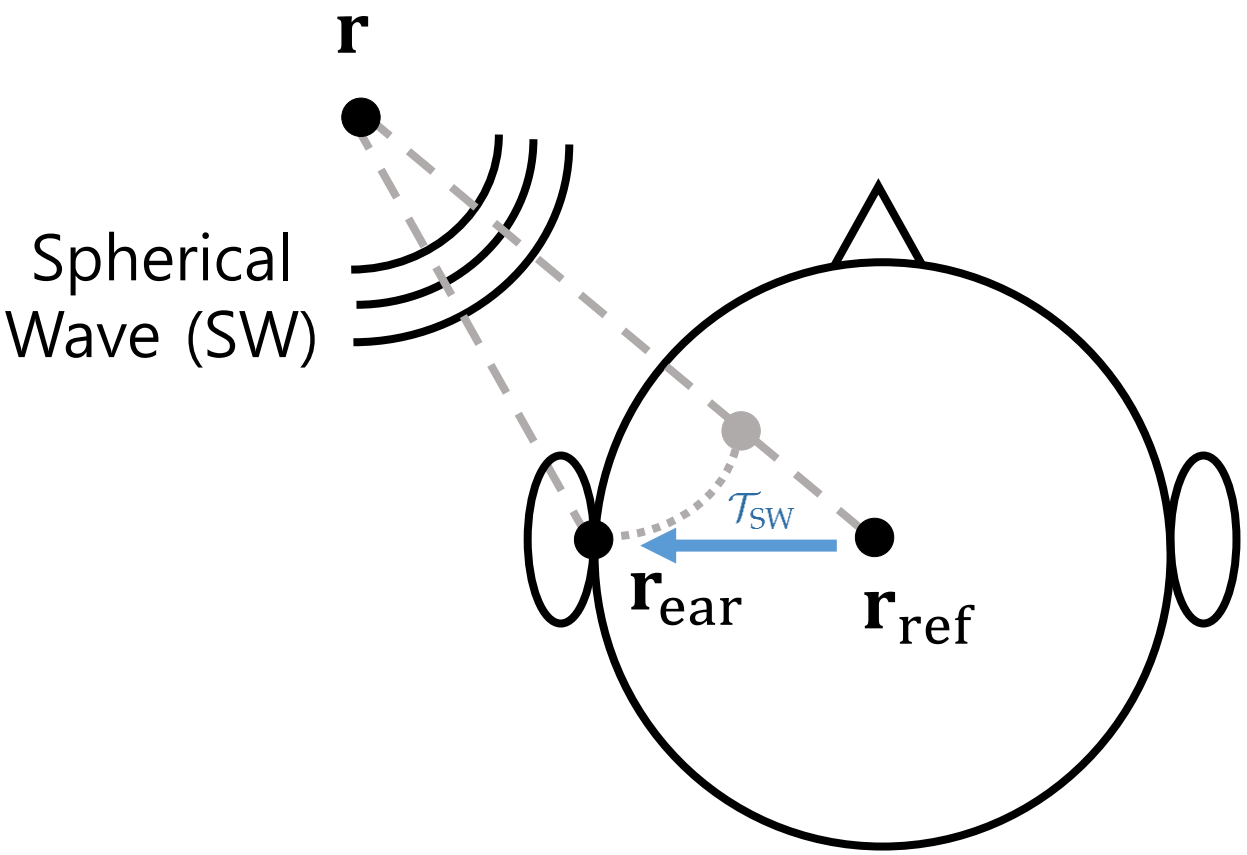
$$\mathcal{H}_{nm}(\|\mathbf{b} - \mathbf{r}_{\text{ref}}\|, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$$

③ Inverse spherical Fourier transform

$$\mathcal{H}(\mathbf{b}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$$

[1] C. D. Salvador *et al.*, "Distance-varying filters to synthesize head-related transfer functions in the horizontal plane from circular boundary values," *Acoust. Sci. Technol.*, vol. 38, no. 1, pp. 1–13, Jan. 2017.

Ear Centering with Translation Operators



Head-related transfer function:

$$\mathcal{H}(\mathbf{r}, \mathbf{r}_{ear}, \mathbf{r}_{ref}) = \frac{\Psi(\mathbf{r}, \mathbf{r}_{ear})}{\Psi_{FF}(\mathbf{r}, \mathbf{r}_{ref})}$$

Ψ : Sound pressure at ear
Ψ_{FF} : Sound pressure at reference in free field

SW translation operator in free field:

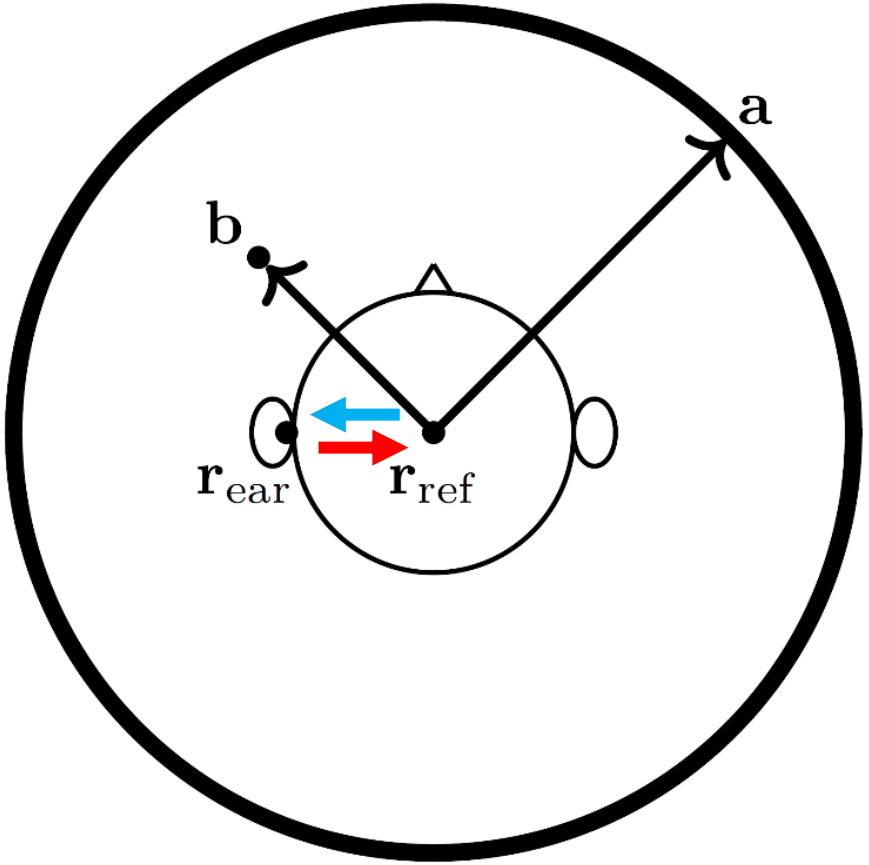
$$\mathcal{T}_{SW}(\mathbf{a}, \mathbf{r}_{ref} \mapsto \mathbf{r}_{ear}) = \frac{\|\mathbf{a} - \mathbf{r}_{ear}\|}{\|\mathbf{a} - \mathbf{r}_{ref}\|} e^{-jk(\|\mathbf{a}-\mathbf{r}_{ref}\| - \|\mathbf{a}-\mathbf{r}_{ear}\|)}$$

Related Research

Overview of research related to ear centering interpreted in terms of translation operators

Domain	Distance	Translation Model	Citation
Spatial domain	Far field	Plane wave on a rigid sphere	Pörschmann *et al.*, 2019 and Arend *et al.*, 2021
Spatial domain	Far field	Plane wave in free field	Zaunschirm *et al.*, 2018
Spatial domain	Far field	Plane wave in free field	Ben-Hur *et al.*, 2019
Spatial domain	Near field	Spherical wave in free field	Urviola *et al.*, 2021 and 2022
Transform domain	Near field	Spherical wave in free field	Richter *et al.*, 2014

Spatial-Domain Ear Centering



Urviola *et al.*, 2021 and 2022

$\mathcal{H}(\mathbf{a}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$

↓

① Direct translation operator: $\mathcal{T}(\mathbf{a}, \mathbf{r}_{\text{ref}} \mapsto \mathbf{r}_{\text{ear}})$

↓ $\mathcal{H}(\mathbf{a}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ear}})$

② Spherical Fourier transform

↓ $\mathcal{H}_{nm}(\|\mathbf{a} - \mathbf{r}_{\text{ref}}\|, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ear}})$

③ Distance-varying filters: $\mathcal{D}_n(\|\mathbf{a} - \mathbf{r}_{\text{ref}}\| \mapsto \|\mathbf{b} - \mathbf{r}_{\text{ref}}\|)$

↓ $\mathcal{H}_{nm}(\|\mathbf{b} - \mathbf{r}_{\text{ref}}\|, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ear}})$

④ Inverse spherical Fourier transform

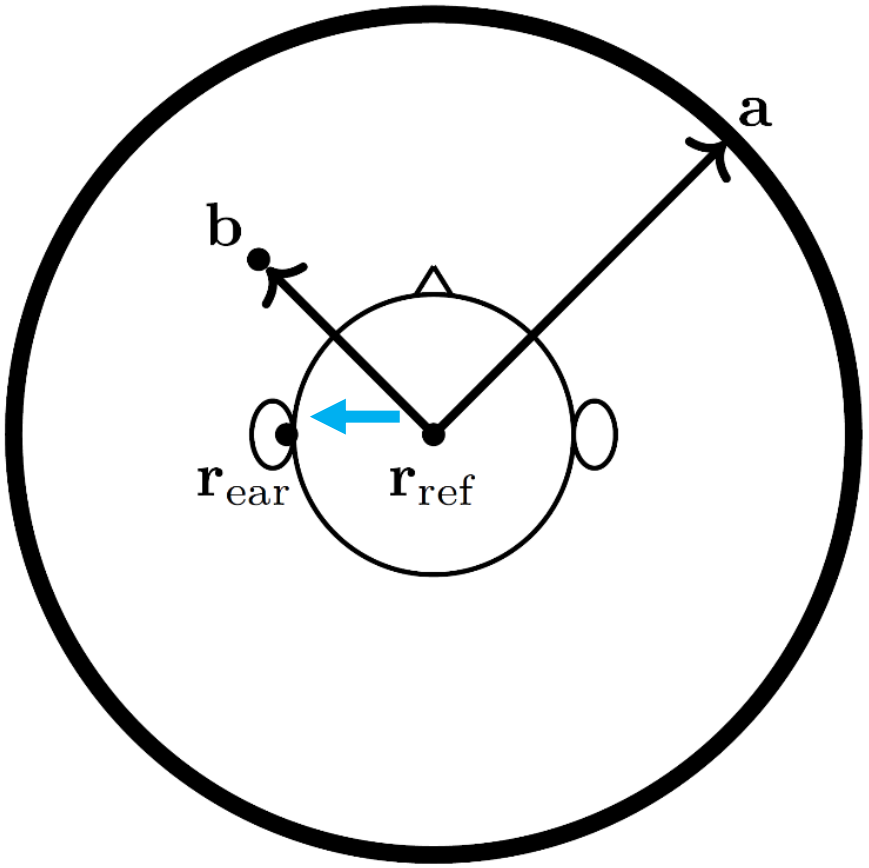
↓ $\mathcal{H}(\mathbf{b}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ear}})$

⑤ Inverse translation operator: $\mathcal{T}^{-1}(\mathbf{b}, \mathbf{r}_{\text{ear}} \mapsto \mathbf{r}_{\text{ref}})$

↓

$\mathcal{H}(\mathbf{b}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$

Transform-Domain Ear Centering



$\mathcal{H}(\mathbf{a}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$

↓

① Spherical Fourier transform

↓ $\mathcal{H}_{nm}(\|\mathbf{a} - \mathbf{r}_{\text{ref}}\|, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$

② Distance-varying filters: $\mathcal{D}_n(\|\mathbf{a} - \mathbf{r}_{\text{ref}}\| \mapsto \|\mathbf{b} - \mathbf{r}_{\text{ref}}\|)$

↓ $\mathcal{H}_{nm}(\|\mathbf{b} - \mathbf{r}_{\text{ref}}\|, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$

← ③ Translation operator: $\mathcal{D}_n(\|\mathbf{b} - \mathbf{r}_{\text{ref}}\| \mapsto \|\mathbf{b} - \mathbf{r}_{\text{ear}}\|)$

↓ $\mathcal{H}_{nm}(\|\mathbf{b} - \mathbf{r}_{\text{ear}}\|, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$

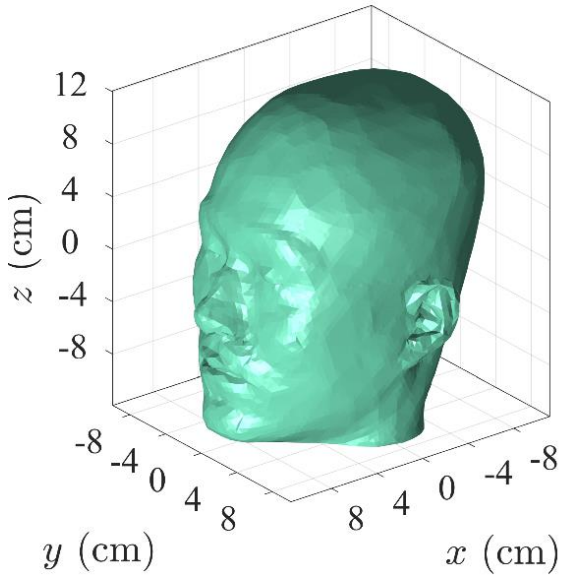
④ Inverse spherical Fourier transform

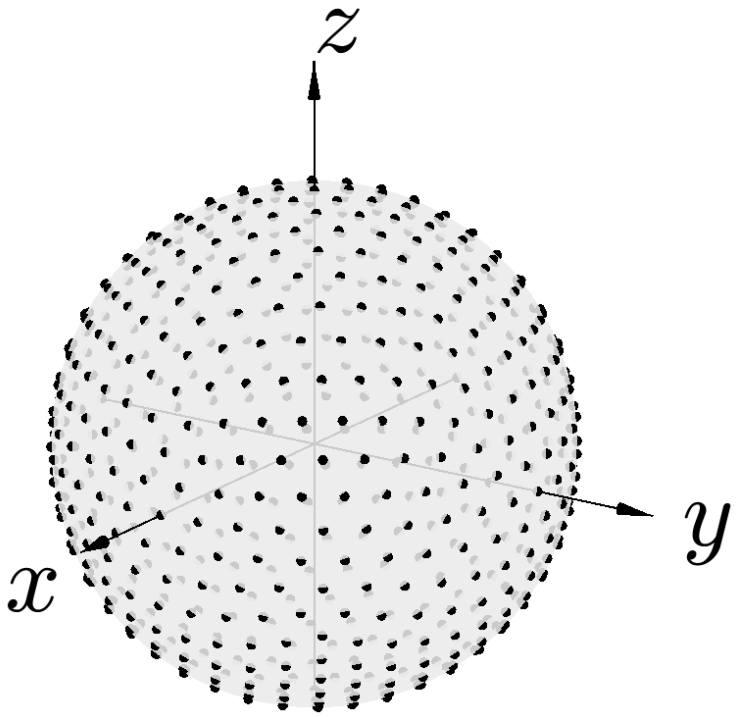
↓

$\mathcal{H}(\mathbf{b}, \mathbf{r}_{\text{ear}}, \mathbf{r}_{\text{ref}})$

The original proposal adds a frequency-dependent ear position optimization (Richter *et al.*, 2014)

Conditions for Evaluation

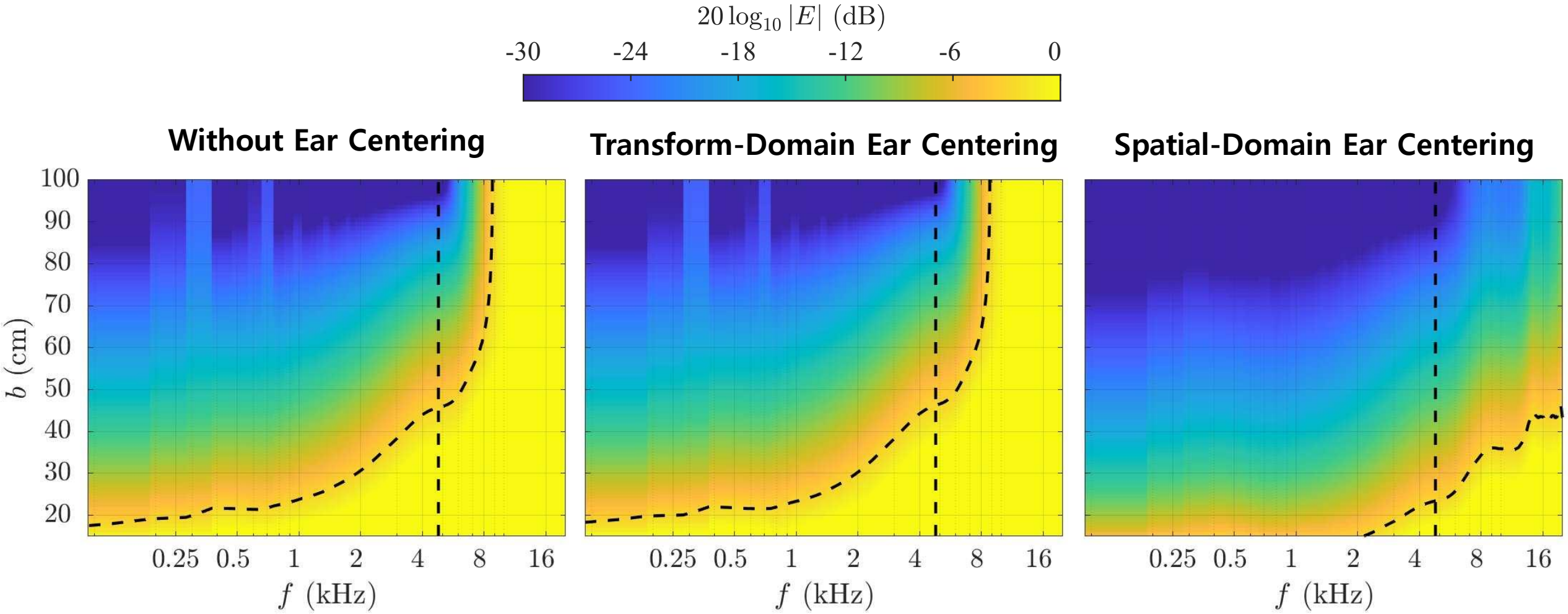




Far-field HRTF dataset:

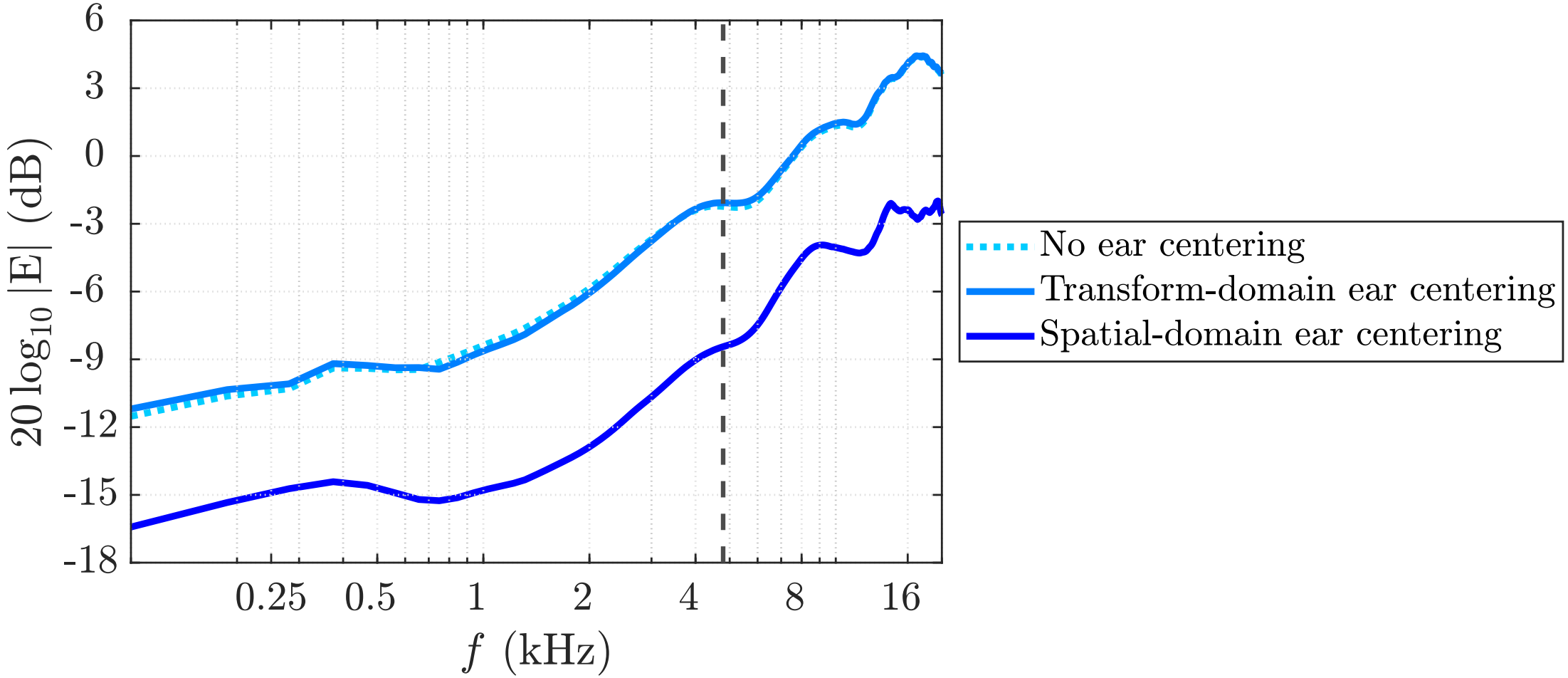
- 1 meter
- 256 sound source positions on an icosahedral grid
- SFT order 14

Synthesis Error: E = ||H-H'|| / ||H||



Dashed Line: Maximum Frequency
Dashed Curve: Error at -3 dB

Synthesis Error: E = ||H-H'|| / ||H||



Conclusion

- Ear centering can be applied:
  - in free field or include a rigid sphere,
  - in the far or near field,
  - in the spatial or transform domain
- Operating in the spatial domain is computationally more efficient than operating in the transform domain
- Operating in the spatial domain is more accurate than operating in the transform domain when ear position optimization is not considered.

Open Access Article

Ear Centering for Accurate Synthesis of Near-Field Head-Related Transfer Functions †

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