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## **Estimation de directivité par décomposition en ondes sphériques du champ rayonné: limites pratiques**

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# Estimation de directivité par décomposition en ondes sphériques du champ rayonné : limites pratiques

Matthieu Hartenstein<sup>1</sup>, Paul Luizard<sup>2,3,4</sup>, Hélène Moingeon<sup>1</sup>, Marc Pachebat<sup>2</sup>, Cédric Pinhède<sup>2</sup>, Christian Ollivon<sup>1</sup>, François Ollivier<sup>1</sup>, Fabrice Silva<sup>2</sup>

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<sup>4</sup> Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, Grenoble, France

# 1. Introduction

1.1 Context

1.2 Choices

# Measuring voice directivity

## Why ?



# Measuring voice directivity

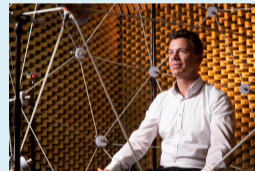
## Why ?



## How ?



Arc of 37 mics <sup>1</sup>



Sphere of 32 mics <sup>2</sup>

<sup>1</sup>Leishman, Bellows and Pincock, JASA 2021

<sup>2</sup>Pörschmann and Arend, JASA 2021

## Directivity estimation tool : the HELS method

- ▶ Input: Pressure measurements and sensor location,
- ▶ Output : far-field directivity function,
- ▶ Performance depends on array parameters (shape, size, number of microphones) <sup>3</sup>.

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<sup>3</sup>Hartenstein et al, Proc. Forum Acusticum 2023

## Directivity estimation tool : the HELS method

- ▶ Input: Pressure measurements and sensor location,
- ▶ Output : far-field directivity function,
- ▶ Performance depends on array parameters (shape, size, number of microphones) <sup>3</sup>.

## The array

- ▶ Precise estimate demands a high number of sensors,
- ▶ Mems microphones can be deployed by hundreds !

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<sup>3</sup>Hartenstein et al, Proc. Forum Acusticum 2023

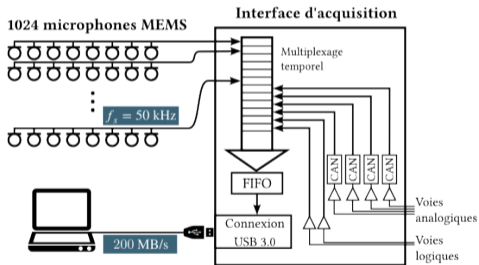
## 2. Methodology

2.1 Experimental setup

2.2 The HELS method

# Acquisition system

Source : 3.5 cm radius speaker on a 7.5 cm radius rigid sphere  $\approx$  spherical cap model



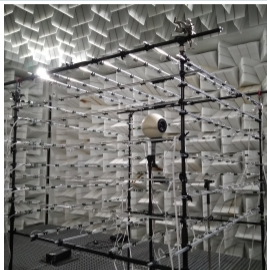
Megamicros acquisition system <sup>7</sup>

<sup>7</sup>H. Demontis (2019), R. Leiba (2017), and C. Vanwynsberghe's (2016) PhD theses

<sup>8</sup>Novak et al, JAES 2015

# Arrays

Cube-like  
256 mics  
1.2m extent

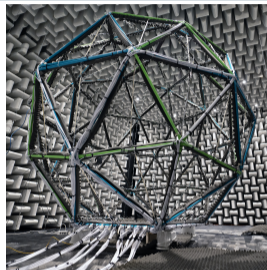
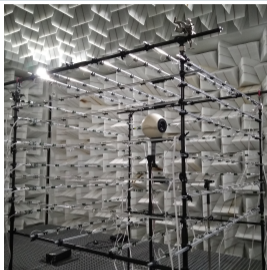


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<sup>9</sup>Vanwysberghe et al, JASA 2019

# Arrays

Cube-like  
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1.2m extent



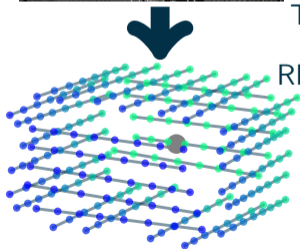
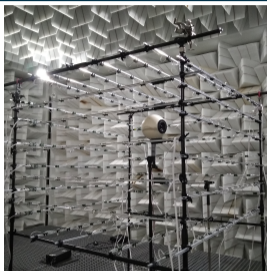
Sphere-like  
588 microphones  
3.6m extent

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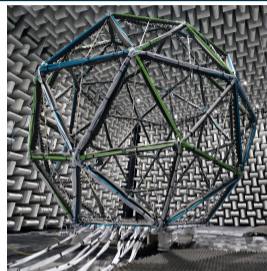
<sup>9</sup>Vanwysberghe et al, JASA 2019

# Arrays

Cube-like  
256 mics  
1.2m extent



TOA estimation  
+  
RMDU algorithm<sup>9</sup>



Sphere-like  
588 microphones  
3.6m extent

<sup>9</sup>Vanwysberghe et al, JASA 2019

# The HELS method (Wu 2015)

Inputs : Sensor location  $(r_q, \theta_q, \phi_q)$ , pressure measurements  $p = [p(r_q, \theta_q, \phi_q, k)]$

Model (truncated spherical wave decomposition):

$$p(r_q, \theta_q, \phi_q, k) = \sum_{n=0}^N \sum_{m=-n}^n c_{mn}(k) h_n^{(2)}(kr_q) Y_n^m(\theta_q, \phi_q) \iff p = Hc$$

Regularized inversion :

$$\hat{c} = (H^H H + \lambda I)^{-1} H^H p$$

Outputs :  $c$  and any acoustic quantity (e.g. **far-field directivity function** <sup>3,5</sup>)

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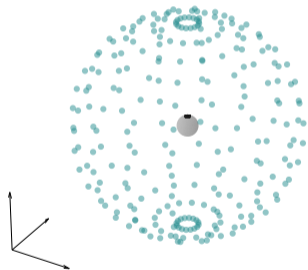
<sup>3</sup>Hartenstein et al, Proc. Forum Acusticum 2023

<sup>4</sup>Bellows and Leishman, Proc. Meet. Acoust. 2020

# 3. Preliminary simulations

- 3.1 Experimental setup
- 3.2 Robustness to experimental uncertainties
- 3.3 Impact of array parameters

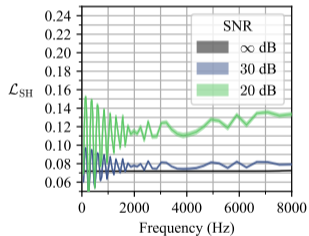
# Experimental setup



- ▶ Array :  
Equal-angle grid, order 7 (256 mics.)
- ▶ Spherical cap,  
baffle : 8.5cm radius, cap : 2.5cm  
radius

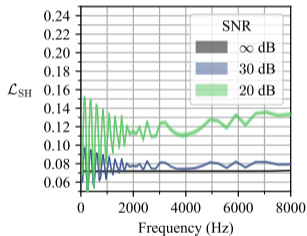
# Robustness to experimental uncertainties

## Measurement noise

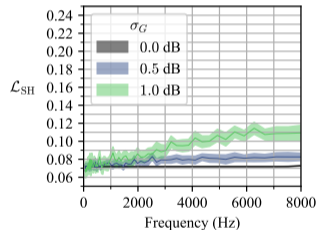


# Robustness to experimental uncertainties

## Measurement noise

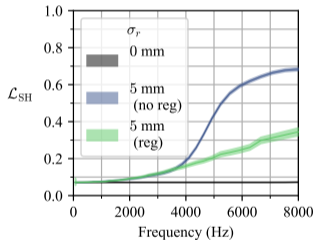


## Gain variability



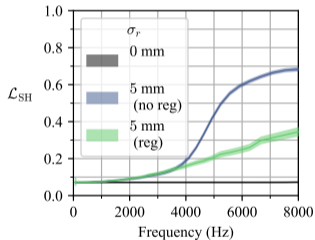
# Robustness to experimental uncertainties

## Uncertainty on mic. pos.



# Robustness to experimental uncertainties

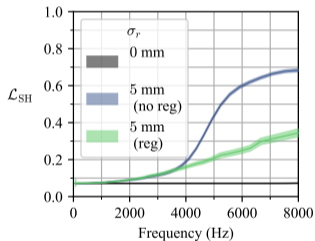
## Uncertainty on mic. pos.



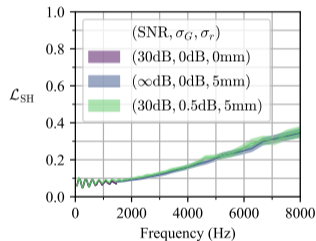
Note : regularisation efficient only at very high frequency  $\Rightarrow$  not used in what follows

# Robustness to experimental uncertainties

## Uncertainty on mic. pos.



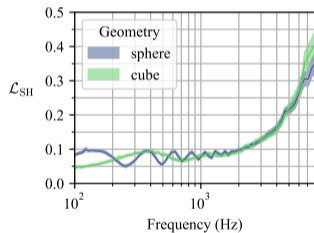
## All uncertainties included



Note : regularisation efficient only at very high frequency  $\Rightarrow$  not used in what follows

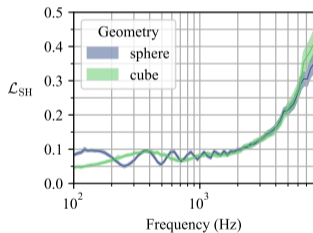
# Impact of arrays parameters

## Geometry

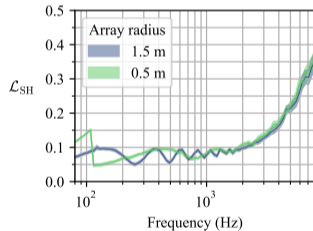


# Impact of arrays parameters

## Geometry

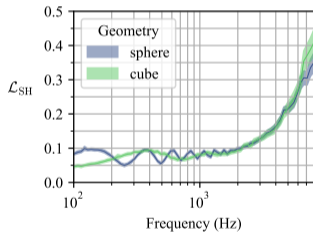


## Size

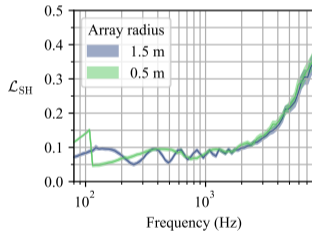


# Impact of arrays parameters

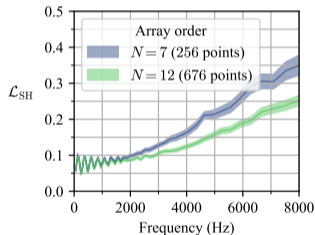
## Geometry



## Size



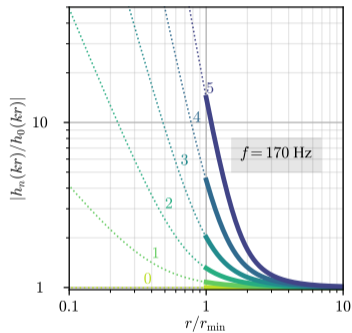
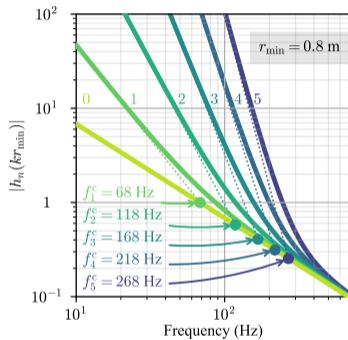
## Nb of points



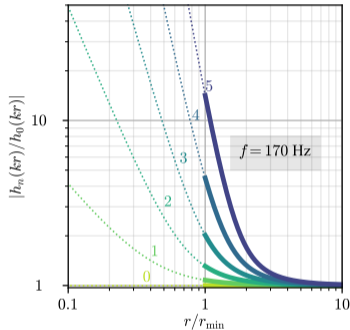
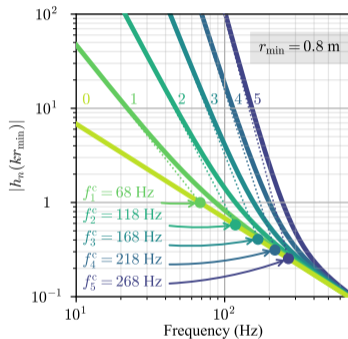
# 4. Truncating the SWD

- 4.1 Limitation given by the observation distance
- 4.2 Limitation given by the distribution of points
- 4.3 Cross-validation framework

# Limitation given by the observation distance

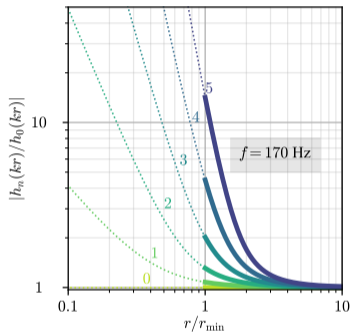
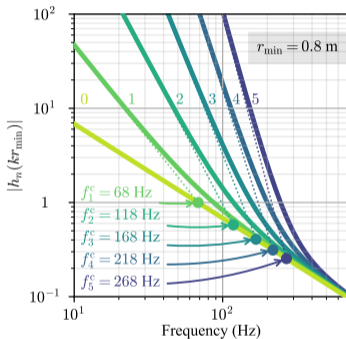


# Limitation given by the observation distance



- Issue :  
High-rate near-field decrease  $\Rightarrow$  instability of the inverse problem at low frequency

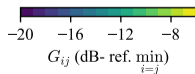
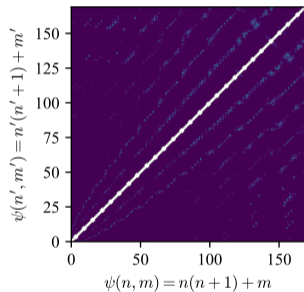
# Limitation given by the observation distance



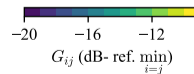
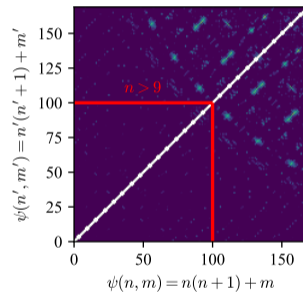
- ▶ Issue :  
High-rate near-field decrease  $\Rightarrow$  instability of the inverse problem at low frequency
- ▶ Solution :  
At low frequency, keep only waves that have left their near-field behaviour.

# Limitation given by the distribution of points

## Gram-matrix (cube)



## Gram-matrix (sphere)



# Cross-validation framework

- ▶ Idea: Use each measurement point for interpolation and validation

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Validation metric

$$\mathcal{L}_{\text{validation}}(f) = \frac{\sqrt{\sum_{i=1}^I \|p_{\text{out}}^i - \hat{p}_{\text{out}}^i\|_2^2}}{\|p_{\text{meas}}\|_2}$$

# 5. Experimental results

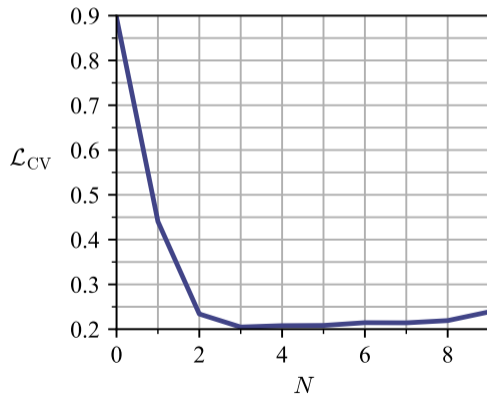
5.1 Optimal parameters

5.2 Frequency evolution of the performance

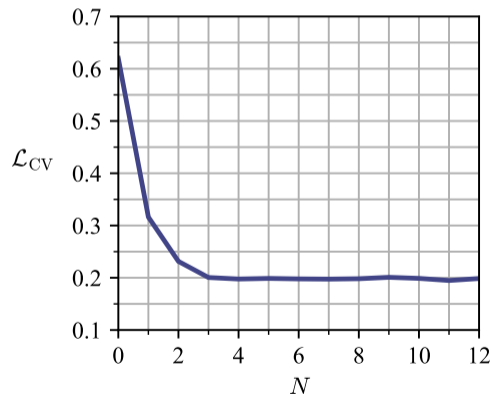
5.3 Examples of directivity estimates (azimuthal angle vs frequency)

## Optimal parameters - controlled source (1 kHz)

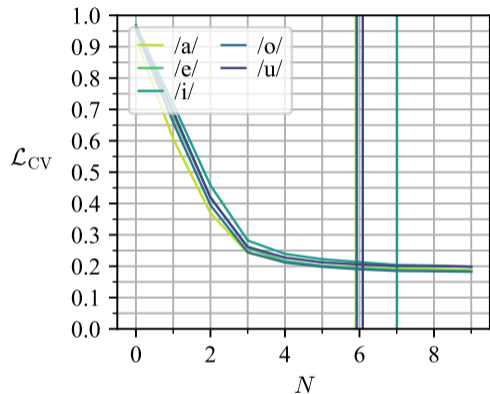
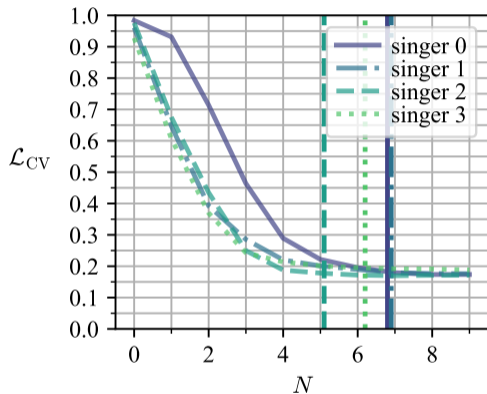
Cube



Sphere



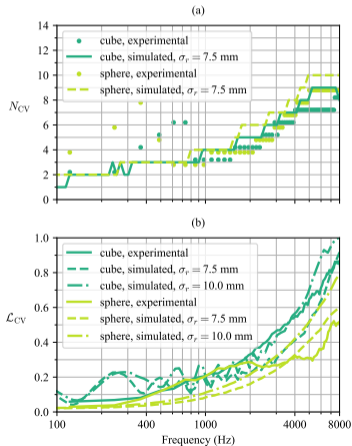
# Optimal parameters - human voice (1 kHz)



- ▶ Issue : Extended range of 'close-to-optimal'  $N$
- ▶ Solution : Include constraint on the condition number to ensure stability of the inversion.

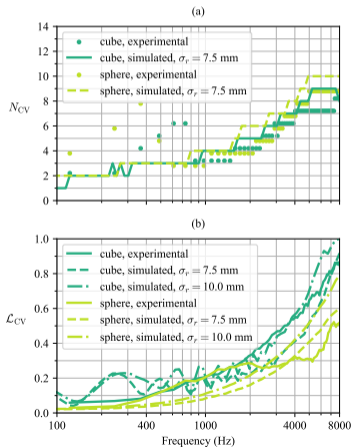
# Frequency evolution of the performance

## Controlled source

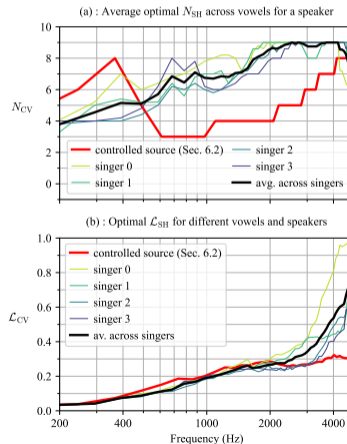


# Frequency evolution of the performance

## Controlled source

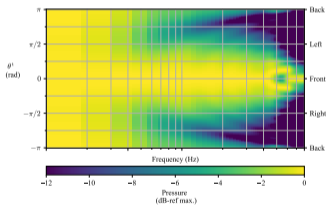


## Singers

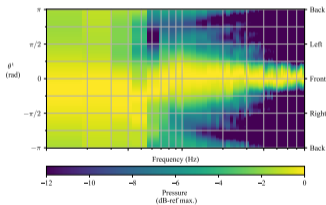


# Examples of directivity estimates

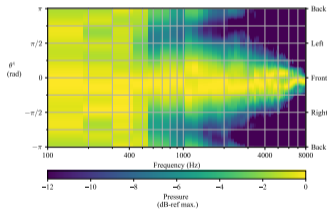
## Theoretical (spherical cap)



## Reconstructed (cube)



## Reconstructed (sphere)



## 6. Conclusions

# Conclusions

## Array processing method

- ▶ application of the HELS method to far-field directivity estimation,
- ▶ Truncation order :
  - ▶ Limitation of the arrays  $\iff$  spatial distribution, size
  - ▶ Cross-validation allows to compute an optimal order for a source

# Conclusions

## Array processing method

- ▶ application of the HELS method to far-field directivity estimation,
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  - ▶ Limitation of the arrays  $\iff$  spatial distribution, size
  - ▶ Cross-validation allows to compute an optimal order for a source

## Measurement system

- ▶ Direct acquisition of 588 microphones
- ▶ Measurement surface  $\approx$  spherical, 3.6m diameter
- ▶ Order 9 in terms of spherical wave
- ▶ For comparison,  $N = 4$  at most for direct measurements<sup>2</sup>,  $N = 15$  for repeated measurements<sup>1</sup>.

Thanks !