2003

Partial Sound Field Decomposition in Multi-Reference Nearfield Acoustical Holography by Using Optimally-Location Virtual References

J Stuart Bolton
Purdue University, bolton@purdue.edu

Yong-Joe Kim

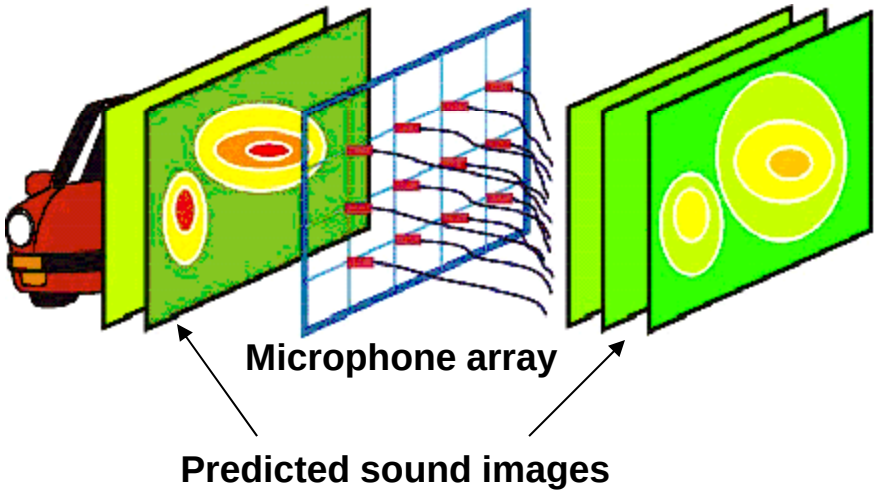
Partial Sound Field Decomposition in Multi-Reference Nearfield Acoustical Holography by Using Optimally-Location Virtual References

Yong-Joe Kim and J. Stuart Bolton

Ray W. Herrick Laboratories
School of Mechanical Engineering
Purdue University

Basic Concept of NAH

Phase-coherent sound field mapping



- **Procedure**

1. Measure sound pressure at a plane (hologram plane)
2. Predict sound field at any planes outside of source plane

- **Acoustic Properties**

1. Sound pressure
2. Acoustic Intensity
3. Particle Velocity

$P(x, y, z_{Pred}; f)$

$V(x, y, z_{Pred}; f)$

Spatial Domain

$P(x, y, z_H; f)$

Spatial FT

Inverse spatial FT

Propagation

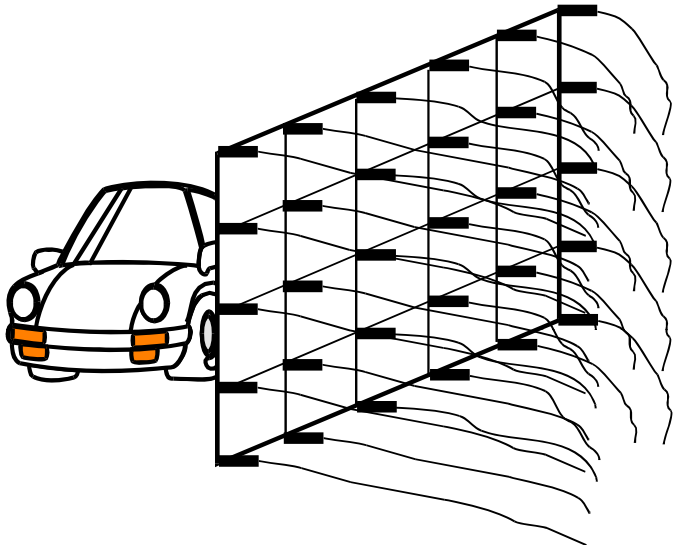
$\hat{\hat{P}}(k_x, k_y, z_H; f)$ → $\hat{\hat{P}}(k_x, k_y, z_{Pred}; f)$

$\hat{\hat{V}}(k_x, k_y, z_{Pred}; f)$

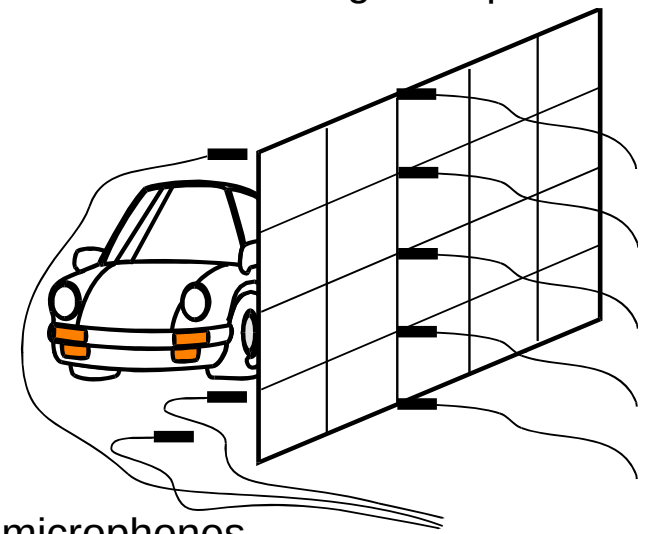
Wavenumber Domain

Purdue University **Herrick Laboratories**

Hologram Measurement



Scanning microphones



Reference microphones

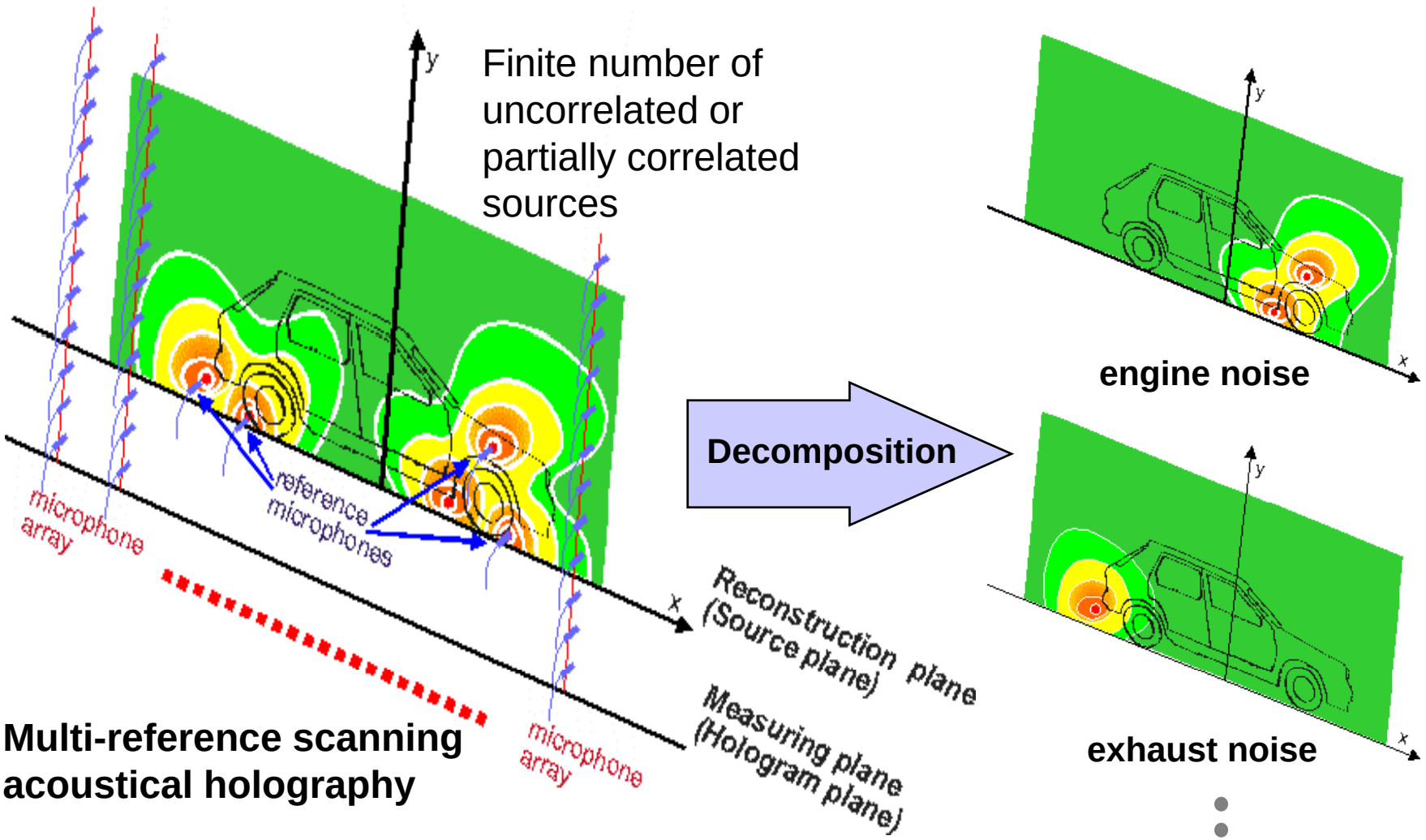
Snap-shot measurement

- Non-stationary NAH
- Large number of microphones

Scanning measurement

- Small number of scanning microphones
- Use of reference microphones
- Assumption: stationary sound field

Partial Field Decomposition



VIRTUAL REFERENCES

- Reference microphones should be positioned as close as possible to the sources to obtain physically meaningful partial fields.
  - Not always possible to identify the optimal reference microphone locations prior to measurement, or to place reference microphones at those optimal locations.
- Virtual reference method
  - Procedures to identify the optimal reference locations and place virtual references at those locations after performing a holographic measurement.

VIRTUAL REFERENCE SIGNALS

$$\mathbf{Y} = \mathbf{H}_{\mathbf{yr}}\mathbf{V}\boldsymbol{\Lambda}^{1/2} = \mathbf{H}_{\mathbf{yl}}\boldsymbol{\Lambda}^{1/2}$$

$\mathbf{Y}$: Partial field matrix on hologram surface

$\boldsymbol{\Lambda}^{1/2}$: Principal reference signal matrix

$\mathbf{H}_{\mathbf{yl}}$: Transfer matrix

$$\mathbf{Y}' = \mathbf{H}_{\mathbf{y'y}}\mathbf{Y} = \mathbf{H}_{\mathbf{y'y}}\mathbf{H}_{\mathbf{yr}}\mathbf{V}\boldsymbol{\Lambda}^{1/2} = \mathbf{H}_{\mathbf{y'y}}\mathbf{H}_{\mathbf{yl}}\boldsymbol{\Lambda}^{1/2} = \mathbf{H}_{\mathbf{y'l}}\boldsymbol{\Lambda}^{1/2}$$

$\mathbf{Y}'$: Partial field matrix on reconstruction surface

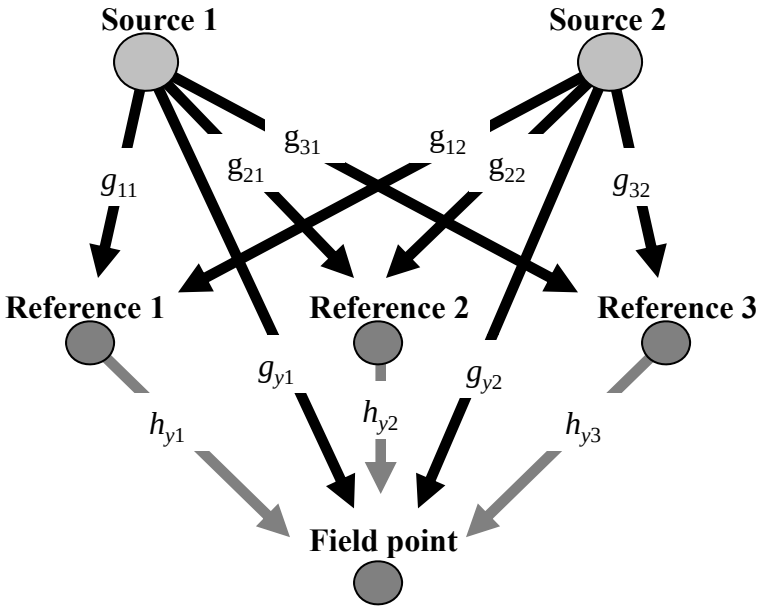
$\mathbf{H}_{\mathbf{y'y}}$: Transfer matrix (NAH projection procedure)

$$\mathbf{X} = \begin{bmatrix} \mathbf{c}_1^{\mathrm{T}}\mathbf{Y}'_1 \\ \mathbf{c}_2^{\mathrm{T}}\mathbf{Y}'_2 \\ \vdots \\ \mathbf{c}_K^{\mathrm{T}}\mathbf{Y}'_K \end{bmatrix} = \begin{bmatrix} \mathbf{c}_1^{\mathrm{T}}\mathbf{H}_{\mathbf{y}'_1\mathbf{l}} \\ \mathbf{c}_2^{\mathrm{T}}\mathbf{H}_{\mathbf{y}'_2\mathbf{l}} \\ \vdots \\ \mathbf{c}_K^{\mathrm{T}}\mathbf{H}_{\mathbf{y}'_K\mathbf{l}} \end{bmatrix} \boldsymbol{\Lambda}^{1/2} = \mathbf{H}_{\mathbf{xl}}\boldsymbol{\Lambda}^{1/2}$$

$\mathbf{X}$: Virtual reference signal matrix

$\mathbf{c}_m$: vitual reference selection vector on reconstruction surface

$\mathbf{Y}'_m$: Partial field matrix for reconstruction surface



Note that the principal reference signals can be obtained from real reference signals

VIRTUAL REFERENCE LOCATIONS

- Location of a virtual reference in a 3-D space is determined by the position of the reconstruction surface in combination with the reference selection vector.
- MUSIC power is maximized at the optimal reference microphone location.

$$P_{\text{MUSIC}} = \frac{1}{\mathbf{u}^{\text{H}}\mathbf{R}_{\text{noise}}\mathbf{u}}$$

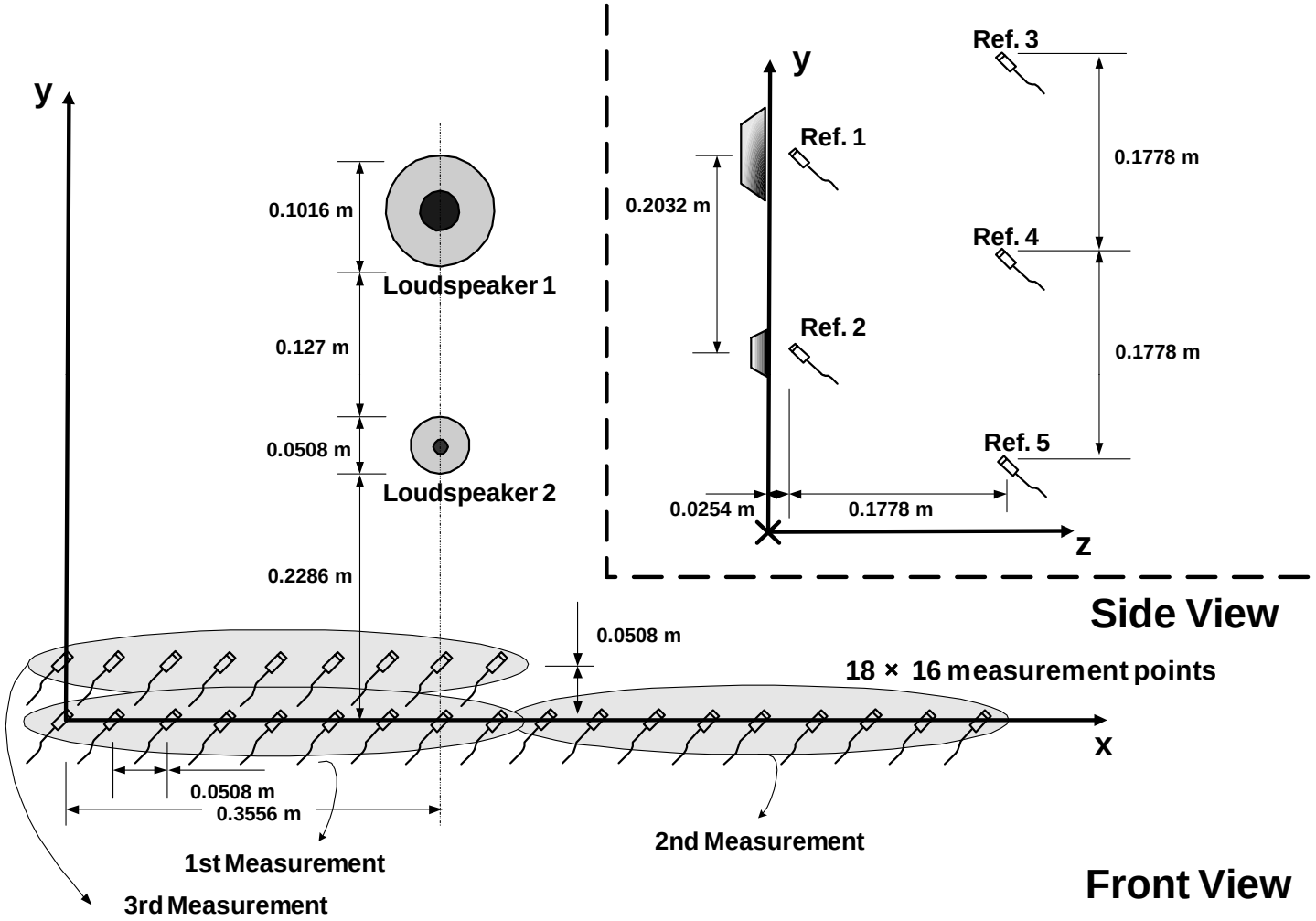
P_{MUSIC} : MUSIC power

$\mathbf{u}$: trial vector

$\mathbf{R}_{\text{noise}} = \sum_{n=K+1}^{N} \mathbf{w}_n \mathbf{w}_n^{\text{H}}$: Noise subspace

$\mathbf{w}_n$: Noise - related eigenvectors of $\mathbf{S}_{\mathbf{y}'\mathbf{y}'}(\mathbf{S}_{\mathbf{y}'\mathbf{y}'})^{\text{H}}$

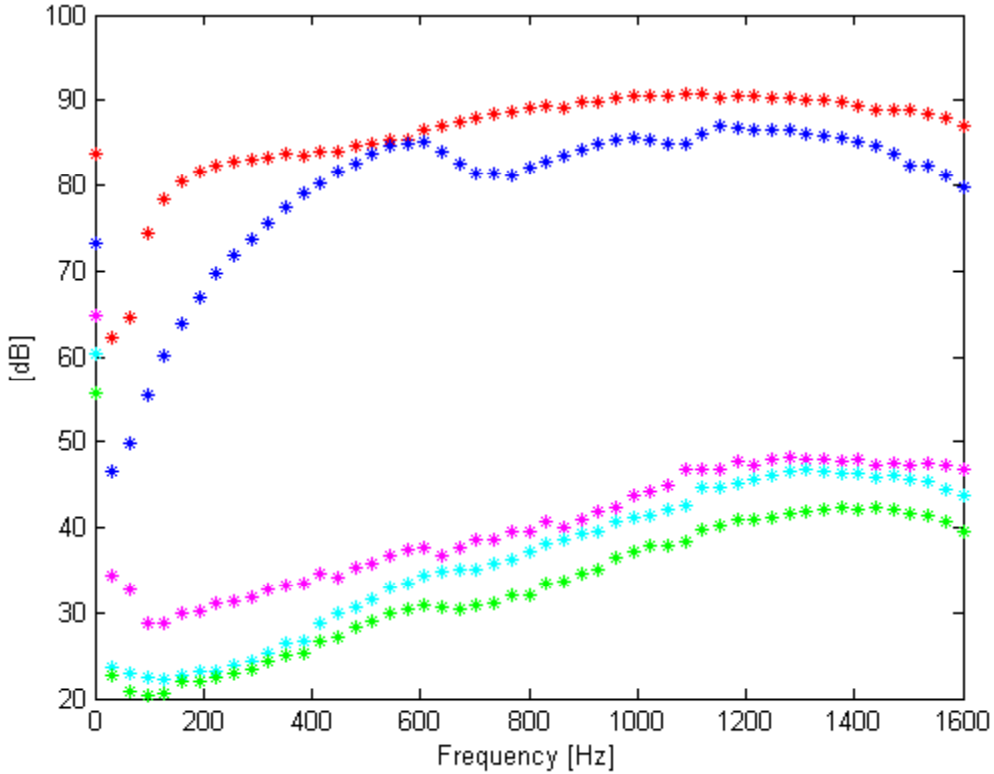
EXPERIMENT



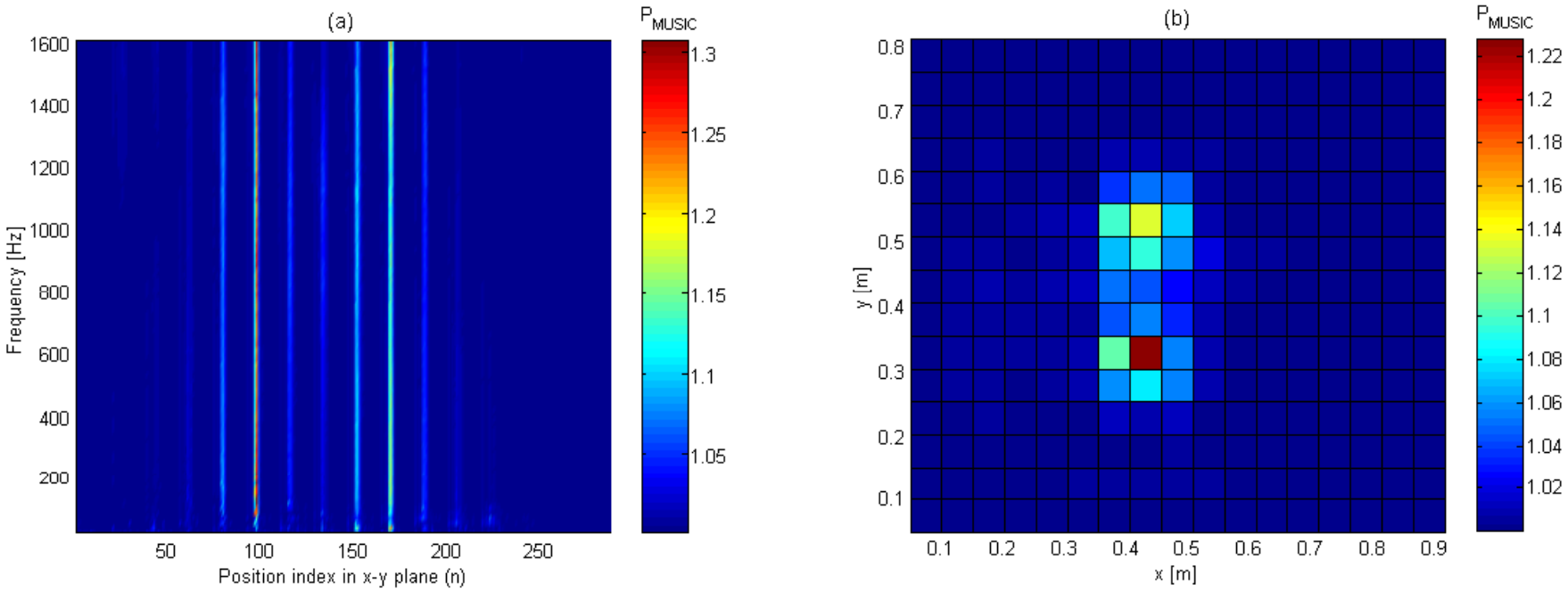
Purdue University Herrick Laboratories

REFERENCE SINGULAR VALUE SPECTRA

- Two incoherent sources exist since there are two significant singular values: two virtual references should be identified.

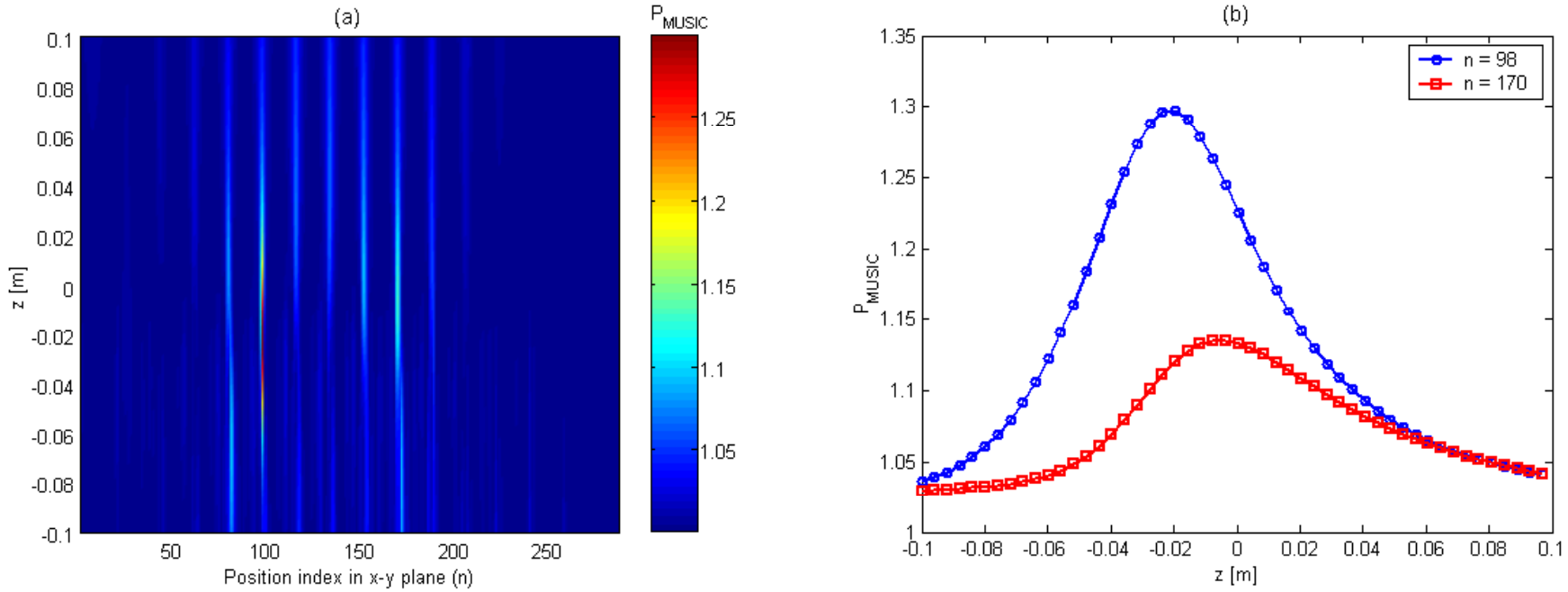


MUSIC POWER (z = 0)



(a) From 0 to 1600 Hz (maxima at n = 98 and 170)
(b) Mapped on x-y plane at 1200 Hz

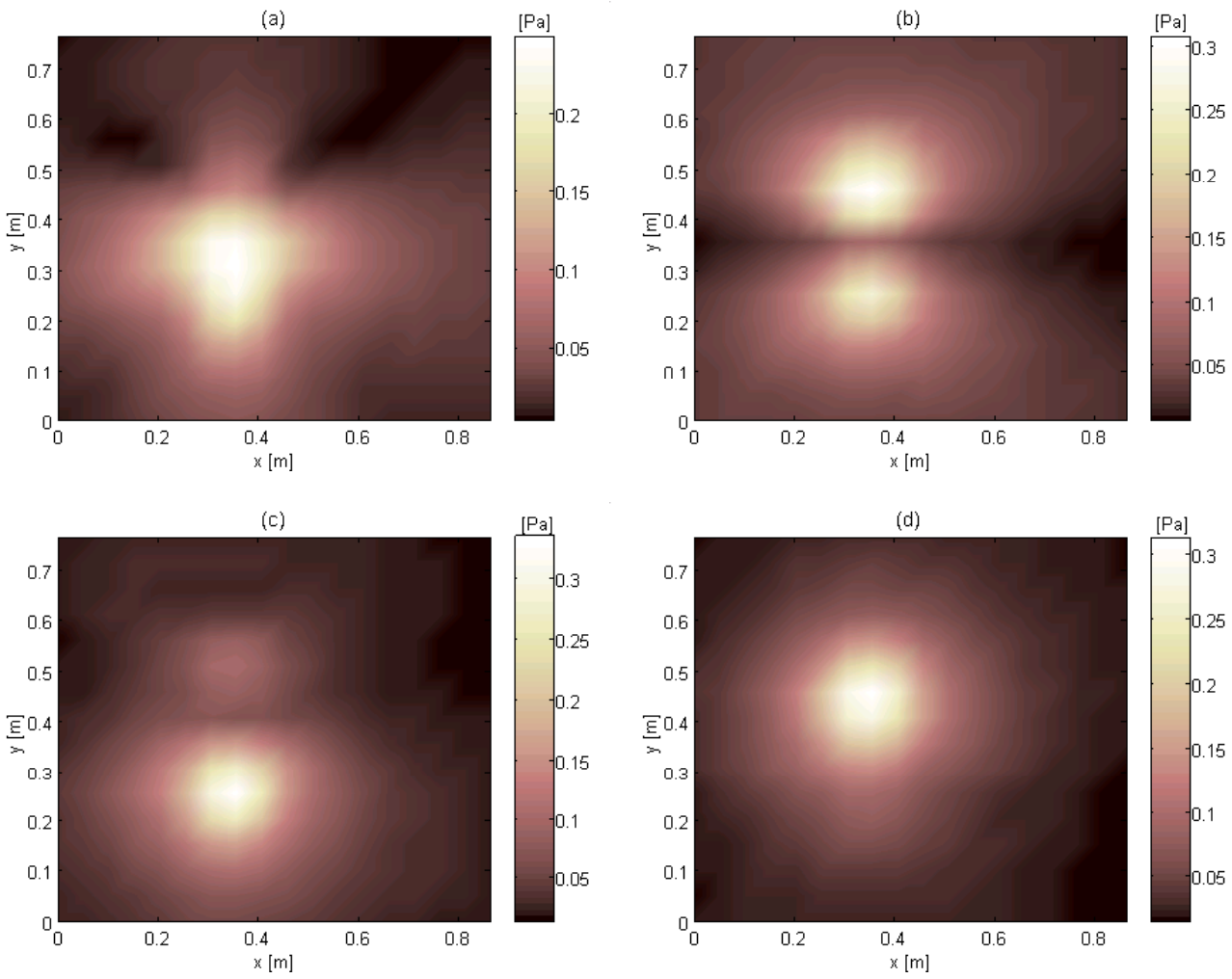
MUSIC POWER (1200 Hz)



(a) As a function of n = 1 to 288 and z = -0.1 to 0.1 m

(b) Plotted from z = -0.1 to 0.1 m when n = 170 (MAX(PMUSIC) = 1.2976 at z = -0.0212 m) and when n = 170 (MAX(PMUSIC) = 1.1351 at z = -0.0054 m)

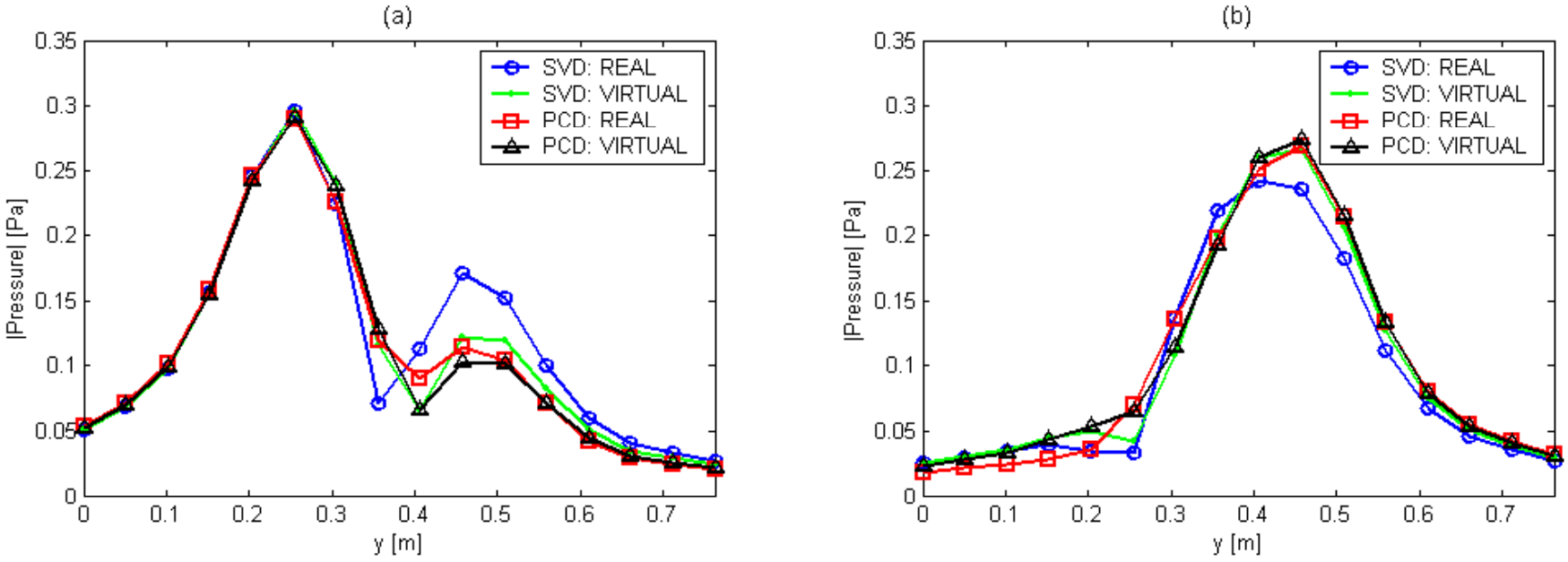
PARTIAL PRESSURE FIELDS (HOLOGRAM, 1200 Hz)



Measurement was made using references 3 and 5 (experiment):

(a) 1st field (real)
(b) 2nd field (real)
(c) 1st field (virtual)
(d) 2nd field (virtual)

PARTIAL PRESSURE FIELDS (x = 0.356 m)

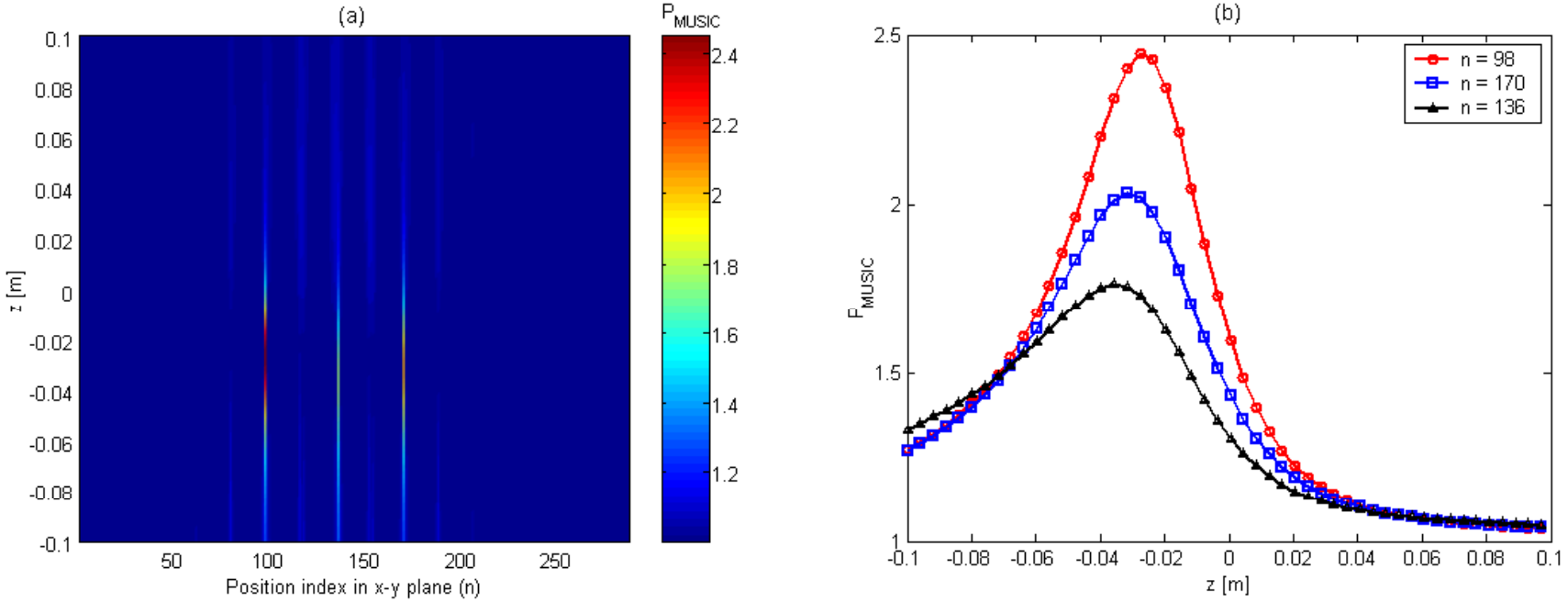


By using sets of real references 1 and 2 and optimal virtual references:

(a) 1st partial pressure field

(b) 2nd partial pressure field

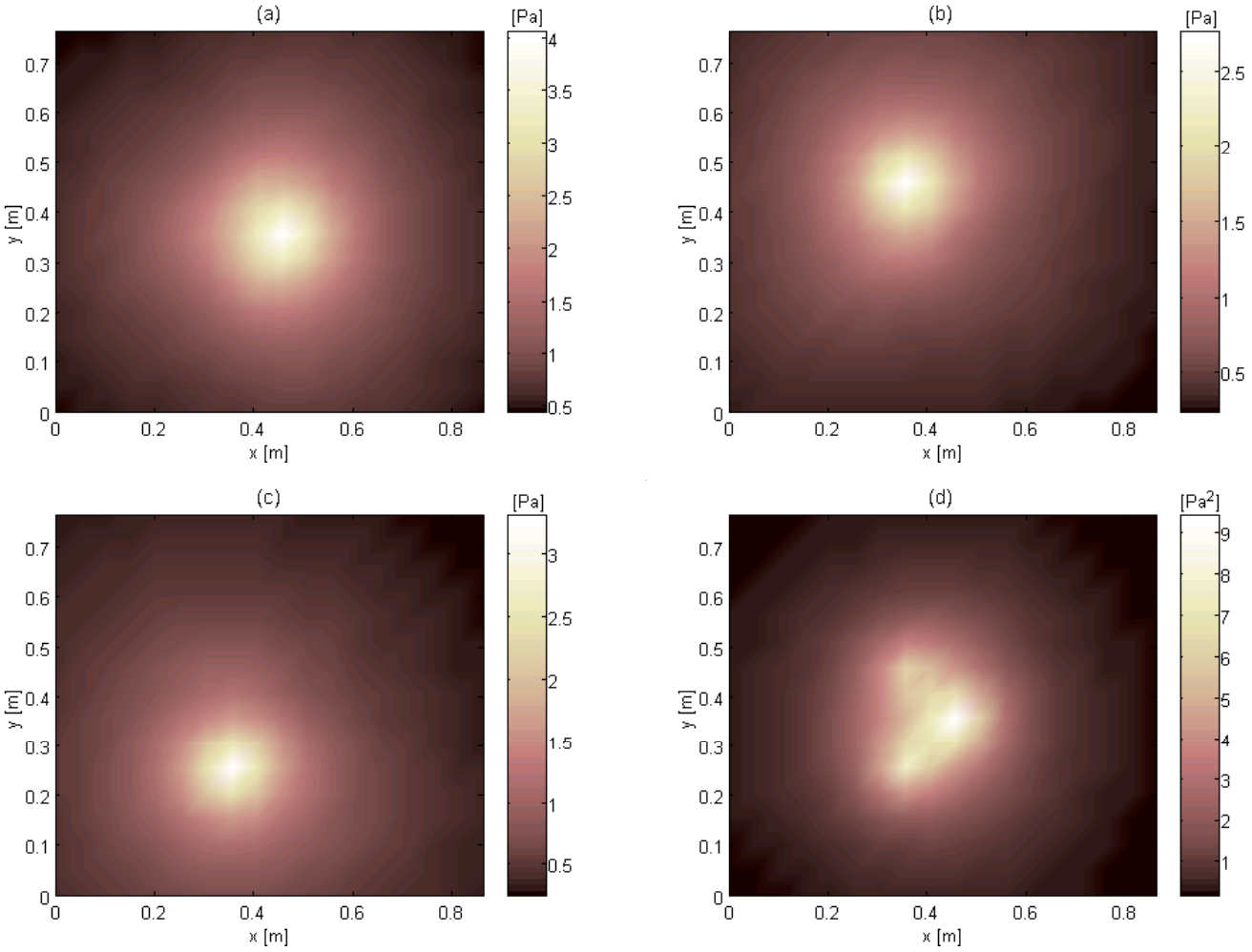
MUSIC POWER
(3 MONOPOLE SIMULATION, 1200 Hz)



(a) As a function of n = 1 to 288 and z = -0.1 to 0.1 m

(b) Plotted from z = -0.1 m to 0.1 m when n = 98 (MAX(P_{MUSIC}) = 2.4484 at z = -0.0268 m), when n = 170 (MAX(P_{MUSIC}) = 2.0323 at z = -0.0311 m), and when n = 136 (MAX(P_{MUSIC}) = 1.7636 at z = -0.0353 m)

DECOMPOSED PARTIAL PRESSURE FIELDS (3 MONOPOLE SIMULATION, 1200 Hz)



By using PCD procedure in combination with optimal virtual references:

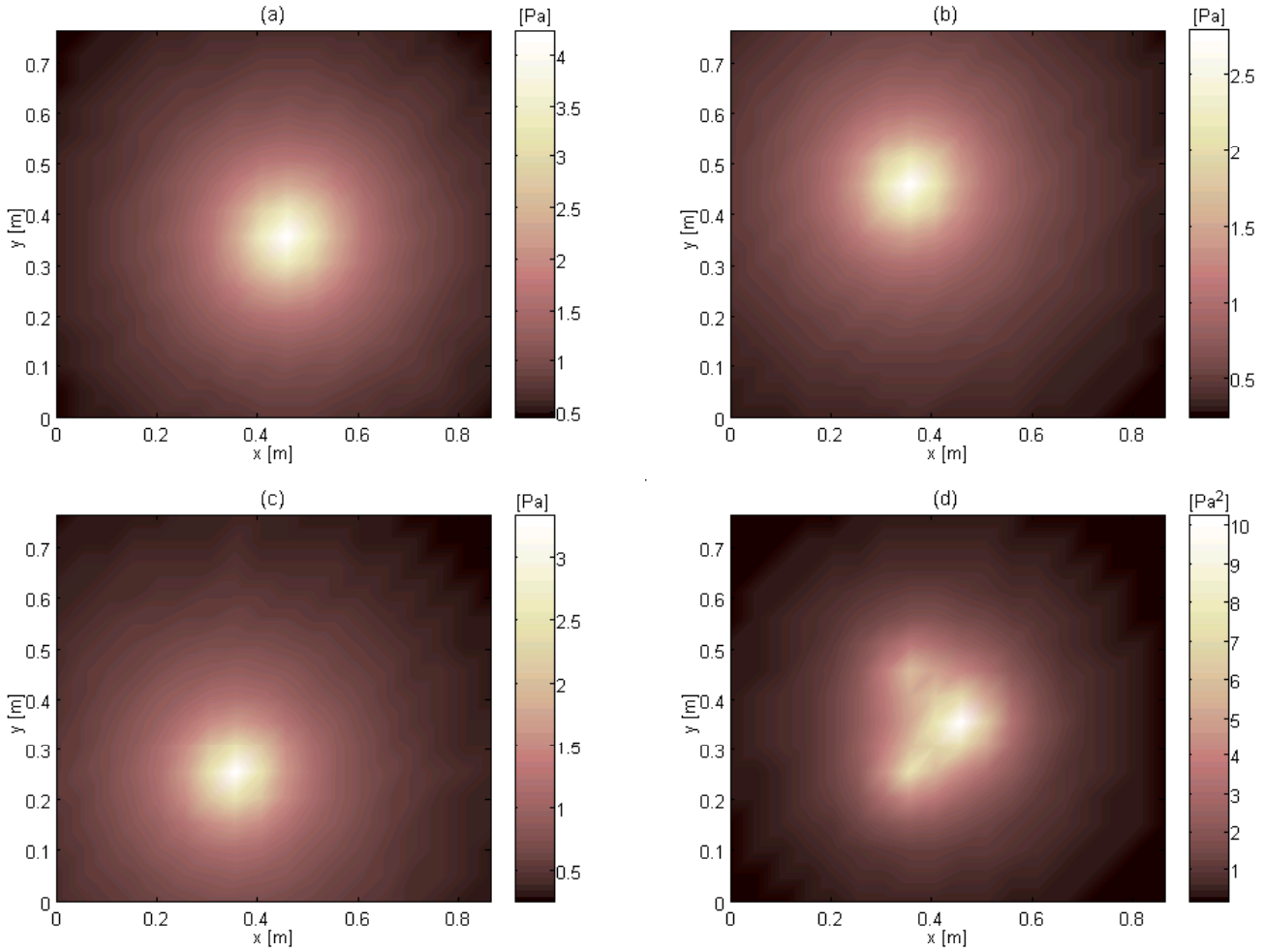
(a) 1st field

(b) 2nd field

(c) 3rd field

(d) total power

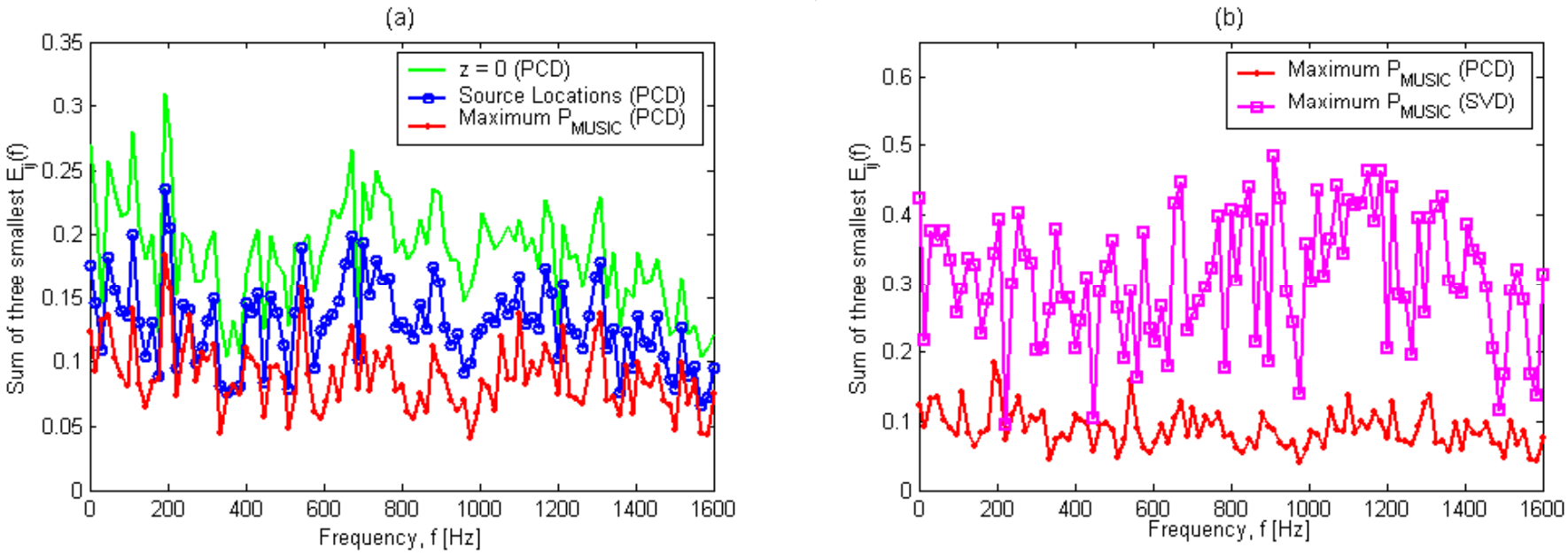
EXACT PARTIAL PRESSURE FIELDS (3 MONOPOLE SIMULATION, 1200 Hz)



(a) 1st field
(b) 2nd field
(c) 3rd field
(d) total power

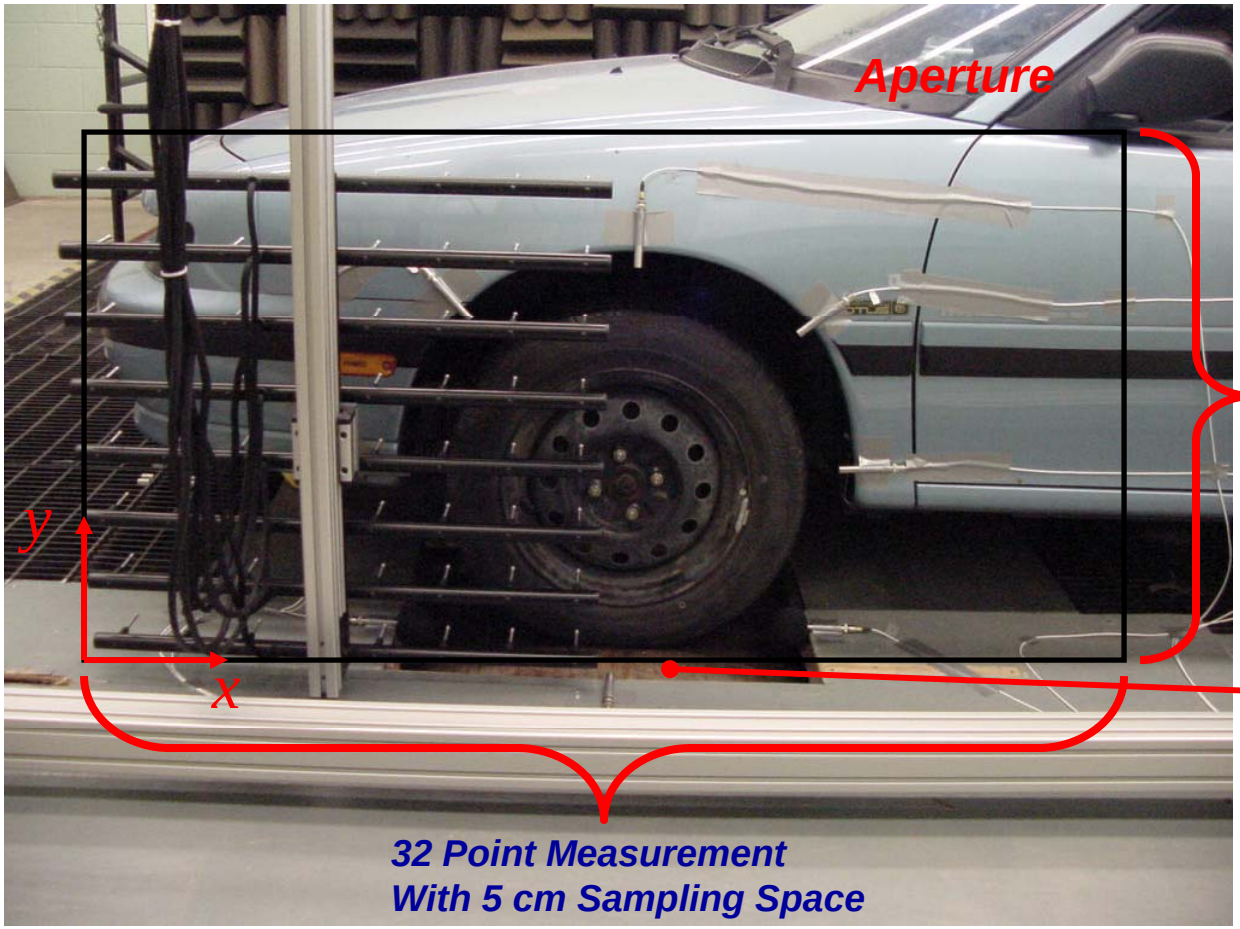
Purdue University **Herrick Laboratories**

ERROR (3 MONOPOLE SIMULATION)



Error between the exact partial pressure fields and those by virtual references with different decomposition methods and locations (simulation)

Rolling Tire Measurement



Tire driven by a roller

8 reference microphones

8 by 8 scanning mic. array

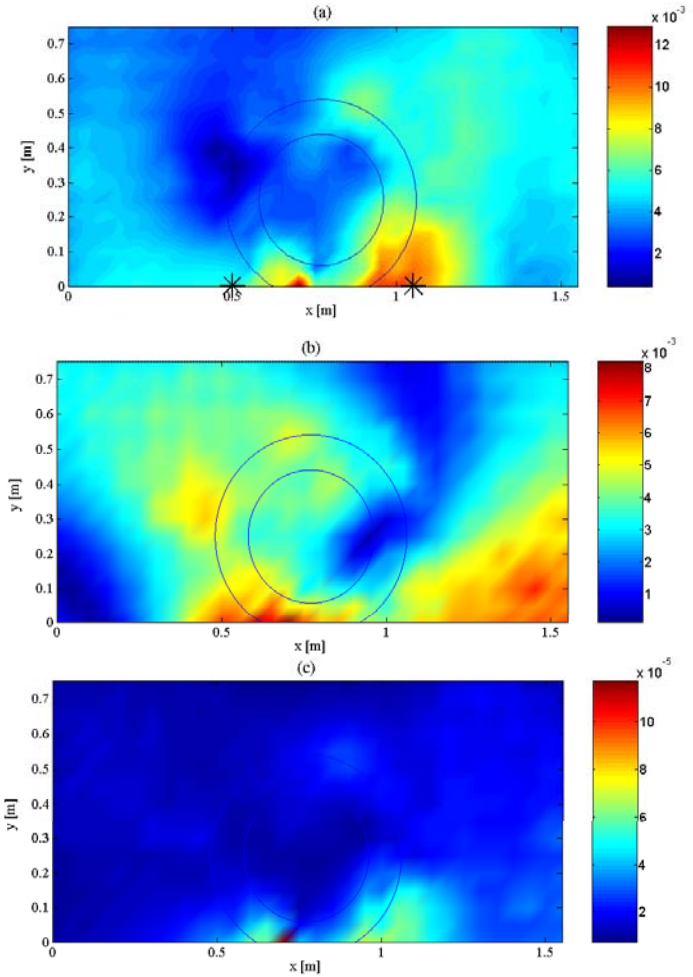
16 Point Measurement
With 5 cm Sampling Space

Hologram Height

$z_h = 6cm$

Smooth Roller Surface

Results (216 Hz & 21 mph)

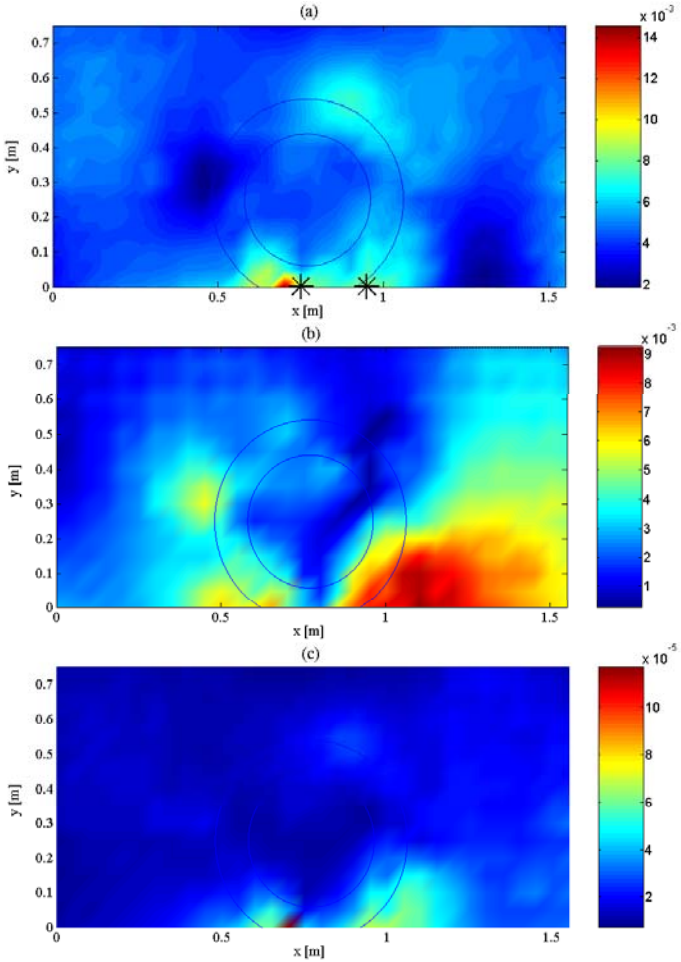


Real references 1 & 2

1st Partial Pressure Field

2nd Partial Pressure Field

Total Pressure Field



Virtual references

Summary (Virtual reference)

- Virtual reference signals can be used to identify physically meaningful partial fields *after* performing a holographic measurement.
- The virtual reference procedure resulted in partial fields associated with individual physical sources regardless of the locations of the real references.
- PCD in combination with virtual references gave the best results.
  - Virtual references located at the maximum MUSIC power locations resulted in the most accurate estimates of the partial fields (even better than a set of “good” real references).
  - The partial fields obtained by using the PCD procedure suffered less leakage than those obtained by using the SVD procedure.
- The proposed optimal virtual reference procedure can be used to separate the sound radiation from the sidewall and the horn region.