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The Design and Evaluation of Microphone Arrays for the Visualization of Noise Sources on Moving Vehicles

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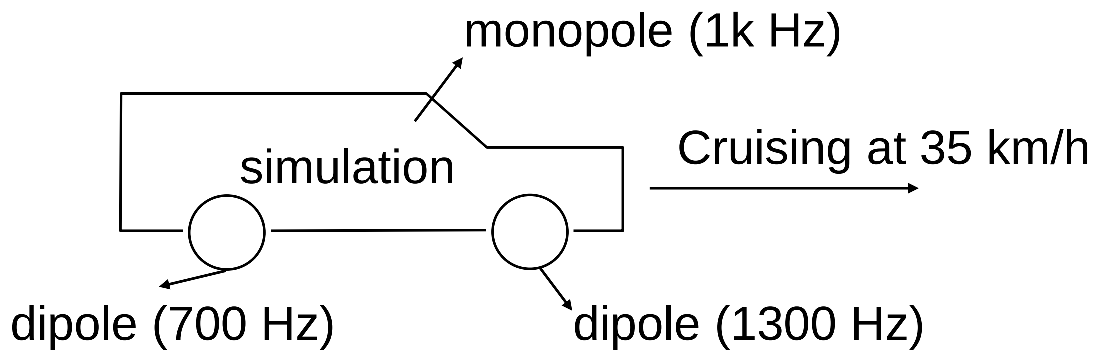
Motivations of Research

- **For large number of sensors, there exist a vast number of possible arrays**
- **Need to incorporate increased number of sensors to improve resolution**
  - for instance, to separate rear tire noise from exhaust noise
- **Need different resolutions in x- and z-directions and specific frequency range of interest for standard vehicle passby tests**
  - -10 to 10 m in x-direction and 0 to 2 m in z-direction are observed
  - 500 to 2000 Hz

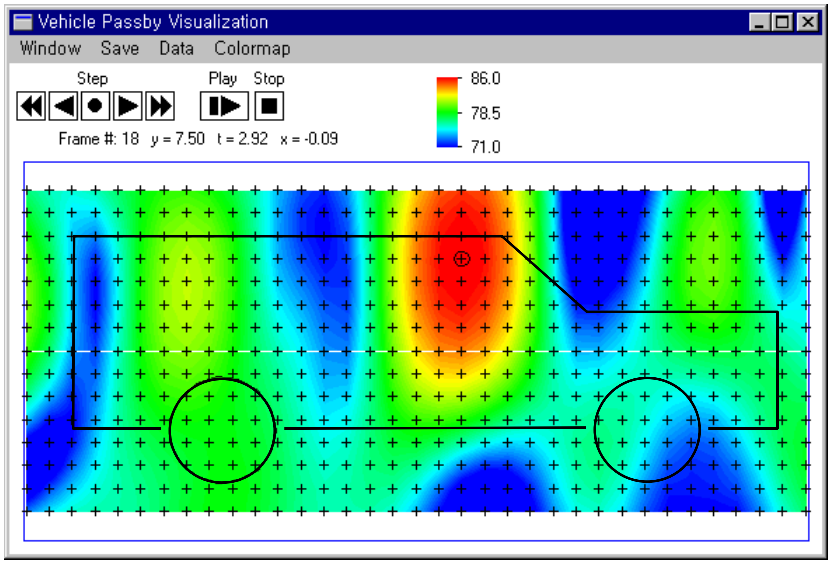
Objectives

- **Develop an efficient 2D-array design method to maximize the visualization capability given a number of sensors**
- **Evaluate and compare the new method with conventional 2D-array design methods**

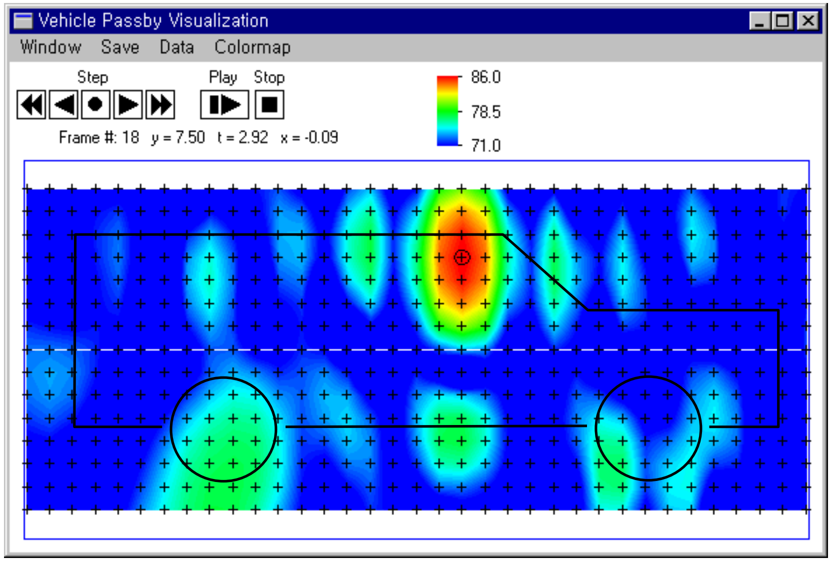
Resolution Improvement



x = -0.09 m, broadband

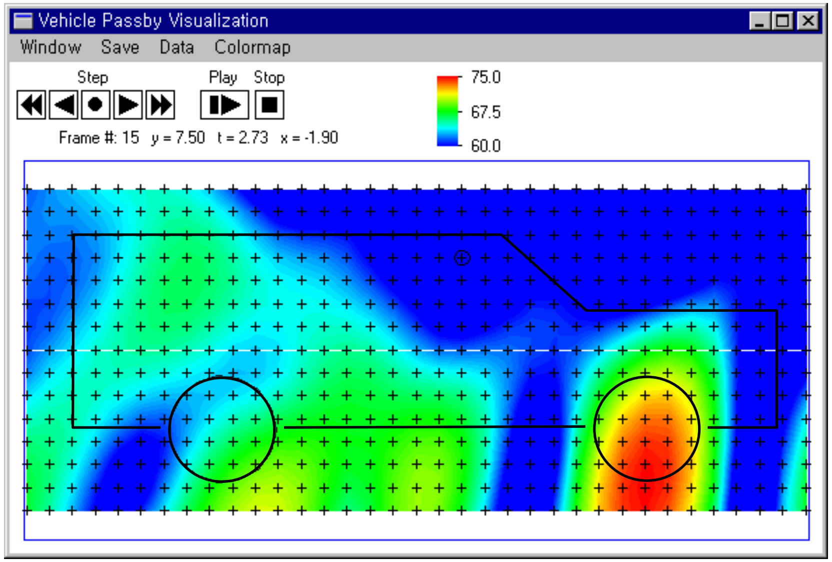


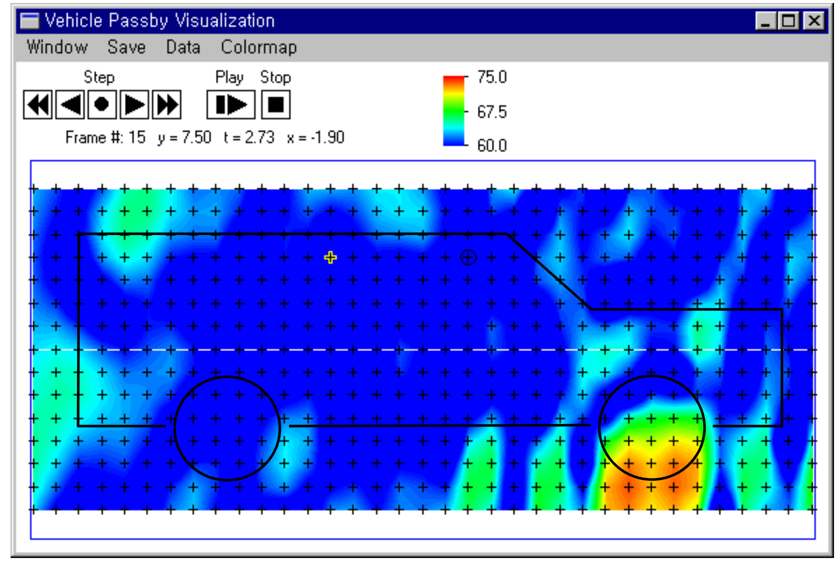
16-microphone array



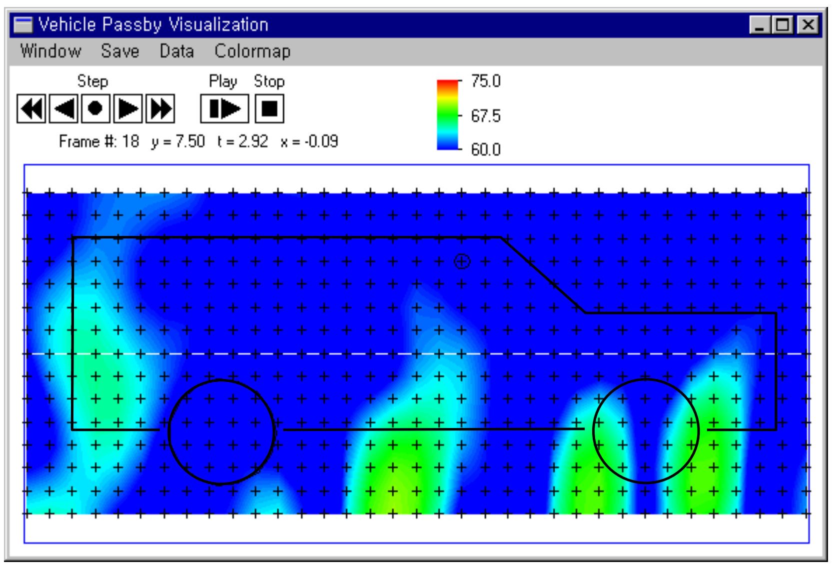
64-microphone array

x = -1.90 m, narrow band (100 Hz band)

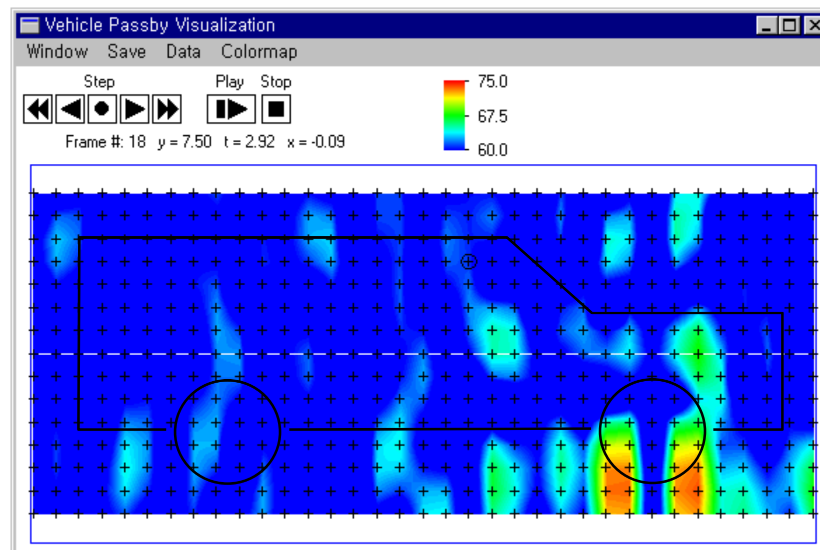




x = -0.09 m, narrow band (100 Hz band)



16-microphone array



64-microphone array

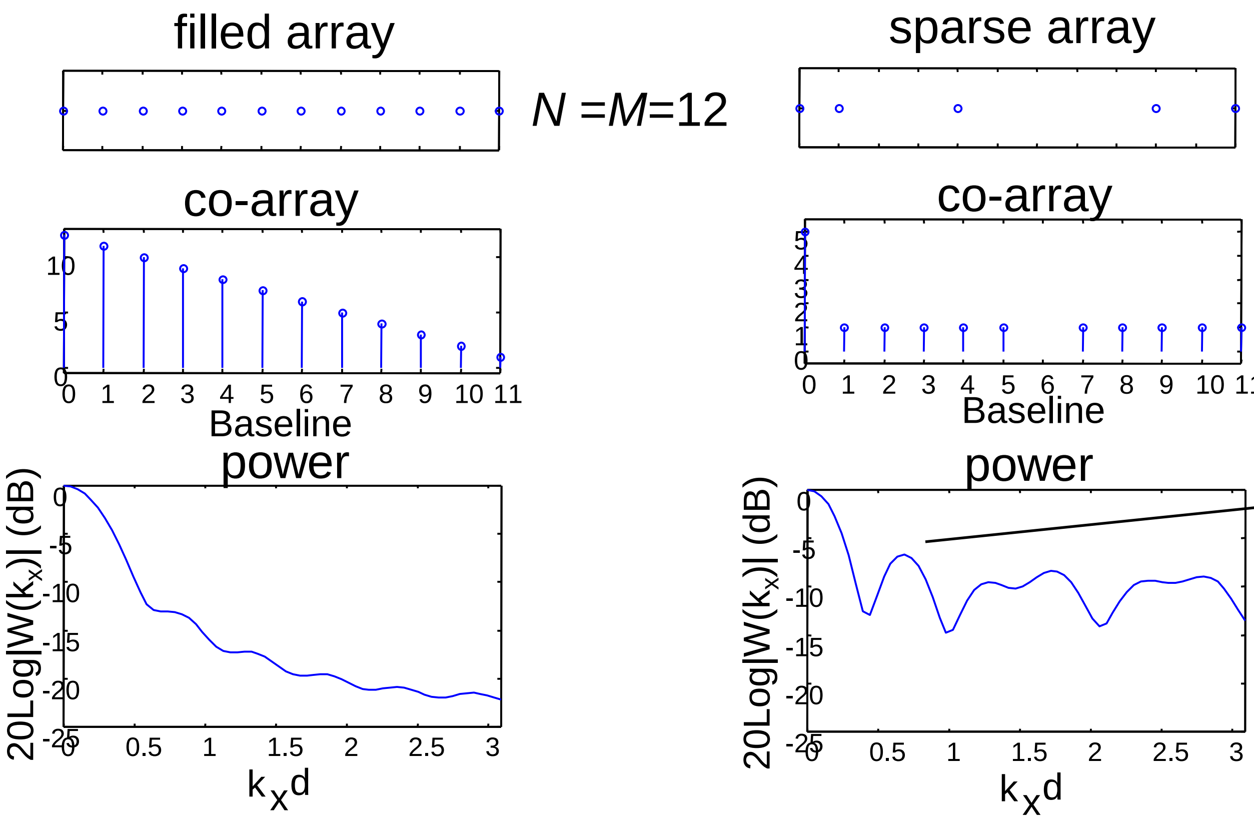
Sparse Arrays

- Conflicting requirements of arrays:

$$\frac{\text{large array aperture (}\textit{high resolution}\text{)}}{\text{small sensor spacing (}\textit{anti-spatial aliasing}\text{)}}$$

= large # of sensors (for filled arrays)

- Sparse arrays can be used to obtain similar mainlobe width.



N= 12, *M*=5

aperture size maintained

but yields higher sidelobe levels

- Sparse arrays:

  Sensors are not placed at all of the underlying grid locations of an aperture.

Co-array

- **Continuous form of autocorrelation function:**

$$c(\vec{\chi}) \equiv \int w(\vec{x})w(\vec{x}+\vec{\chi})d\vec{x}$$

- **Discrete form:**

$$c(\vec{\chi}) \equiv \sum_{(m_1,m_2)\in\vartheta(\vec{\chi})} w_{m_1} w_{m_1}^{*}$$

- **Spatial window**

  - estimate of power spectrum of stationary random field, $S_f(\vec{k},\omega)$ is smoothed by the Fourier Transform of $c(\vec{\chi})$

$$\mathrm{FFT}\{c(\vec{\chi})\} = \left|W(\vec{k})\right|^2$$ (***for planar beamforming***)

  - that is why mainlobe width remained almost the same as long as the aperture size remained unchanged

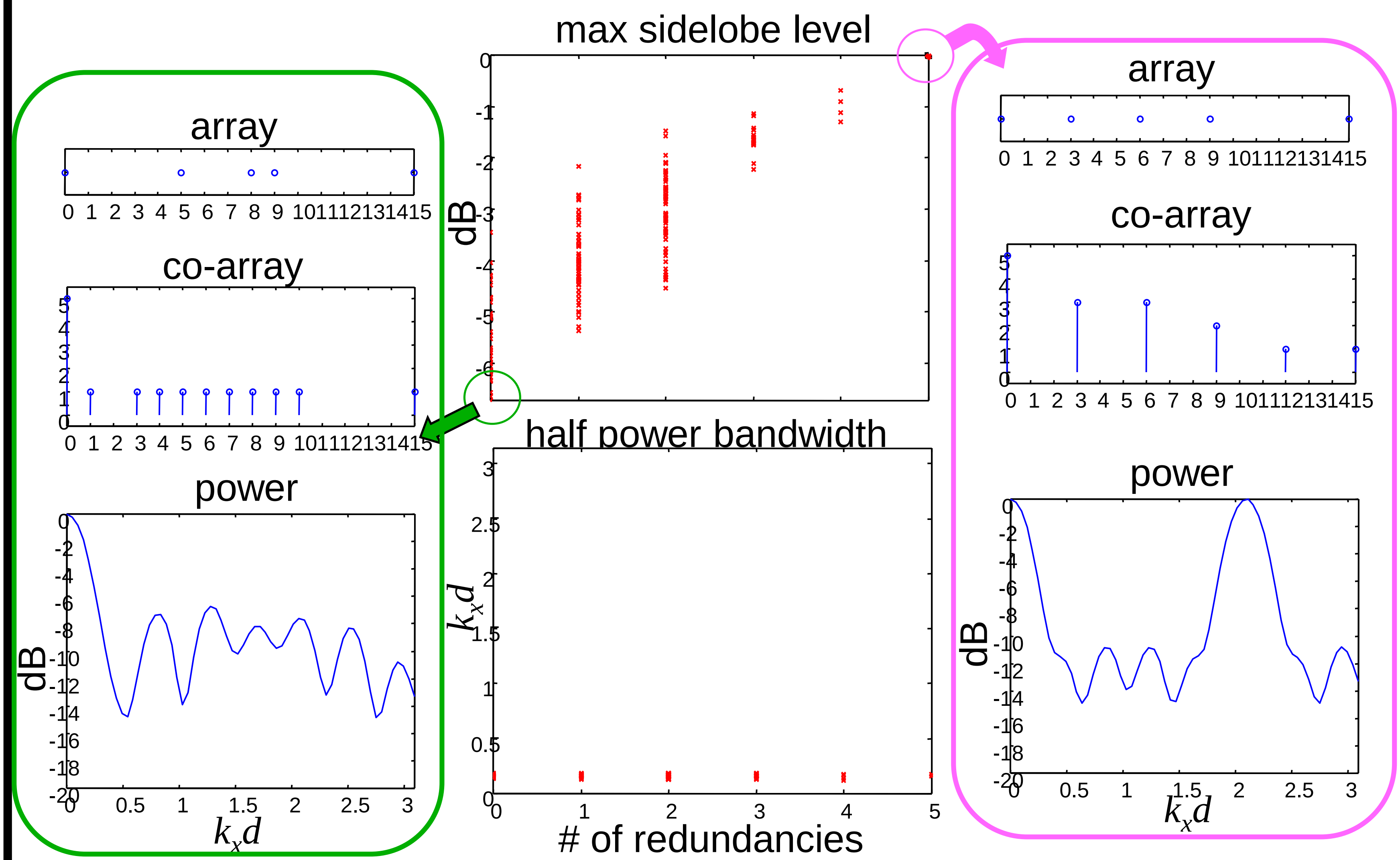
Notes

- For grid size of *N* and *M* # of sensor, total # of possible array configurations is ${}_{N-2}C_{M-2}$ (with two sensors fixed at both ends of the aperture).
- Maximum sidelobe levels differ for each array configuration.
- For linear arrays with *M* =< 4 and associated *N* (= *M*(*M*-1)/2+1), there exist non-redundant arrays with no-gaps in the co-array, which coincide with the array with lowest # of redundancies.
- For arbitrary numbers of *N* and *M* , there is no known method to directly solve the "best" array with the lowest maximum sidelobe level in the group of possible array configurations , and correlation btwn # of redundancies & maximum sidelobe levels unknown.

for numbers of N and M, correlation between # of redundancies, maximum sidelobe levels and power bandwidths are simulated for linear arrays

of Grid Points = 16, # of Sensors = 5 (Linear)

(*With first & Last grid points taken by sensors*)



Correlation btwn # of Redundancies & Sidelobe Levels

of Grid Points *N* = 16

M=4,

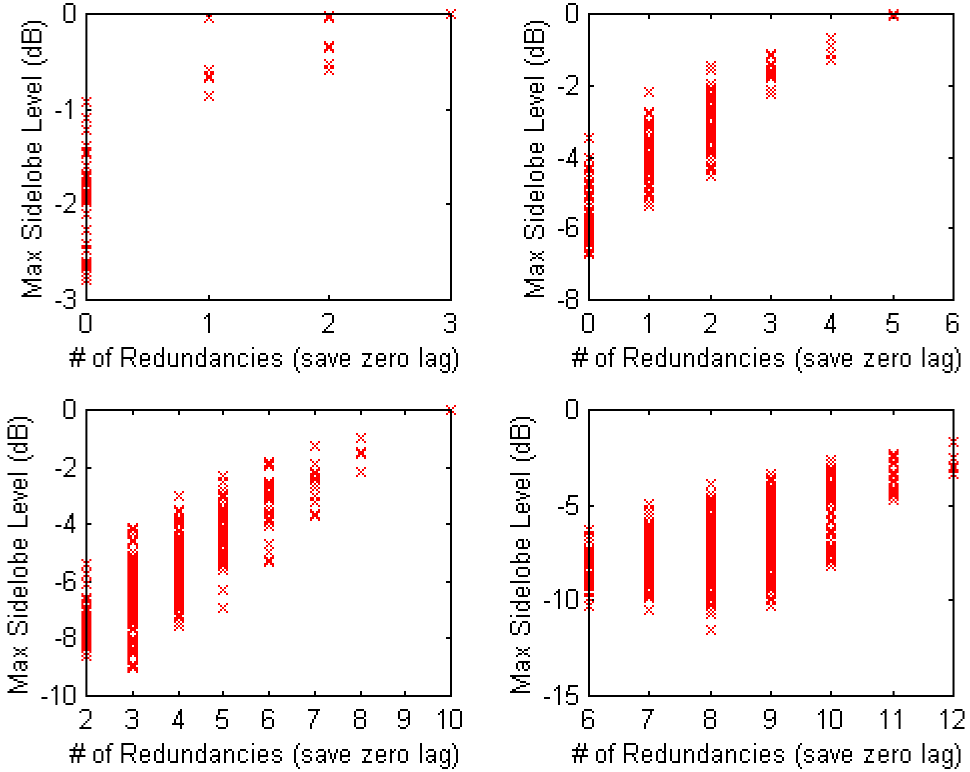
$_MC_2$=6 < *N*-1

(under packed)

M=5,

$_MC_2$=10 < *N*-1

(under packed)



M=6,

$_MC_2$=15 = *N*-1

M=7,

$_MC_2$=21 > *N*-1

(over packed)

"Under packed" : *N*-1 greater than # of possible baselines

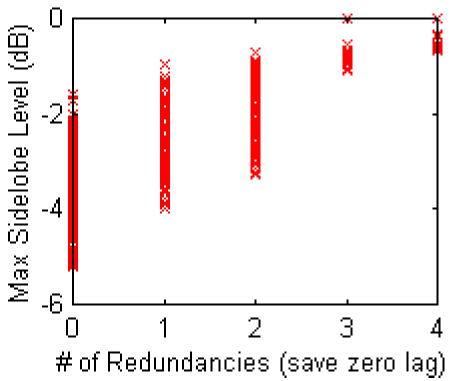
Correlation btwn # of Redundancies & Sidelobe Levels

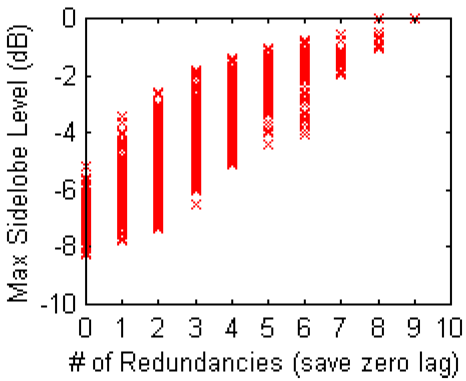
of Grid Points N = 22

M=5,

${}_{M}C_2$=10 < N-1

(under packed)





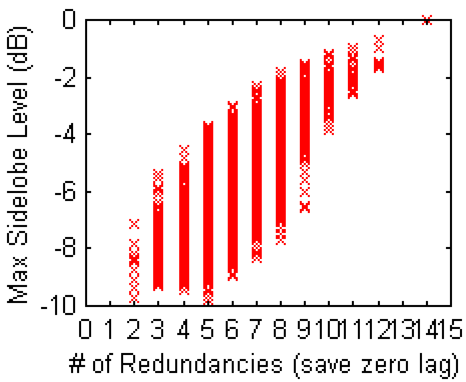
M=6,

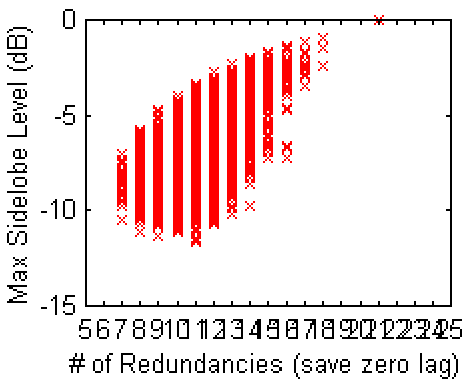
${}_{M}C_2$=15 < N-1

(under packed)

M=7,

${}_{M}C_2$=21 = N-1





M=8,

${}_{M}C_2$=28 > N-1

(over packed)

Roughly, low # of redundancies yields better sidelobe level reductions.

Summary

- When under-packed, the array with the lowest maximum sidelobe level is in the array groups with the lowest # of redundancies.
- Some arrays in the group has higher maximum sidelobe levels.

Design Strategy

(1) *M* sensors are placed on the given grid, and the number of redundancies is computed.

(2) a list of a number of best array configurations is maintained based on the # of redundancies.

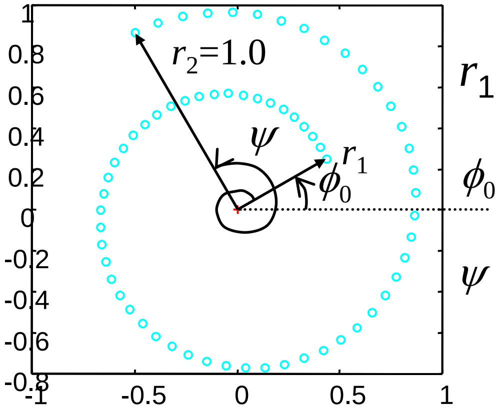
(3) repeat step (1) and (2) to test as many array configurations as possible.

(4) compute the powers of the arrays in the list and select the best array (for example by inspection).

A "good" array design method maximizes the chance to "hit" an array configuration with low redundancies in step (1), among the large number of candidate configurations.

Elliptically Spiral Array Design Method

parameters: r_1, ϕ_0 ,and ψ

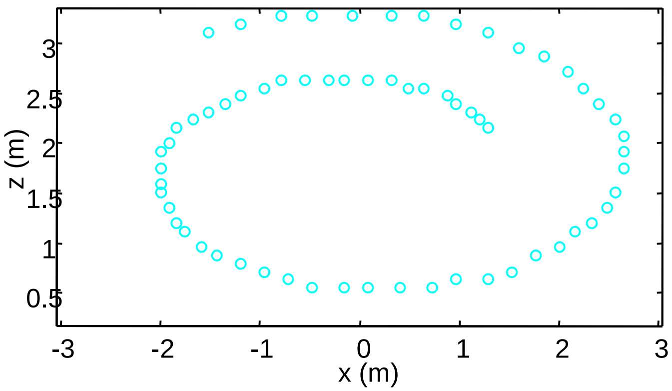


r_1 : 0 to 1 (33 increments)

ϕ_0 : 0 to 2 pi (43 increments)

ψ : 2 pi to 6 pi (85 increments)

mapped and snapped onto the underlying grid

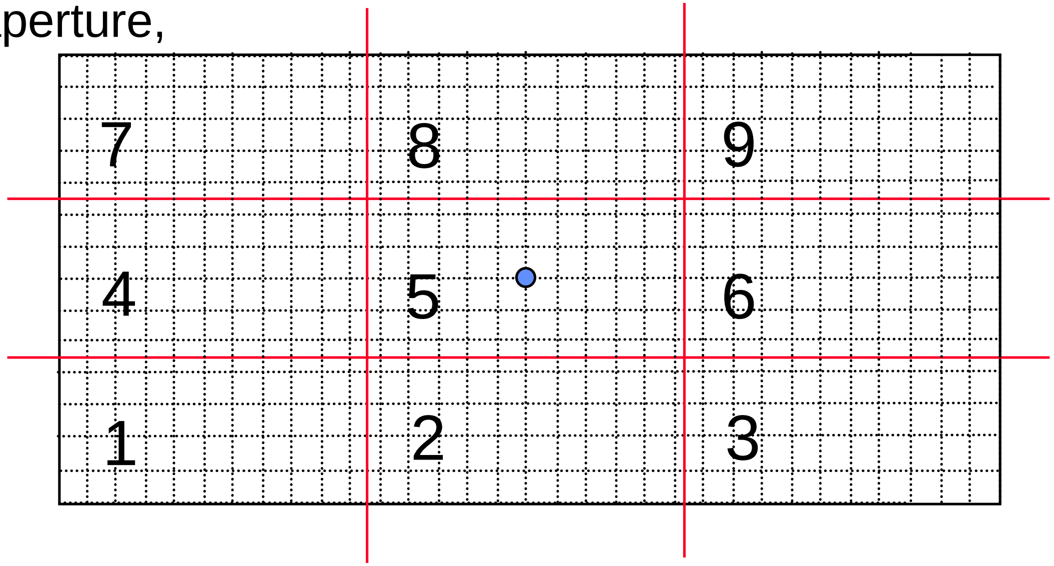


can generate elliptical arrays with non-constant angular spacing (when ψ is not an integer number of 2π).

Random Array Design Method w/ Segmenting Scheme

- A random array is an extreme version of a non-redundant array.
- In practice, array elements can “clump” together spatially.

to control the possibility of “clumping” of sensors in one region of the aperture,



first sensor is placed at the aperture center, then remaining sensors are randomly placed in the subsection in the order

When less than 9 sensors left -> in the order of subsection 5, 5, 4, 6, 2, 8, 5, 5

Improved Random Array Design Method

m = 1;

for m^{th} sensor;

generate random numbers for unoccupied grid points and sort the grid points(either in ascending or descending order);

compute the further # of redundancies by taking the grid point as the sensor place;

if # of further redundancies is zero, place the sensor at the grid point;

if not, investigate the next grid point until a grid point with no further # of redundancies is found;

if no such grid point exists, choose the grid point with minimum further # of redundancies;

repeat

Computation Summary

d = 8 cm was determined to avoid aliasing for frequency 2k Hz.

Array design Input parameters.

Number of sensors	64
Best possible baseline (lag) numbers	${}_{64}C_2 + 1 = 2017$
Grid size	$75 \times 39 = 2925$
Number of possible array configurations	${}_{2925}C_{64}$ = ??? a very large number
Packing ratio = Best possible baseline numbers / grid size	$2017/2925 \times 100 = 68.9$ %

Results from three different array design methods

Array design method	Run time	Best redundancy obtained	Number of redundancies in nonzero lags	Occupancy % in co-array
Random arrays with segmenting scheme	601.9 minutes (78000 runs)	**427**	427 – 63 = 364	(2017 – 427)/2925 *100 = 54.4 %
The improved random array design method	623.1 minutes (37 runs)	**184**	184 - 63 = 121	(2017 - 184)/2925 *100 = 62.7 %
Elliptically spiral arrays	672.3 minutes (120615 runs)	**317**	317- 63 = 254	(2017 – 317)/2925 * 100 = 58.1 %

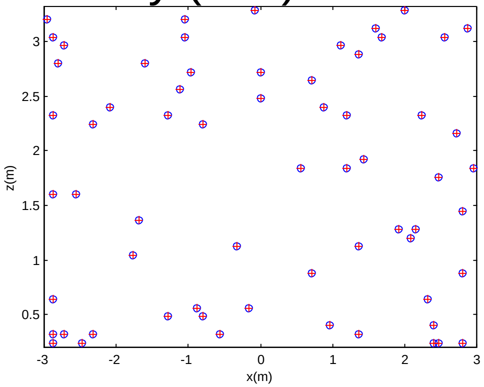
Best 10 Arrays with Minimum Redundancies

Array #	modified random array	rank #1	rank #2	elliptical array	rank #1	rank #2	random array with segmenting scheme	rank #1	rank #2
1	*184*	3	2	*317*	8	6	*427*	2	4
2	*184*	4	9	*320*	10	3	*430*	8	2
3	*184*	6	3	*321*	5	10	*433*	7	3
4	*185*	7	7	*326*	3	4	*436*	1	7
5	*186*	2	8	*326*	1	1	*436*	4	5
6	*187*	8	4	*327*	2	7	*437*	3	9
7	*191*	9	10	*328*	4	2	*437*	10	1
8	*192*	1	1	*329*	6	5	*439*	5	8
9	*194*	5	5	*329*	7	8	*439*	9	6
10	*195*	10	6	*329*	9	9	*439*	6	10

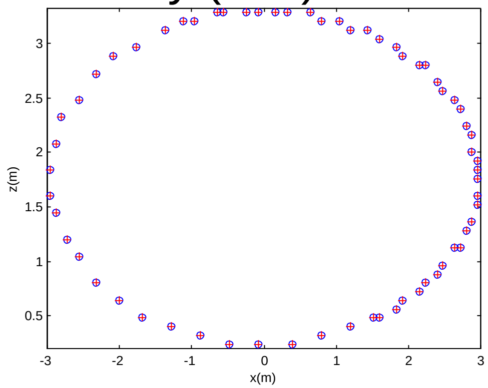
Arrays were ranked by inspecting power spectrums with source freq. at f=500, 1k, 1.5k and 2k Hz, positioned at x_0= 0m (*rank*#1) and x_0=10m (*rank*#2).

Selected Arrays to be Compared

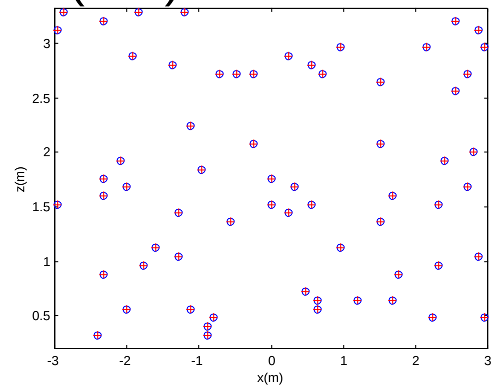
modified random array (192)



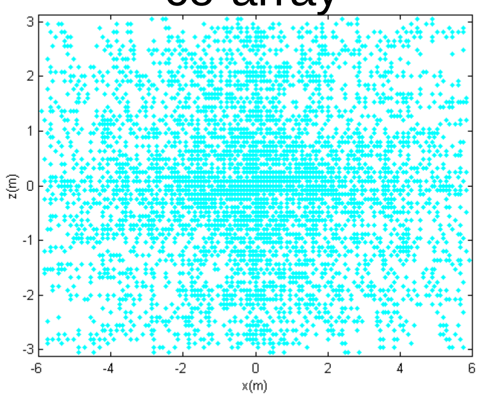
elliptically spiral array (326)



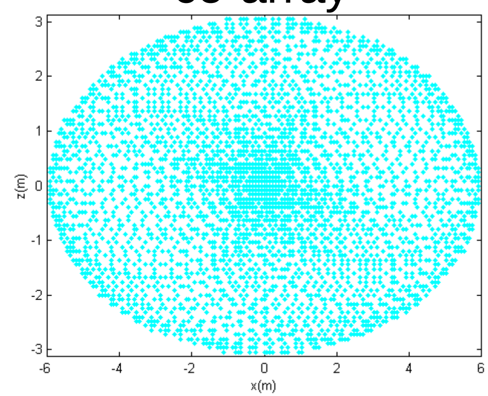
random array with segmenting scheme (427)



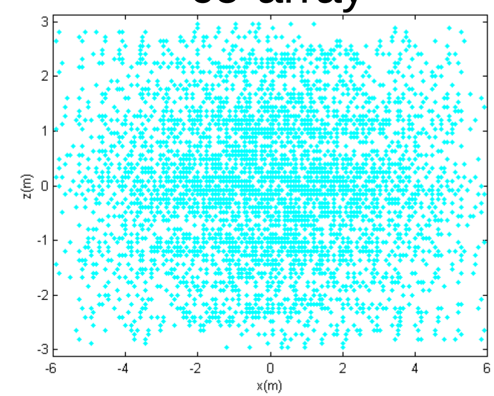
co-array



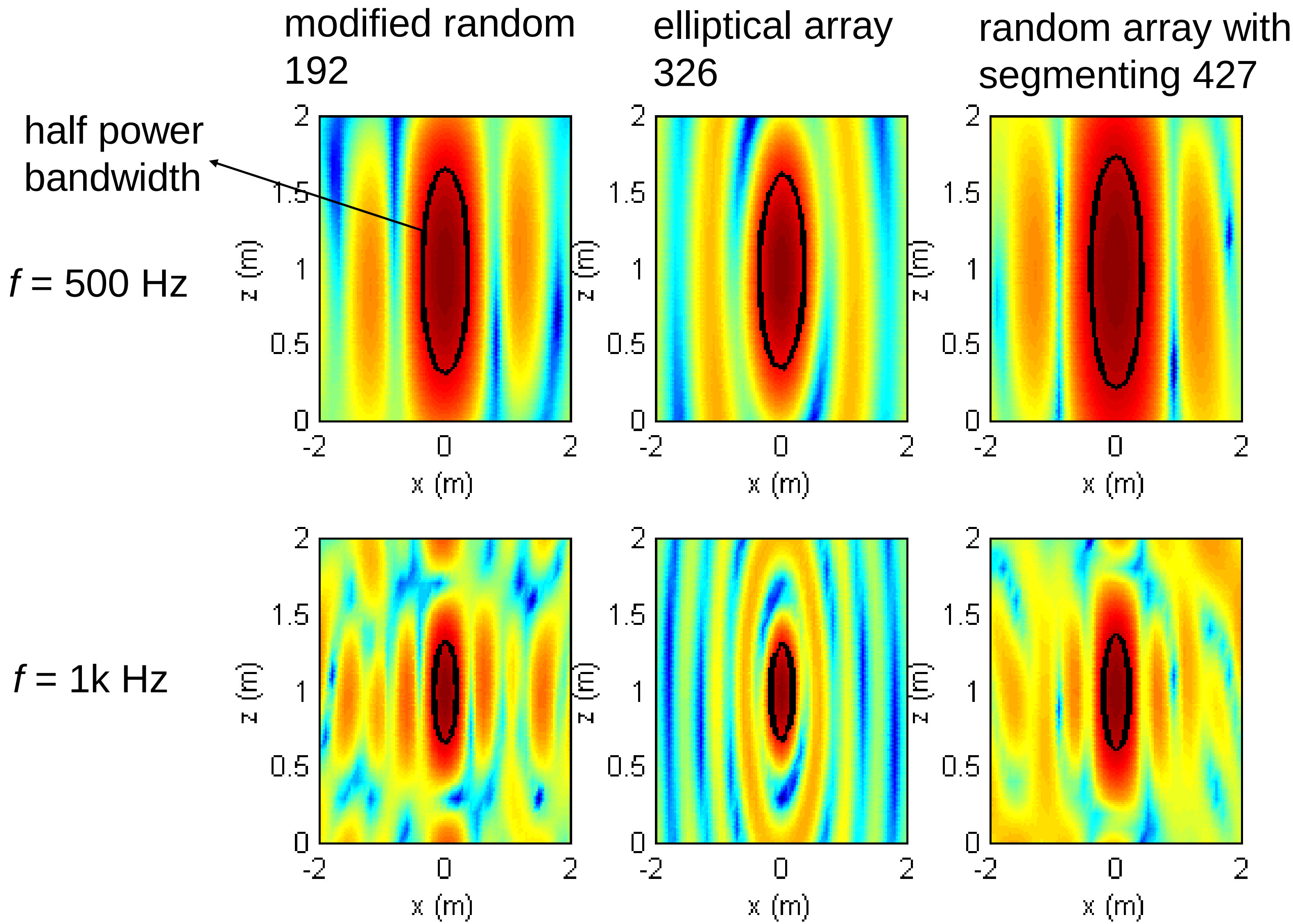
co-array



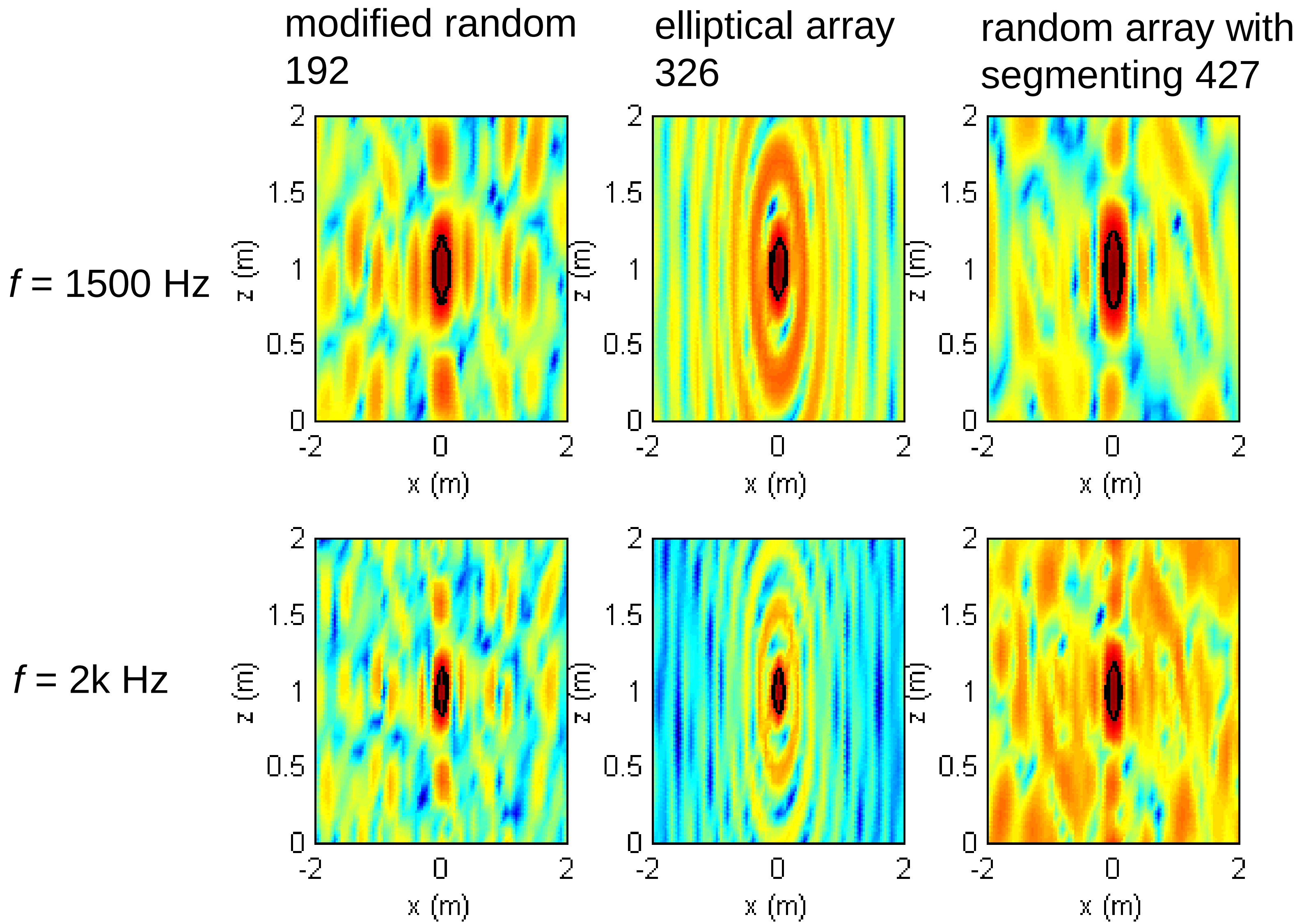
co-array



Simulated Power at x_0 = 0 m



Simulated Power at x_0 = 0 m

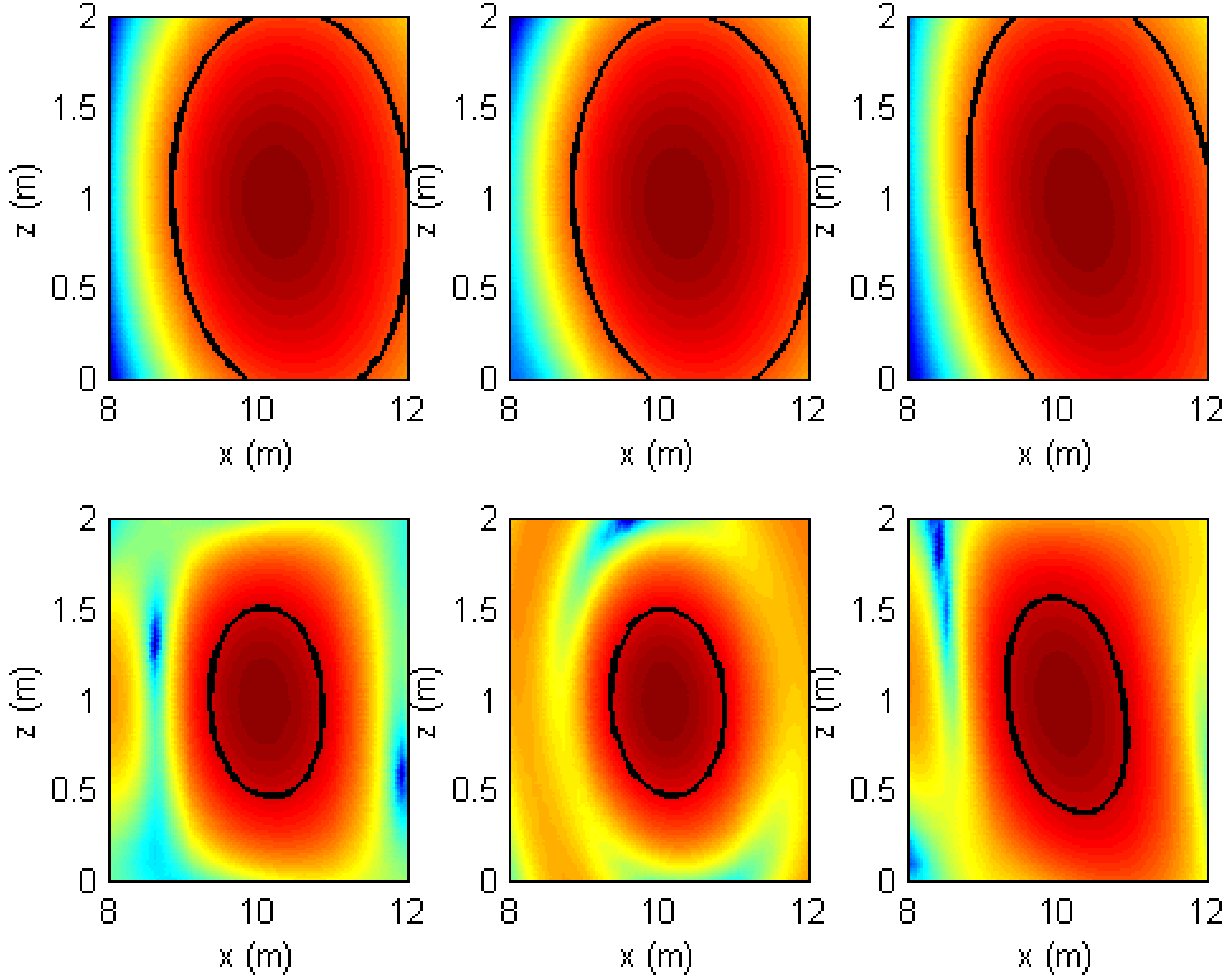


Simulated Power at x_0 = 10 m

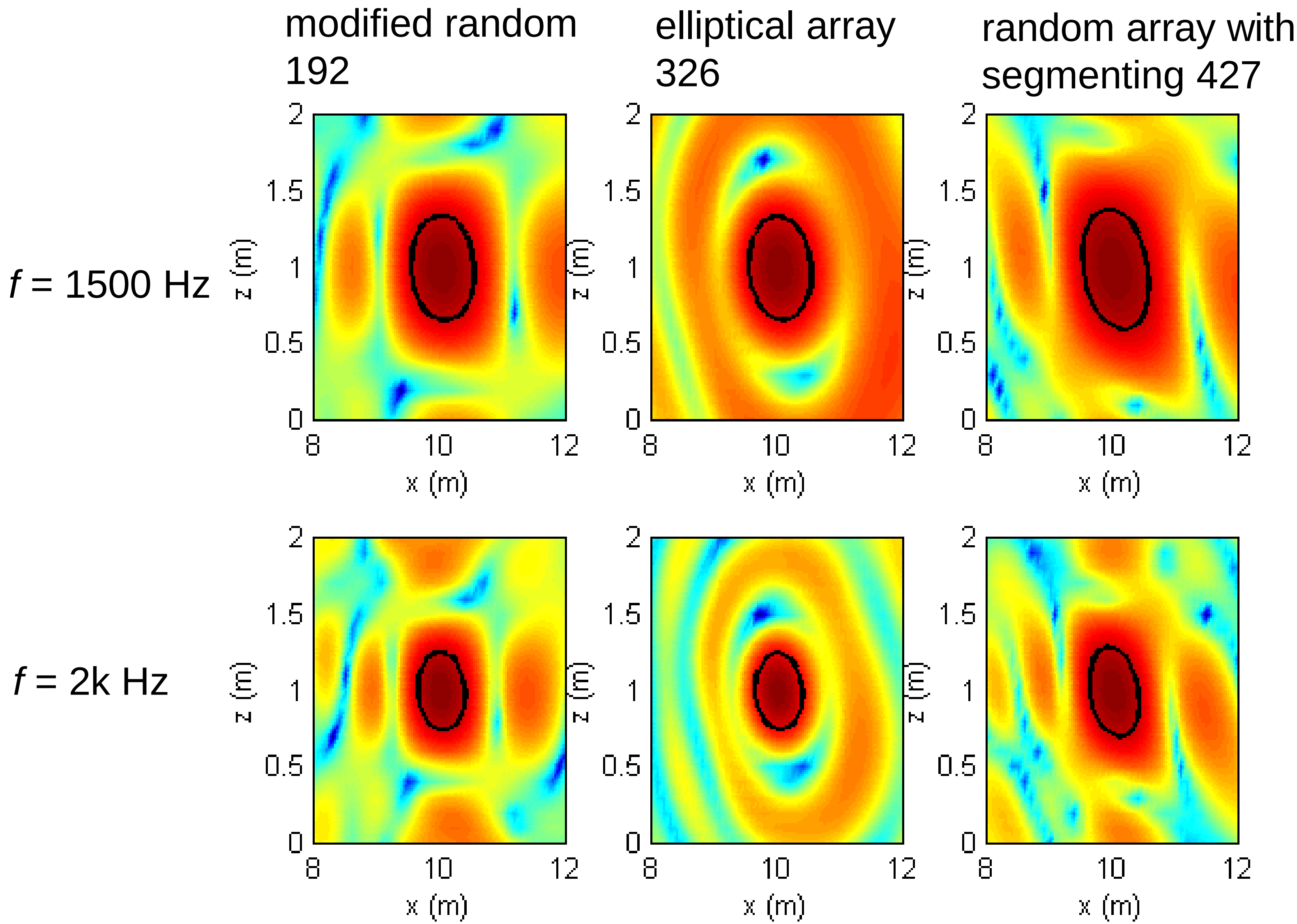
modified random 192 | elliptical array 326 | random array with segmenting 427

f = 500 Hz

f = 1k Hz



Simulated Power at x_0 = 10 m



Conclusions

- An heuristic array design method was developed that can be used for arbitrary shaped grid.
- The new array design method generated array configurations with the lowest numbers of redundancies among the array design methods compared.
- The array generated from the new method yielded narrower mainlobe compared with the array resulted from random array design method with segmenting scheme, and lower sidelobe levels compared with the elliptically spiral array.

Recommendations

- The number of candidate array configurations which are inspected after the iteration procedure should be increased to enhance the chance to find a good array with relatively higher # of of redundancies in each group.
- Develop a method to optimize the # of grid points, *N*, when *M* sensors are given to increase the array design performance.