Using arrays of loudspeakers for focusing or diffusing sound

February meeting of Pacific Northwest section of Audio Engineering Society (AES)

Agenda

- Loudspeaker arrays applications in home entertainment and in the office
  - Mike Seltzer, Microsoft Research
- Focusing sound principle and generic beamforming
  - Jasha Droppo, Microsoft Research
- Robust beamformer design for loudspeaker arrays
  - Ivan Tashev, Microsoft Research
- Generating diffuse sound with loudspeaker arrays
  - James (jj) Johnston, Microsoft Corporation
- Demos of loudspeaker arrays:
  - Focusing sound
  - Multiple beams
  - Diffusing sound
  - Home entertainment

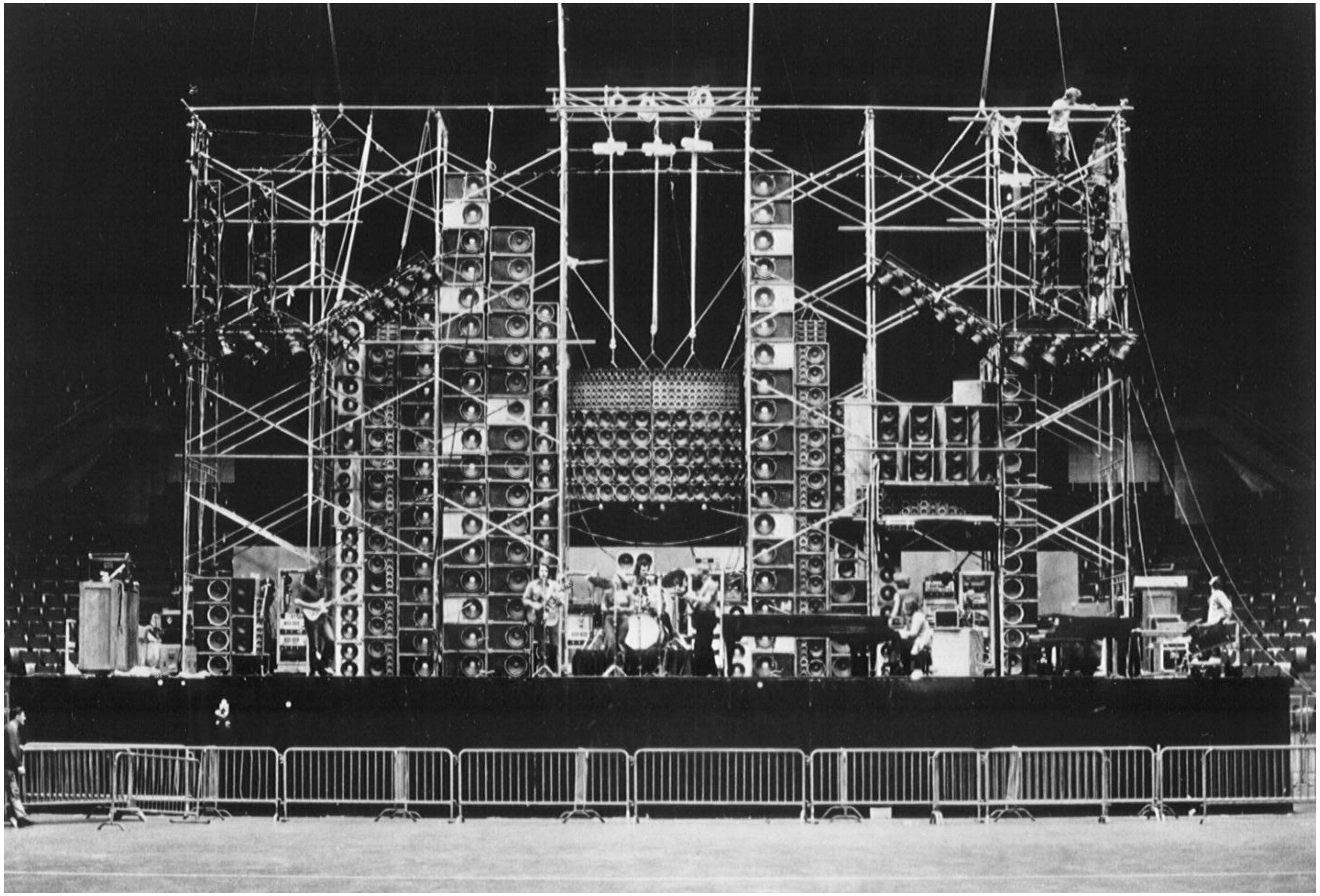
Loudspeaker arrays applications in home and in the office

Mike Seltzer, Microsoft Research

Loudspeaker Arrays

- Chain multiple speakers to create a more uniform sound field in a performance space
  - Undo the directivity of the individual speakers
  - Every seat is a good seat
- Requires healthy dose of art and science
  - Commodity parts
  - Performance space is not well behaved
  - Size and cost constraints
  - On-site installation

I should put ***this*** in my home?



Well, sort of…

- Question of the night:
  - *What (other) experiences can be enabled with loudspeaker arrays in the home and office?*
  - *Can these experiences be realized?*
    - Commodity parts
    - Performance space is not well behaved
    - Size and cost constraints
    - ~~On-site installation~~
    - Mass production scale quantities

Scenarios: Office

Listening to private phone call …

… instead of holding a handset

Scenarios: Office

Listen to favorite music not wearing headset …

… instead of wearing headset and not able to hear anything else.

Scenarios: Home

Create personal audio space and listen to music/TV while the baby is sleeping, …

… or wear a headset all time, …

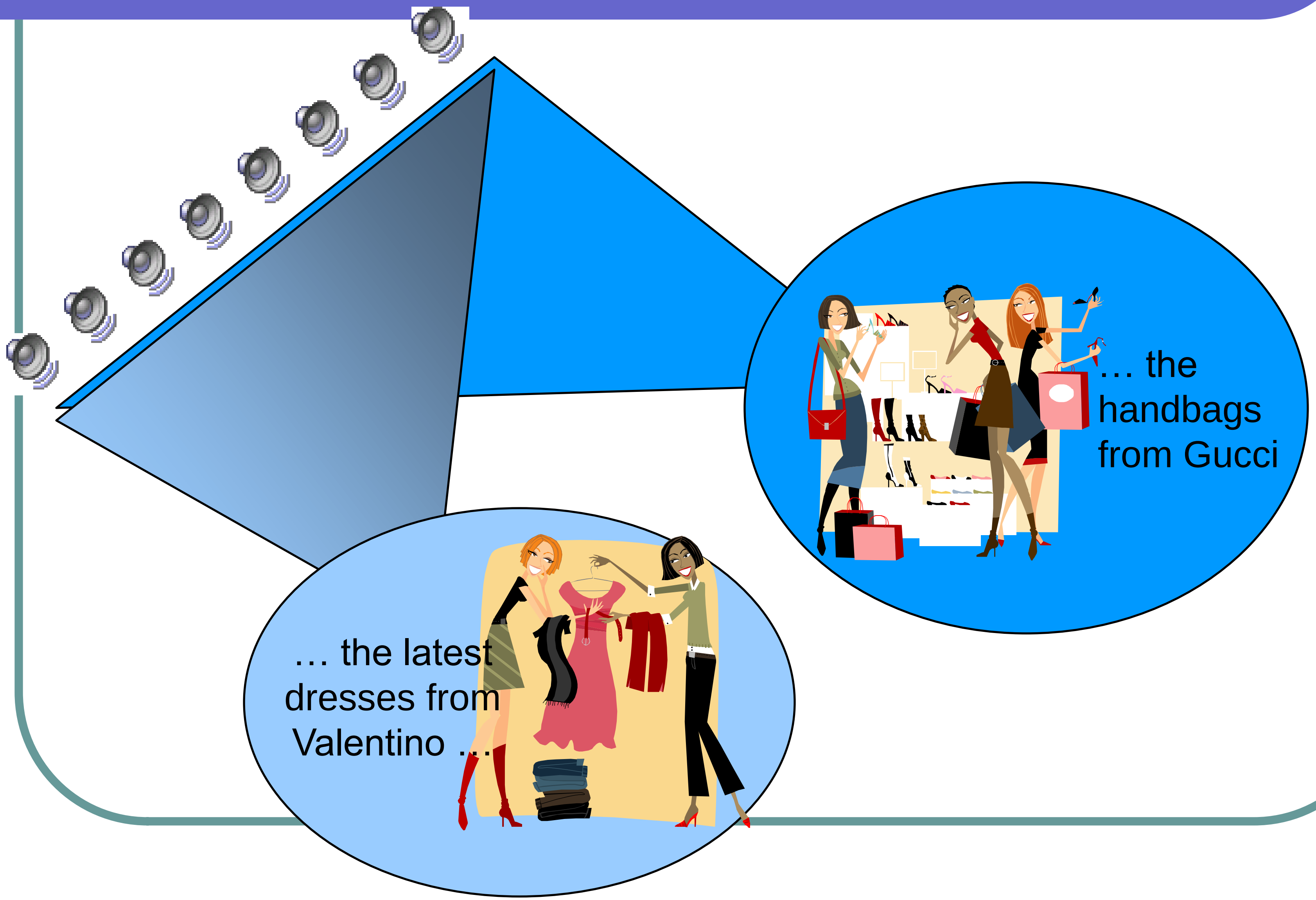
… or deal with the crying baby!

Scenarios: Home

- Different strokes for different folks: multiple sound beams!

…picture-in-picture TV watching,
DVDs in different languages, split screen gaming, etc

Scenarios: Retail/Museum



Anyone doing this?

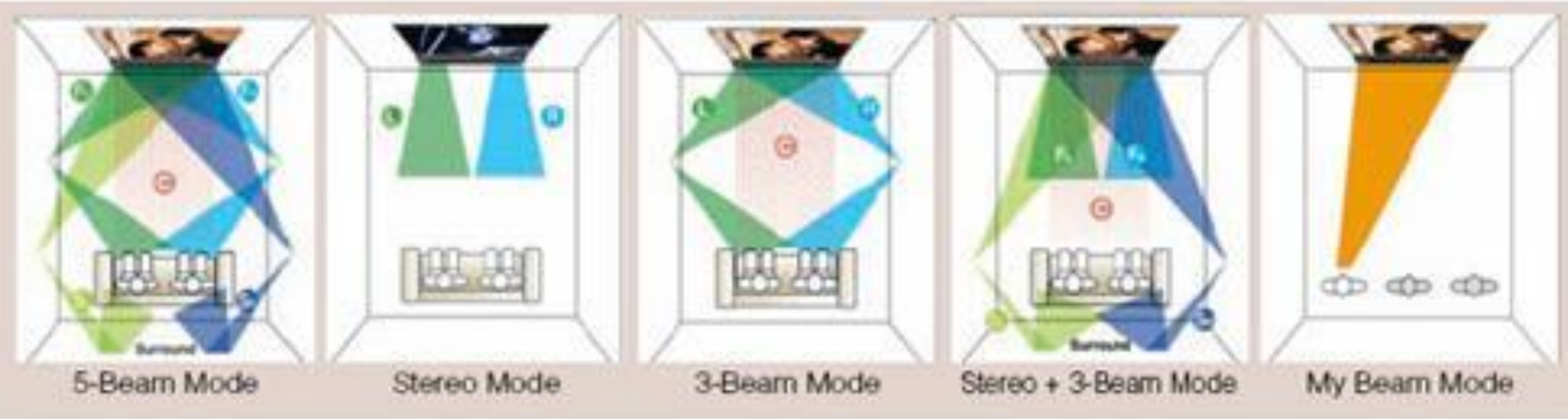
- YAMAHA Sound Projector line of products
  - Licensed technology from 1Limited (UK)
  - 6 different models

Under the hood:

- 40 drivers (2W)
- 2 woofers (20W)

- They make a compact model with 21 drivers

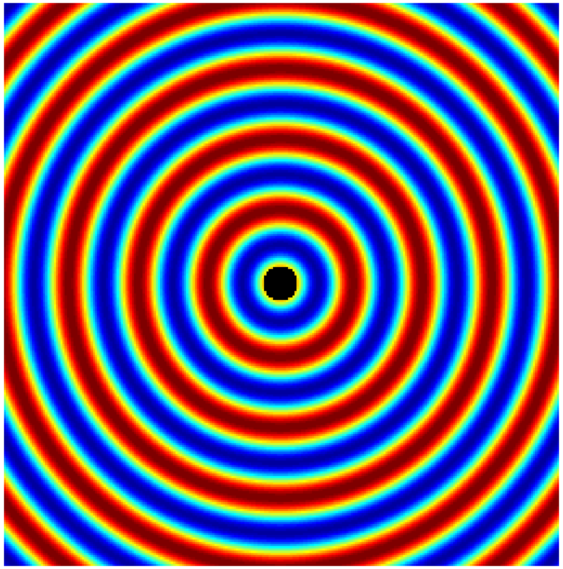
What can it do?



Focusing sound principle and generic beamforming

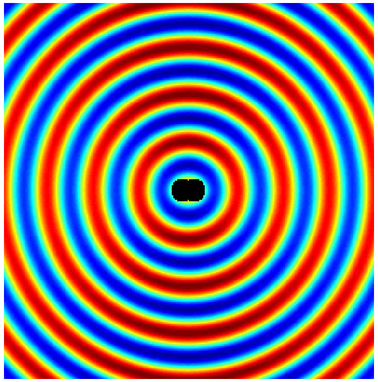
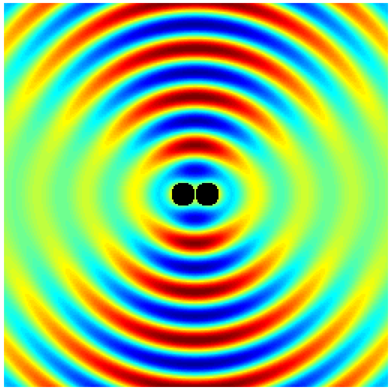
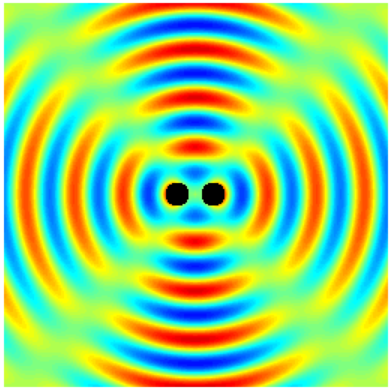
Jasha Droppo, Microsoft Research

A Single Point Source



- Speaker in the center of room.
- Radiates sound in all directions equally.
- Red and blue are high and low pressure waves.

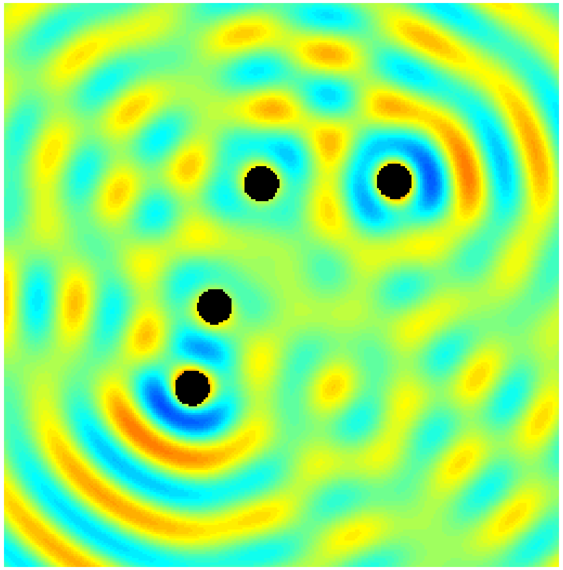
Two Point Sources

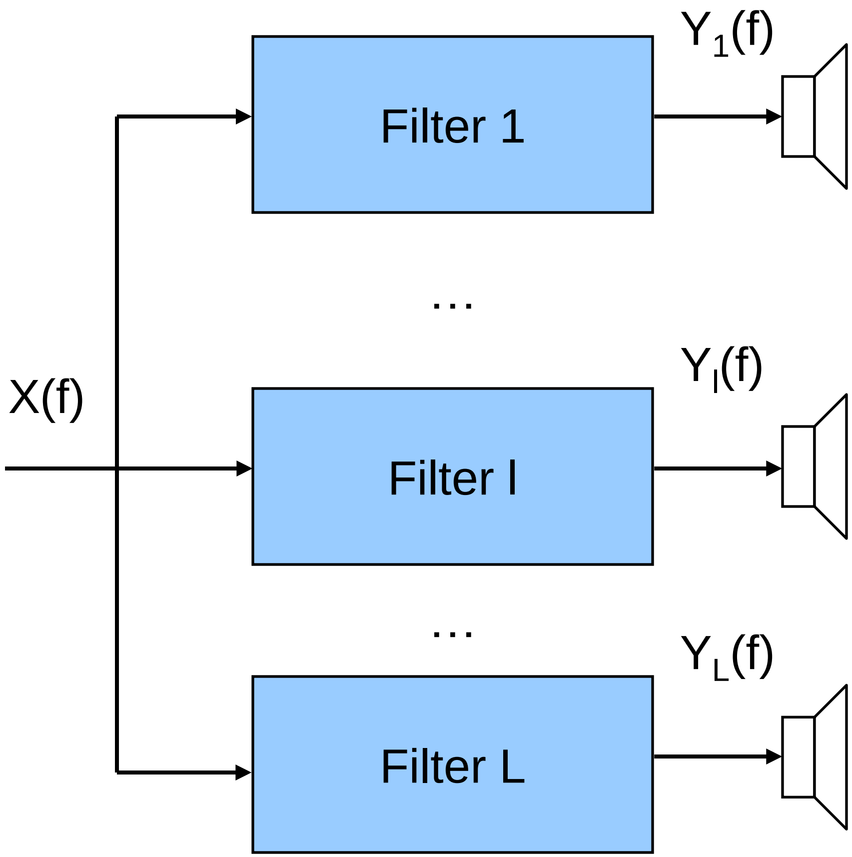
- The waves from two speakers overlap.
- Too close together, they appear like a single point source.
- As they separate, the pattern becomes more complex.

A Jumble of Point Sources

- Four speakers placed at random within the room, fed with the same source.
- Neighboring pairs of speakers broadcast audio depending on their relative positions.
- This would sound pretty awful.



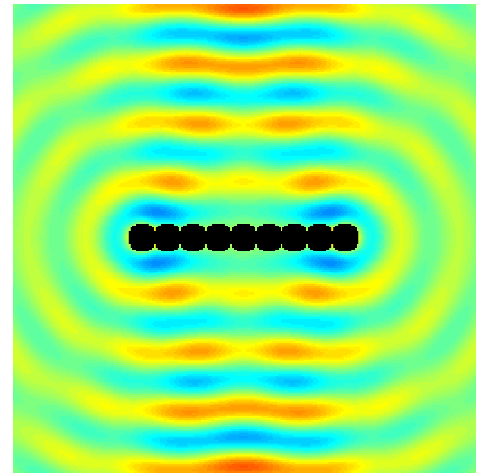
Beamforming

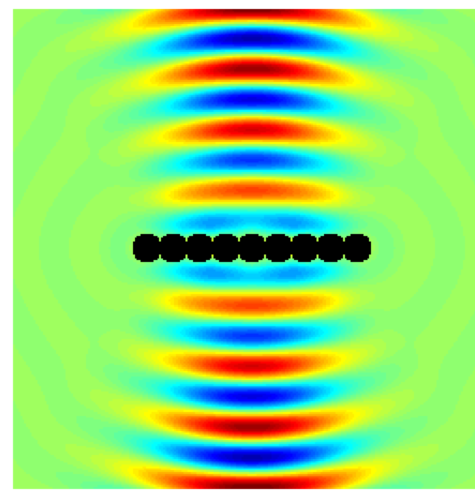


- Take the input signal
- Filter it with different for each loudspeaker filter
- Send the output to the loudspeaker
- Listen

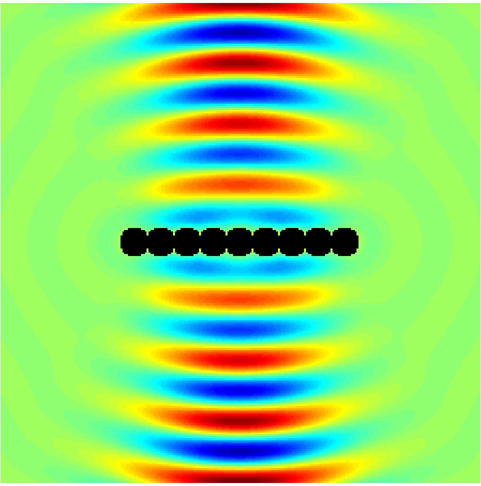
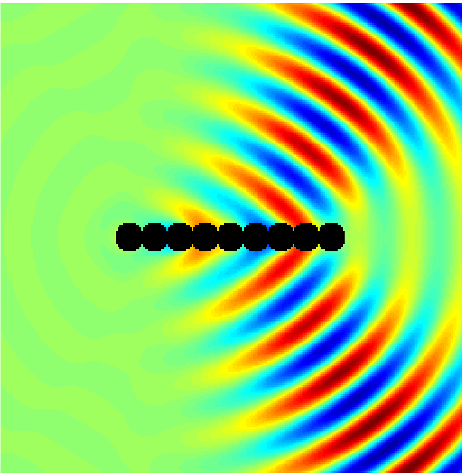
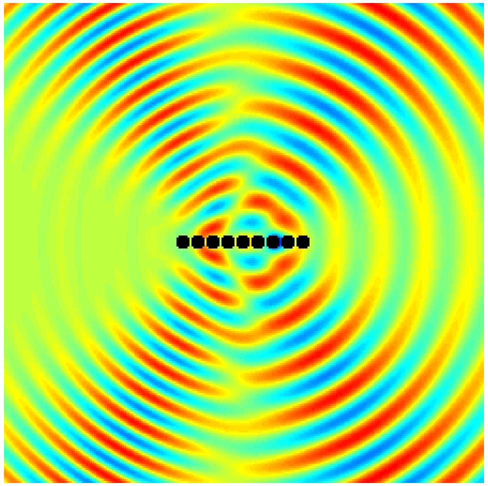
An array of Point Sources

- A linear array makes a nicer pattern by default compared to the jumble.
- (Top) nine speakers fed with the same source.
- (Bottom) slightly different signal sent to each speaker produces a more coherent pattern.





Steering the Array

- (Left) speakers fed with "no delay"
- (Center) speakers fed "linear delay"
- (Right) Because the process is linear, different sounds can be sent in different directions.

When Theory meets Reality

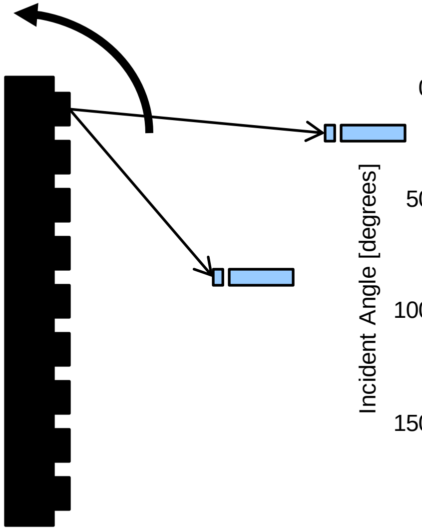
- The amplifier channels aren't identical.
- Each speaker's response isn't ideal.
  - Varies over frequency, angle, and distance.
- No two speakers are the same.
  - Manufacturing tolerances, baffling box effect.
- Which effects are important? What can we do to mitigate them?

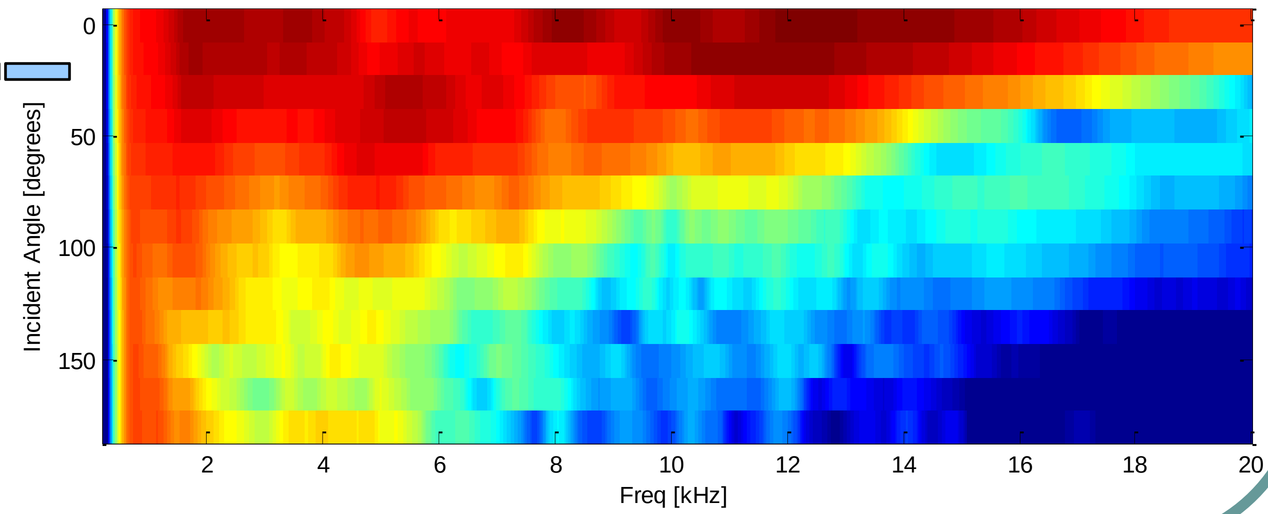
Practical Solutions (Easy)

- Ignore the problem
  - You can still get some steering of the sound, even though the components are non-ideal.
- Do simple calibration
  - Measuring or adjusting the relative gain of your channels can improve the system.

Practical Solutions (Moderate)

- Characterize the system
  - (simple) Measure or equalize signal gain through each channel.
  - (complex) For each speaker in the array, for 36 angles, at two different distances, measure the end-to-end impulse response.





Practical Solutions (Fun)

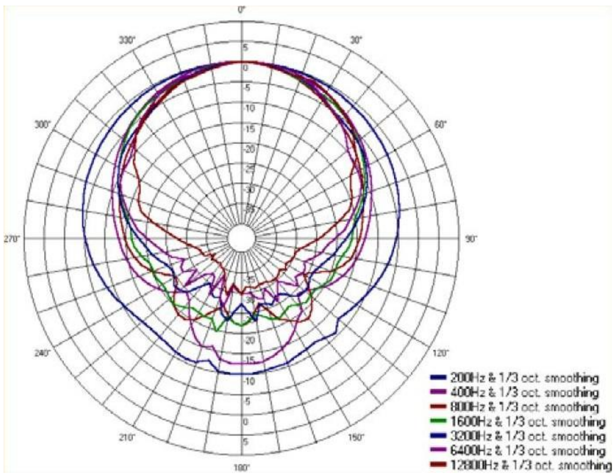
- Develop new math!

Robust beamformer design for loudspeaker arrays

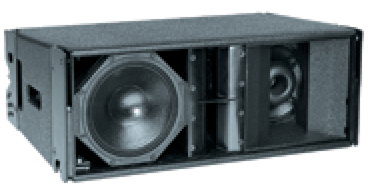
Ivan Tashev, Microsoft Research

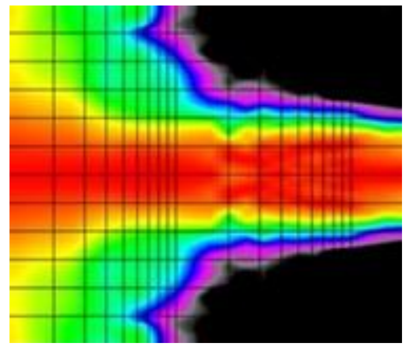
What we know so far?

- Loudspeakers have directivity pattern $U(f,\varphi,\theta)$

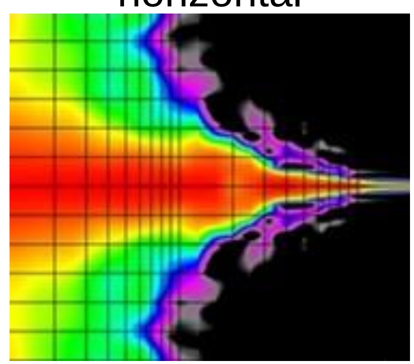


horizontal

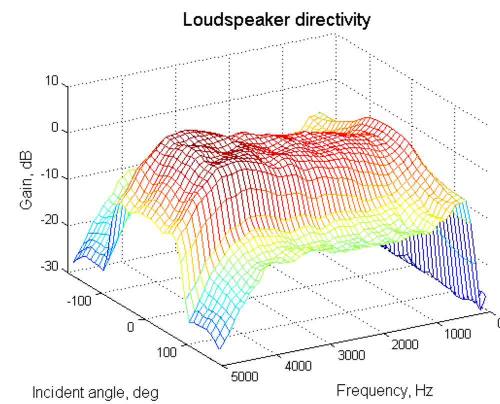


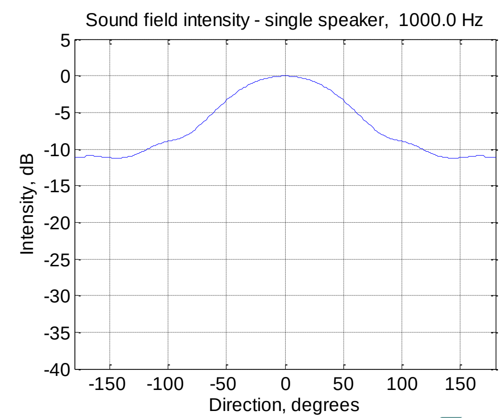


horizontal



vertical





Martin-W8LM **Monarc MLA6** **MSR Experimental**

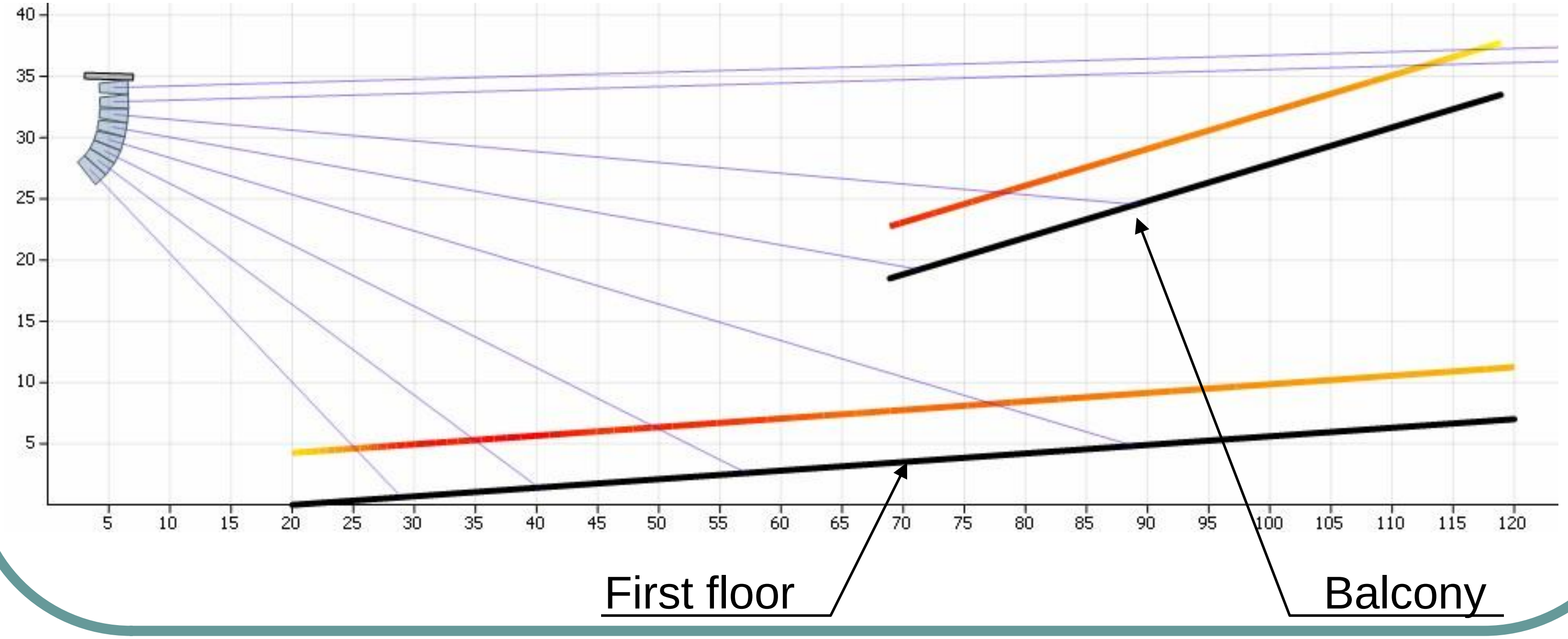
What we might want to do with an array of loudspeakers?

- To cover a large area with same sound level – sound reinforcement
- To focus the sound in a small area, or towards given direction
- To send multiple sound beams towards different directions
- To generate a diffuse sound field with no detectable sound source direction

How to cover a large area?

- Project sound beams, covering the area relatively evenly

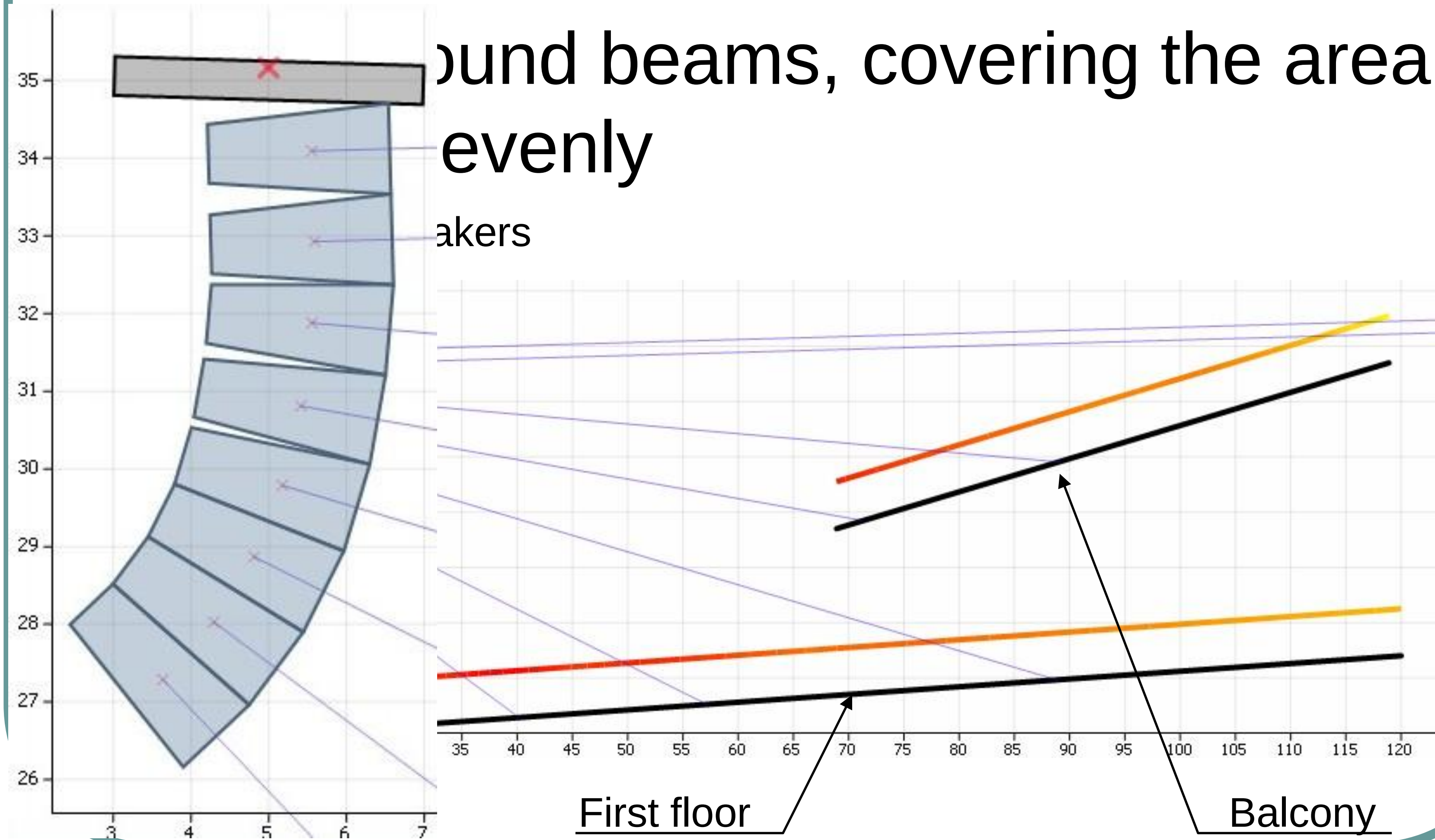
J-array of speakers



How to cover a large area?

ound beams, covering the area evenly

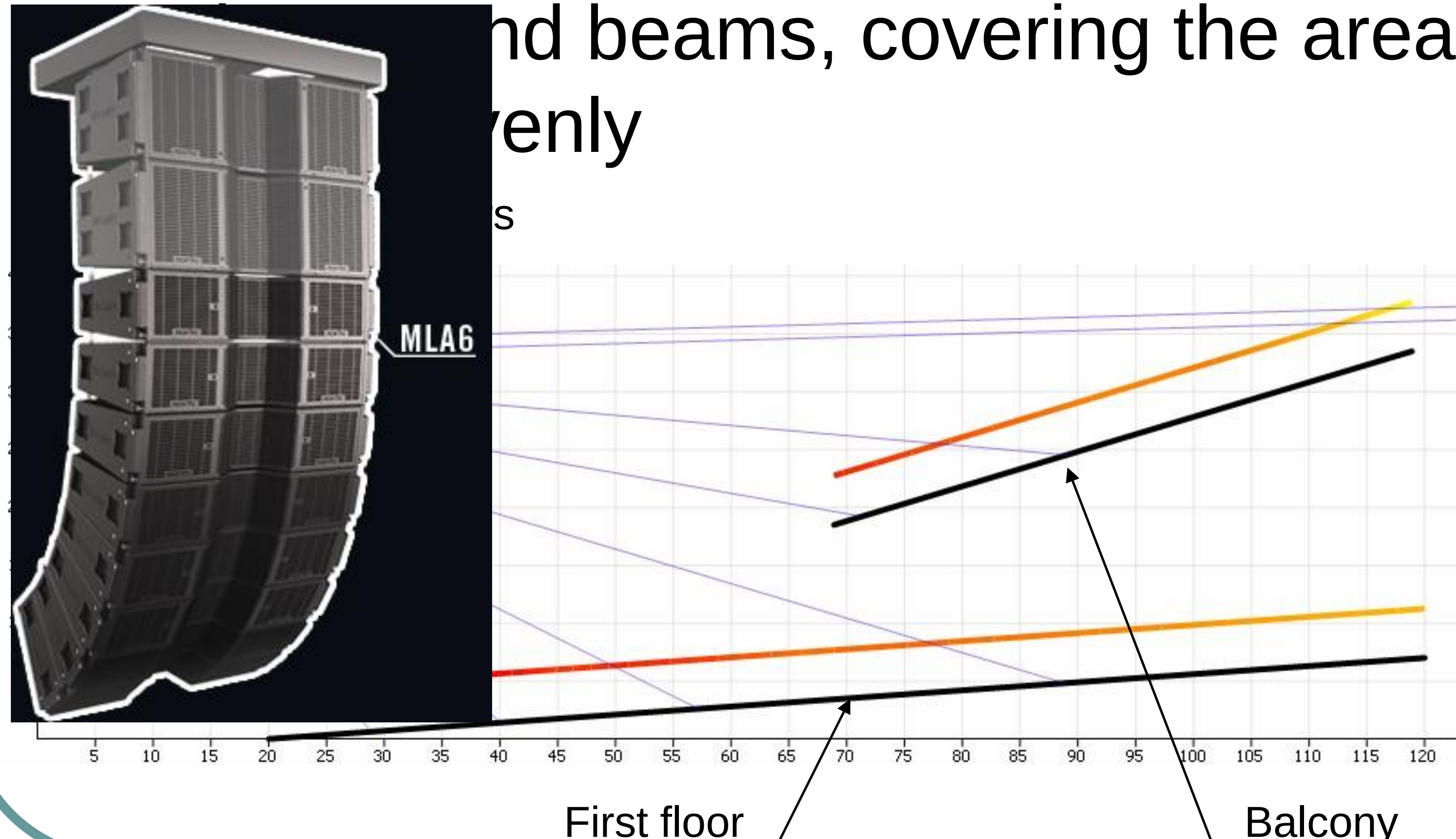
akers



How to cover a large area?

nd beams, covering the area
venly

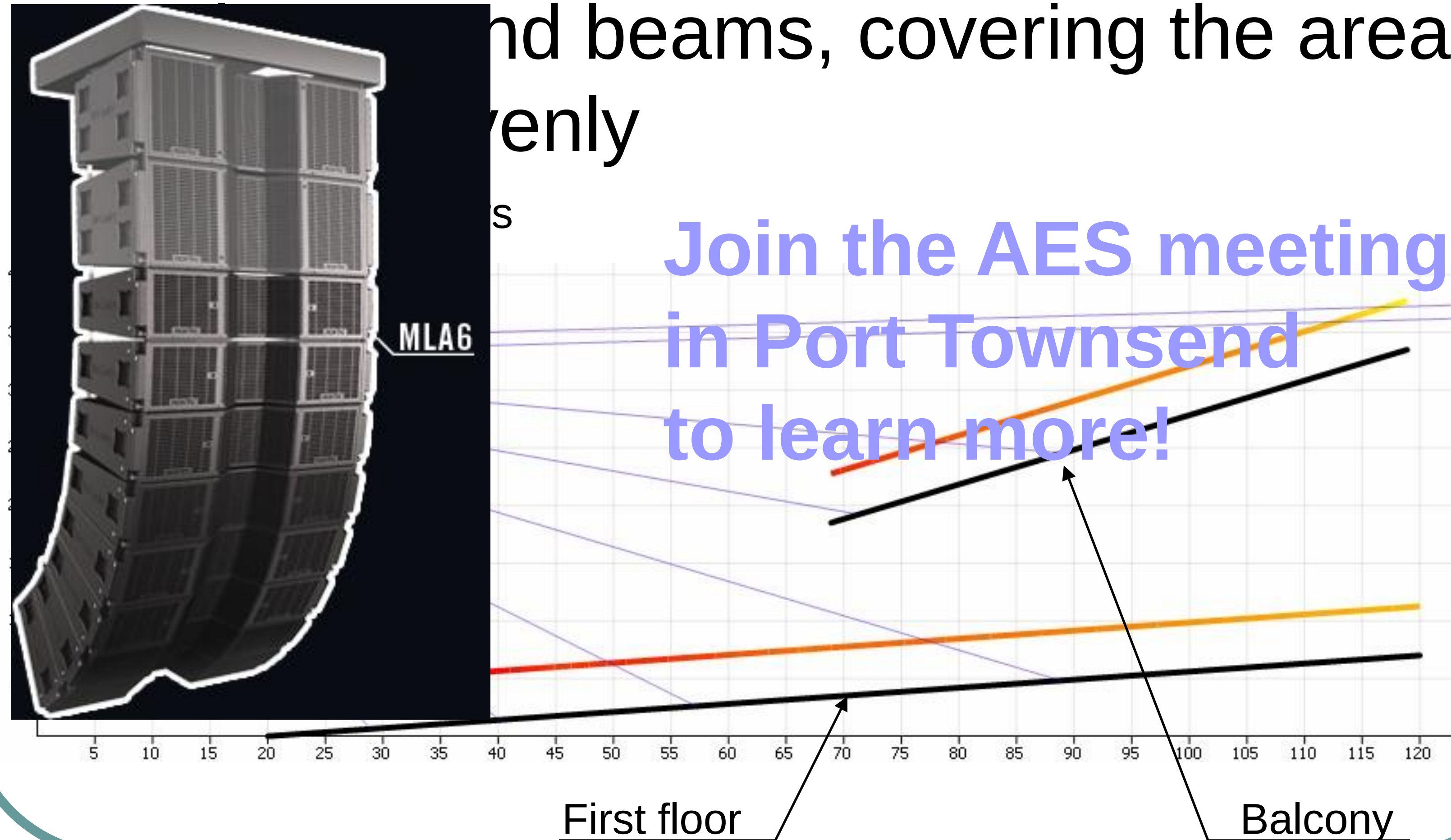
s



How to cover a large area?

…nd beams, covering the area …venly

…s



Join the AES meeting in Port Townsend to learn more!

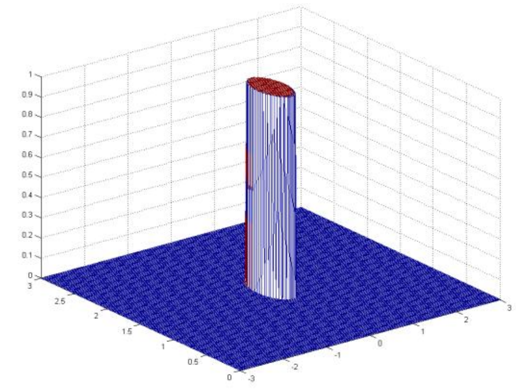
Focusing the sound?

- Generalized beamforming:

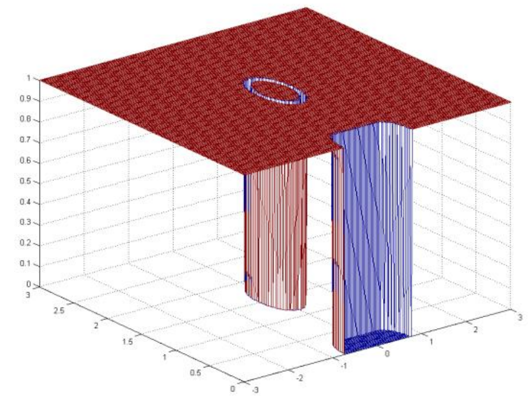
$$Y_l(f) = W_l(f).X(f) \quad l = 1 \div L$$

- How to design the filters?
  - given listening area $\mathbf{S_L}$
  - given silent area $\mathbf{S_S}$
  - find $W_l(f)$ such as to maximize

$$\mathbf{W}(f) = \underset{\mathbf{W}(f)}{\arg\max} \frac{\int_{S_L} \sum_{l=1}^{L} D(f,s) W_l(f) X(f) ds}{\int_{S_L} \sum_{l=1}^{L} D(f,s) W_l(f) X(f) ds} = \underset{\mathbf{W}(f)}{\arg\max} \mathbb{R}$$

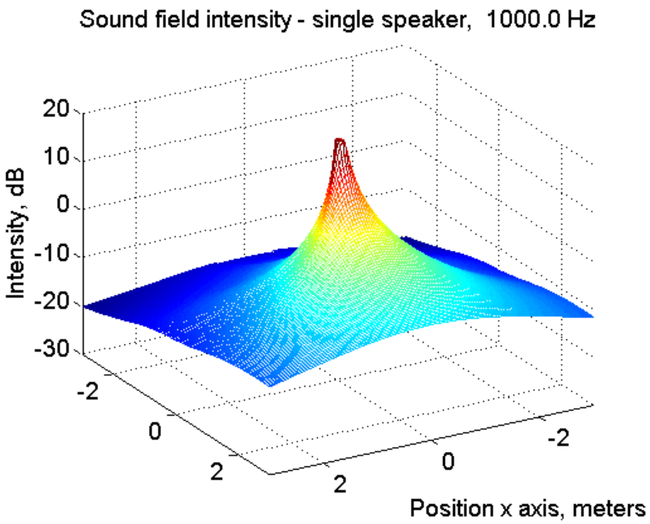


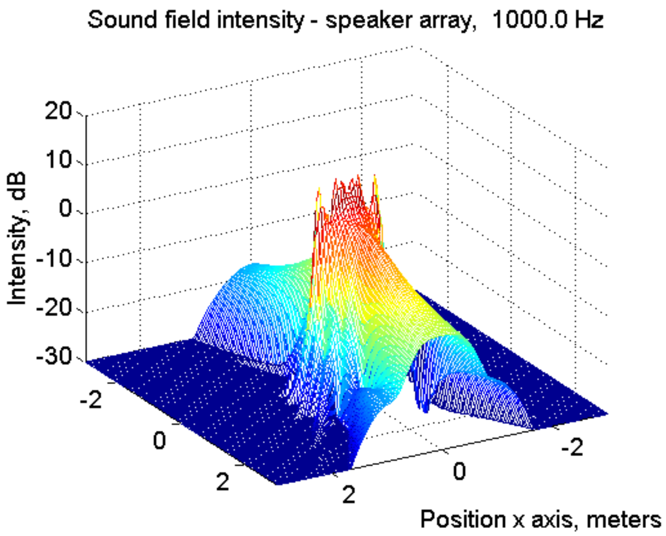
listening area

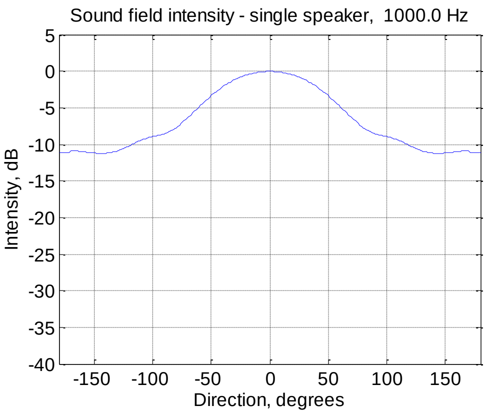


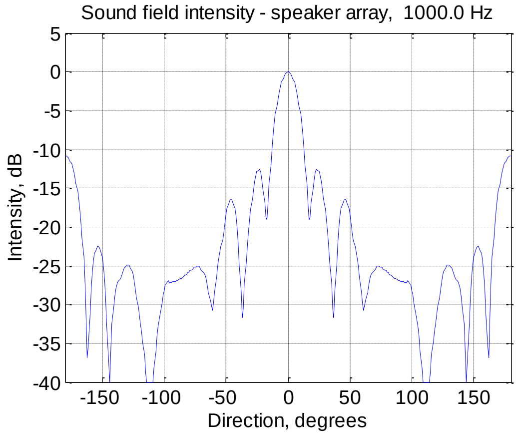
silent area

Cool! The theory works!



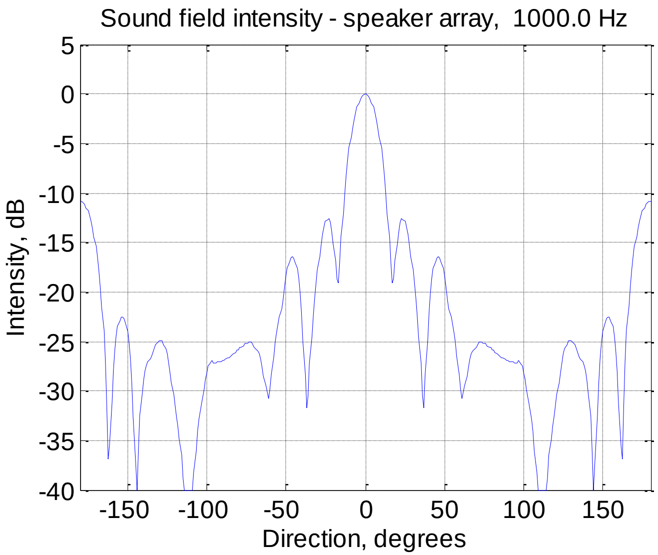




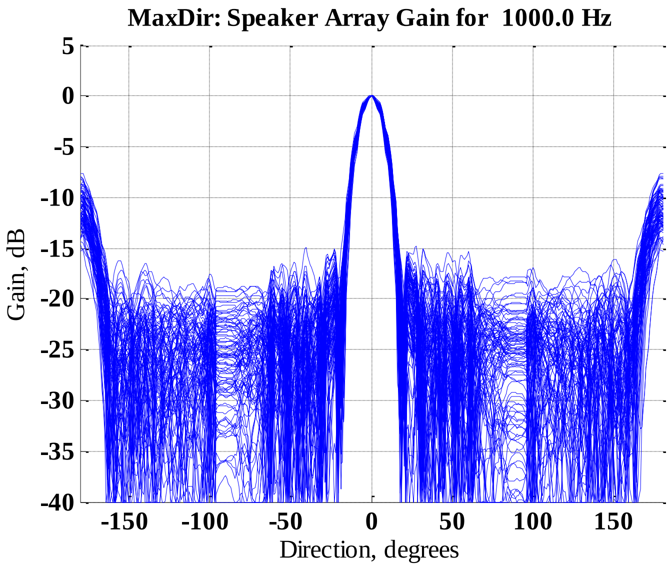


Works? Really?

- What if the loudspeakers are not exactly the same?



exact matching

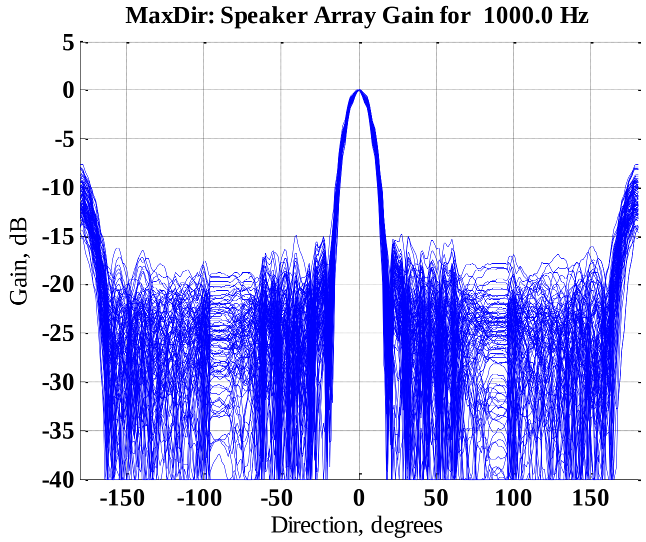


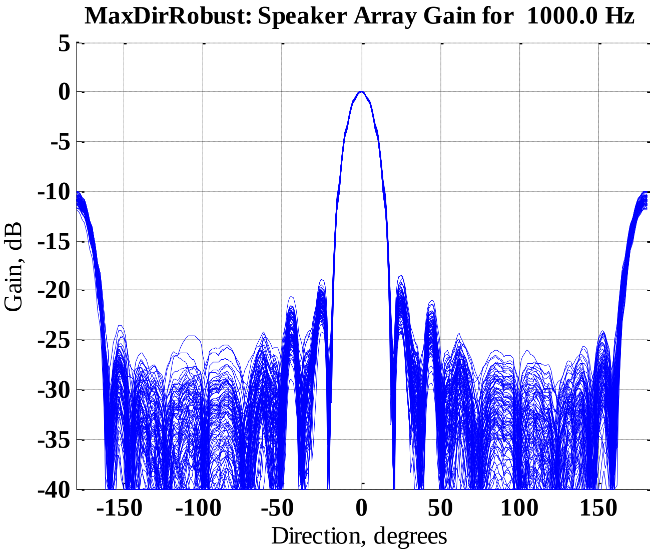
$$U_l(f,\varphi,\theta)=\bar{U}_l(f,\varphi,\theta)+\mathbb{N}\left(0,\sigma^2(f)\right)$$

Robust beamformer design

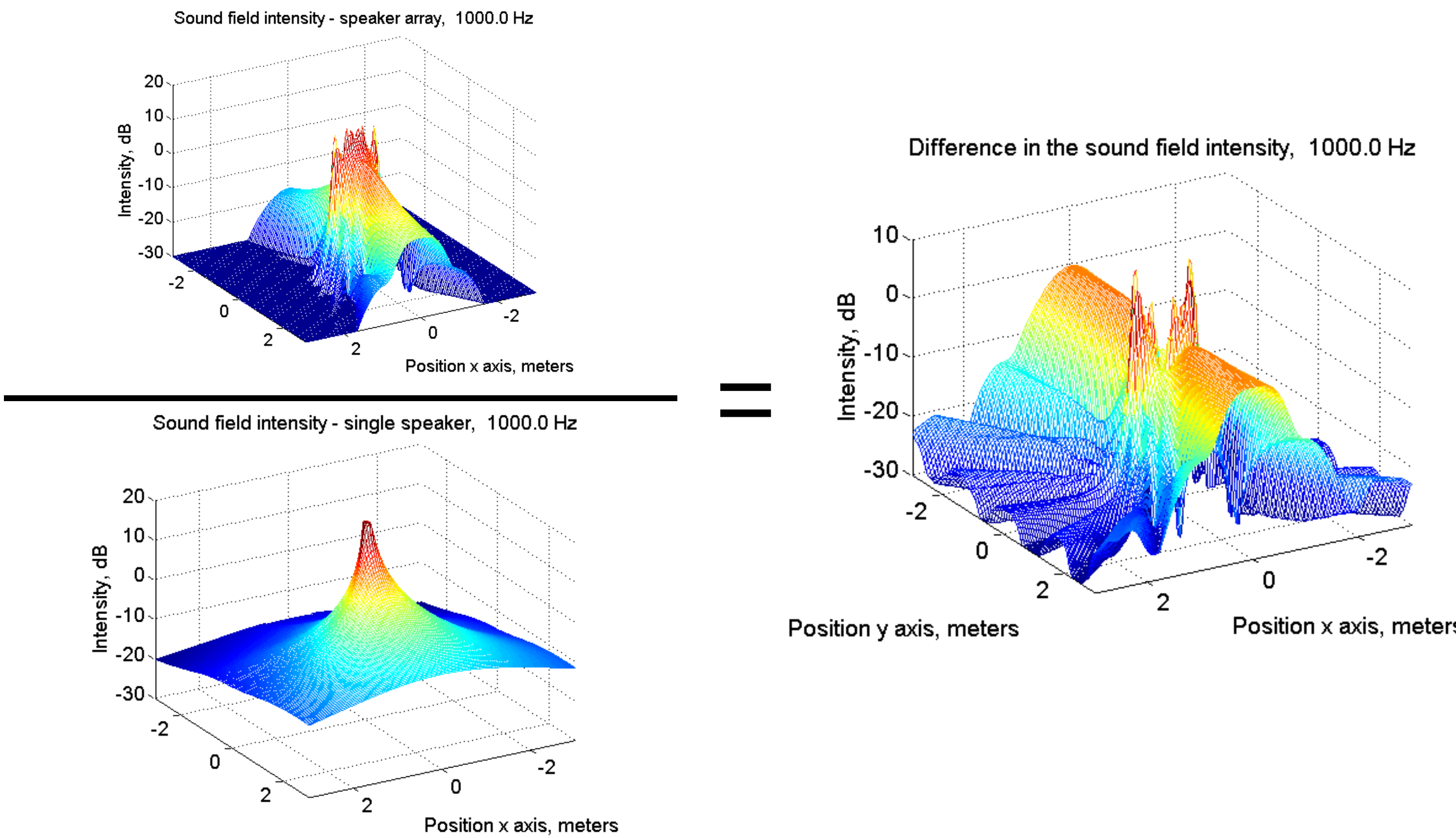
- After some derivations we find that we have to maximize:

$$\mathbb{R}_{\min} = \mathbb{R}\,\frac{1}{1+\frac{(2.5\sigma)^2}{2\left|\bar{R}_S\right|}\sqrt{P_{tot}}} - \frac{\frac{(2.5\sigma)^2}{2\left|\bar{R}_A\right|}\sqrt{P_{tot}}}{1+\frac{(2.5\sigma)^2}{2\left|\bar{R}_S\right|}\sqrt{P_{tot}}}$$



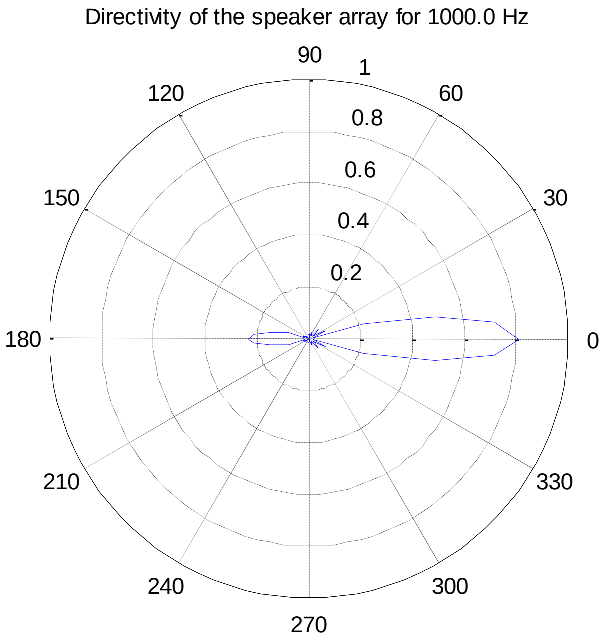


Not bad!



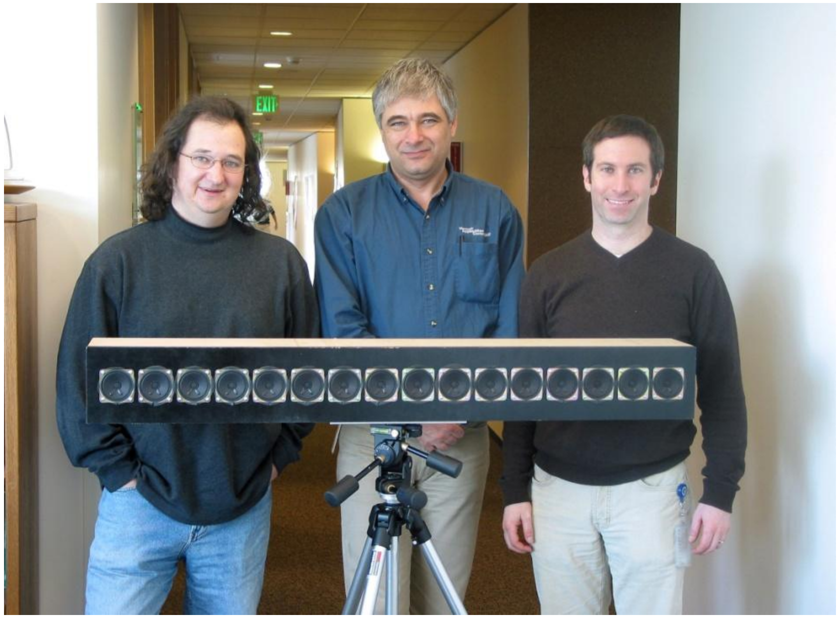
Sound field intensity - speaker array, 1000.0 Hz
Intensity, dB
20
10
0
-10
-20
-30
-2
0
2
2
0
-2
Position x axis, meters
Sound field intensity - single speaker, 1000.0 Hz
Intensity, dB
20
10
0
-10
-20
-30
-2
0
2
2
0
-2
Position x axis, meters
=
Difference in the sound field intensity, 1000.0 Hz
Intensity, dB
10
0
-10
-20
-30
-2
0
2
2
0
-2
Position y axis, meters
Position x axis, meters

Not bad! Not bad at all!



Is it real?

- Two demos for focusing the sound after the talk:
  - Focusing one beam towards the front of the array (the example so far)
  - Two beams simultaneously playing different sound tracks
- 16 element linear loudspeaker array



Generating diffuse sound with loudspeaker arrays

James (jj) Johnston, Microsoft

So far, what have we seen?

- Being able to synthesize a plane/circularly convergent wave has great advantages.
- You can synthesize such a wave without too much trouble with a loudspeaker array.

- What about the “diffuse” soundfield that one hears in a good acoustic venue?
  - It’s more or less the opposite of a direct wave.
  - Perceptually, it’s decorrelated at the two ears.
  - Acoustically, it doesn’t actually have to be decorrelated.

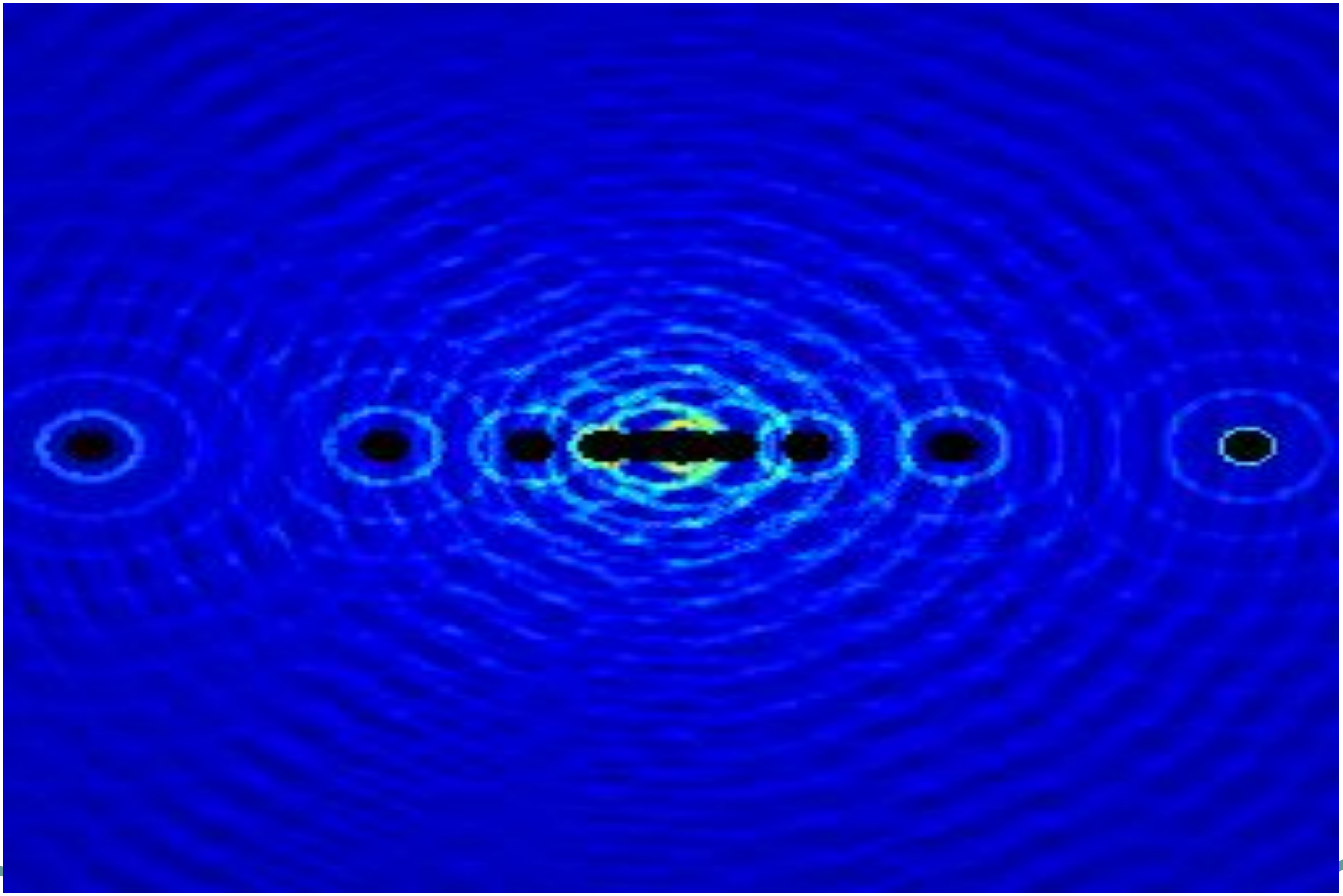
Why would we do this?

- Simply put, when we issue a one-point recording of a diffuse waveform from a single loudspeaker, we turn it into a single-point-source version of a diffuse waveform.
  - It is, therefore, heavily correlated at the ears, both perceptually and mathematically.

So?

- What we do, then, is create a pattern that is diffuse in terms of the hearing apparatus.
  - This means that in each critical band, onsets for the signal envelope are scrambled somehow.
  - This onset is different for adjacent critical bands.
  - It helps if the frequency response is also “scrambled”.
- You can “overlay” a listening room’s acoustics via first arrival from an array speaker.

An example:



Diffuse sound demo

Since a beam can be steered, etc, as you've seen from the other talks, we are going to demonstrate a fixed direct beam (2 meters directly in front of the center of the array) along with a diffuse radiation superimposed on the direct beam.

In order to experience the different effects, all that is necessary is to walk up on axis between the two arrays and listen as you approach the 'X' on the floor.

In a real application, it would be, of course, possible to provide different direct and indirect signals.

Demos

- Focusing sound
  - Beam focused towards the array broadside
- Multiple beams
  - Two beams, one broadside, one under 45 degrees
- Diffuse sound
  - Stereo sound track, with both direct and diffuse radiation
- Home entertainment
  - Yamaha 1100 speaker array for surround sound